UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
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Development and management of collective network and cloud computing infrastructures

Roger Baig Viñas

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Advisor: Leandro Navarro Moldes

Industrial advisor: Ramon Roca i Tió

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Roger Baig Viñas
roger.baig@guifi.net
rbaig@ac.upc.edu

Universitat Politècnica de Catalunya

Computer Networks and Distributed Systems Group (CNDS)
Departament d'Arquitectura de Computadors (DAC)

Jordi Girona 1-3 C6, D6
08034 - Barcelona, Catalonia

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`http://people.ac.upc.edu/rbaig/phd_latest.pdf`

[1] TDX: http://www.tdx.cat, CBUC: http://ccuc.cbuc.cat, CSUC: http://www.csuc.cat, NDLTD: http://www.ndltd.org

Abstract

In the search and development of more participatory models for infrastructure development and management, in this dissertation we investigate on models for the finance, deployment and operation of network and cloud computing infrastructure. Our main concern is to overcome the inherent exclusion, in the capability of participation in the processes of development and management as well as in the right of use of current dominant models. Our work starts by studying in detail the model of Guifi.net, a successful bottom-up initiative for building network infrastructure, generally referred as community networks (CNs). We pay special attention to its governance system and economic organisation, as we argue that these are the key components of the success of this initiative. Then, on one side, we generalise our findings for any CN aiming at becoming sustainable and scalable and, on the other side, we explore the suitability of the Guifi.net model to cloud computing infrastructure. As a result of both, we coin the attribute *extensible* to refer to infrastructure that is relatively easy to expand and maintain in contrast to those naturally limited or hard to expand such as natural resources. The Guifi.net model is deeply rooted in the commons and, thus, the last has left a profound imprint in our work, in particular Elinor Ostrom's work. Our results indicate that the Guifi.net model is applicable to any extensible infrastructure and that Ostrom's principles are not only valid for this particular kind of infrastructure but also for any kind of infrastructure in general.

This work has been developed as an industrial doctorate. As such, it combines academic research with elements of practice and pursued an effective knowledge transfer between academia and the private sector. Given that the private sector's partner is a not-for-profit organisation, the effort to create social value has prevailed over the ambition to advance on the development of a specific industrial product or a particular technology.

Keywords *Collective infrastructure, Guifi.net, Community networks, Cloud commons, Shared infrastructure, Infrastructure as commons, Infrastructure deployment, Infrastructure management*

Resum

En la recerca de models més participatius per a la provisió d'infraestructures, en aquesta tesi s'investiga sobre un nou model per al desplegament i l'operació d'infraestructures de xarxa i computació. La nostra principal preocupació és superar l'exclusió inherent, en la capacitat de participació en el procés d'aprovisionament, així com en el dret d'ús, dels models dominants actuals. El nostre treball comença estudiant amb detall el model de Guifi.net, una reeixida iniciativa de base per a la construcció d'infraestructures de xarxa, generalment denominada xarxes comunitàries (*community networks* en anglès). Prestem especial atenció al seu sistema de govern i organització econòmica, ja que defensem que aquests són els components clau de l'èxit d'aquesta iniciativa. A continuació, per un costat generalitzem els resultats per a qualsevol xarxa comunitària amb l'objectiu de convertir-se en sostenible i escalable i, per l'altre costat, explorem la idoneïtat del model de Guifi.net a la infraestructura de computació en núvol. Com a resultat de tots dos, encunyem l'atribut *extensible* per referir-nos a una infraestructura relativament fàcil d'expandir i mantenir en contrast amb aquelles que són naturalment limitades o difícils d'expandir, com els recursos naturals. El model Guifi.net està molt arrelat en els comuns i, per tant, aquest ha deixat una empremta profunda en el nostre treball, en particular l'obra d'Elinor Ostrom. Els nostres resultats indiquen que el model Guifi.net espot aplicar a qualsevol infraestructura extensible i que els principis d'Ostrom no només són vàlids per a aquest tipus d'infraestructura particular, sinó també per a qualsevol tipus d'infraestructura en general.

Aquest treball s'ha desenvolupat com a doctorat industrial. Com a tal, combina la investigació acadèmica amb elements de pràctica i persegueix una transferència efectiva de coneixement entre l'àmbit acadèmic i el sector privat. Atès que el soci del sector privat és una organització sense ànim de lucre, l'esforç per crear valor social ha prevalgut en l'ambició d'avançar en el desenvolupament d'un producte industrial específic o d'una tecnologia particular.

Paraules clau *Infrastructura col·lectiva, Guifi.net, Xarxes comunals, Núvol comunal, Infraestructura compartida, Infraestructure de comuns, Desplegament d'infraestructures, Gestió d'infraestructures*

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List of publications

Main publications

Articles in journals

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List of acronyms

ANNGTS access networks to next-generation telecommunication services

AP access point

APC Association for Progressive Communications

API application programming interface

B4RN Broadband for Rural North

BEREC Body of European Regulators of Electronic Communications

CAPEX capital expenditure

CATNIX Catalan neutral internet exchange point

CBPP commons-based peer production

CC community cloud

CDN content delivery network

CN community network

CNMC Comisión Nacional de los Mercados y la Competencia

CPR common-pool resource

CV coefficient of variation

CXOLN Llicència de comuns per a la xarxa oberta, lliure i neutral (Free, open and neutral network commons license)

DIY do-it-yourself

DRL Demand-readiness level

DSL Digital subscriber line

EC European Commission

EU European Union

EXO Associació expansió de la xarxa oberta

FBSS file backup and synchronisation service

FONN free, open and neutral network

FTTH fibre to the home

GSM Global system for mobile

IaaS infrastructure as a service

ICT information and communications technology

ICT4D information and communications technology for development

IEEE Institute of Electrical and Electronics Engineers

IoT internet of things

IP Internet protocol

ISOC Internet Society

ISP internet service provider

ITU International Telecommunication Union

IXP internet exchange point

LTE Long-term evolution

MRE maximum relative error

NGA next generation access network

NGO non-governmental organisation

NOC network operation centre

NRA National regulatory authorities

NSP network service providers

OAN open access network

OF fibre optic

OPEX operational expenditure

P2P peer-to-peer

PaaS platform as a service

PoPIX territorial point of presence – Guifi.net specific

PPP public-private partnership

RA research activity

REST representational state transfer

RIPE-NCC Réseaux IP Européens Network Coordination Centre

ROI return of investment

RQ research question

SaaS software as a service

SDG Sustainable development goals

SLA service-level agreement

SLO service-level objective

SME small and medium-sized enterprise

TRL Technology readiness level

TV television

UDHR Universal declaration of human rights

UNESCO United Nations Educational, Scientific and Cultural Organization

UPC Universitat Politècnica de Catalunya

VOIP Voice over IP

WiFi Wireless fidelity

XAFOGAR Xarxa de fibra òptica de la Garrotxa (Fibre optic network of Garrotxa)

Chapter 1

Introduction

1.1 Context

In this dissertation, we investigate on the Guifi.net model, a new model for the financing, deployment, operation, maintenance and operation of telecommunications infrastructure, and explore its applicability to cloud computing infrastructure as contributions in the search of new models for infrastructure development and management that overcome the limitations of the currently used.

1.1.1 Motivation

Our research fits for a PhD due to the following main reasons:

Disruptive model Due to its underpinning principles, i.e. (i) a unified infrastructure is collectively built and managed in a non-discriminatory manner, (ii) is made available to everyone on equal and non-discretionary terms for any purpose, including, but not limited to, the commercial exploitation, and (iii) the participation in the construction and maintenance of the infrastructure is made according to its usage, the Guifi.net model is characterised by being:

- **Bottom-up** The inclusion of new participants that are free from any conflict of interest and that are not subject to the public and private sectors inertia allows radical proposals entailing profound reforms, opening the door to the reactivation of local participation and other unforeseen scenarios.
- **More efficient** The relocalisation of the economy as well as the empowerment of the civil society and its implication in the governance affairs, puts the Guifi.net model is in a better position to confront many of the gaps of other currently known models without diminishing effectiveness in the areas where these models perform satisfactorily.
- **Scalable** There are no clear evidences of suffering from insurmountable scale limitations, either in practice or in theory.
- **Exportable** The model seems applicable to other infrastructures and facilities.
- **Complementary** The case studies lead to the conclusion of satisfactory coexistence with other currently existing models.[1]

[1] non-problematic coexistence facilitates the adoption of the new model in underserved areas. Later, these deployments can be used as a reference to expand the model in areas with other infrastructure already in place.

Existence of at least one large-scale success case Guifi.net [67] is a self-sustained citizen driven telecommunications project started in 2004 in Catalonia that currently accounts for +50.000 households connected using Wireless fidelity (WiFi) and fibre optic (OF) technologies that operates according to the commons model, "resource management principle by which a resource is shared within a community" according to [55]. Broadly speaking, Guifi.net falls within the so-called CNs, a term used to refer to bottom-up initiatives aimed that building network infrastructure by pooling resources and managing it collectively. Guifi.net is widely recognised as the largest and the most sophisticated CN in the world.

Complexity and multidisciplinarity The research objectives involve a complex analysis that involves several disciplines including social sciences, economics, law and technology. According to our experience, such objectives can only be accomplished through a long term project like a PhD.

Lack of literature CNs in general and Guifi.net in particular have attracted significant attention from many actors including the academia for their potential in helping to reduce the digital gap and their innovative ways to address some challenges in different fields like technology or law among other reasons, but despite this interest, no one to the best of our knowledge has studied a case in such detail and has explored its implications as we present it in this work.

Alignment with the UNESCO SDGs Many of our contributions are well-aligned with the United Nations Educational, Scientific and Cultural Organization (UNESCO) Sustainable development goals (SDG) [151] in general and to some of them very specifically. The advances towards more efficient models for infrastructure development and management through scientific research fall completely within into SDG9 *Industry, Innovation, and Infrastructure*, and the promotion social economy, ethic work, and youth employment into SDG8 *Decent work and economic growth*. Ethical and efficient infrastructure development contributes to SDG11 *Sustainable Cities and Communities* and to SDG12 *Responsible Consumption and Production*. Enabling effective means for civil society engagement in the development and governance is among the global targets of SDG17 *Partnerships for the Goals*. And, last but not least, the commitment to make infrastructure ubiquitous has direct impact on SDG10 *Reducing Inequality*.

1.1.2 Industrial doctorate

This dissertation has been developed under the Industrial Doctorates Plan of the Government of Catalonia [1]. This plan promotes the development of strategic research projects within a company through private sector and research institutions partnerships. Strategic research projects are expected to combine academic research with elements of practice to tackle challenges of strategic importance for the industry and must involve substantial knowledge transfer bidirectionally. In the case of this dissertation the collaboration has been established between the Universitat Politècnica de Catalunya (UPC)[2] and the non-governmental organisation (NGO) Fundació privada per a la xarxa oberta lliure i neutral, Guifi.net (Private foundation for the open, free and neutral network – Guifi.net[3]), the Guifi.net foundation or simply the Foundation henceforth [58]. The nature of the private sector partner involved implies an expected outcome with a strong

[2] https://www.upc.edu/en
[3] https://fundacio.guifi.net/en_US/

social value more than contributing to the development of a specific industrial product or a particular technology.

The research objectives, the methodology as well as the resources made available are specified in the collaboration agreement, signed in September 2016. Through this Industrial doctorate the Guifi.net foundation pursued the strengthening and dissemination of the model that this NGO together with the Guifi.net community had been developing and using for more than a decade. The tasks agreed include (i) a review of the existing literature related to the research, (ii) an accurate analysis of the work already done, (iii) the identification and description of possible inconsistencies or gaps, (iv) to make recommendations and to test solutions, and (v) to disseminate the results in the research and the industry fora, and in the policy-making and practitioners environments. For UPC this was an opportunity to advance in the research in the fields of CNs and the commons, an activity started in 2011 and that has entailed three European research projects (FP7-CONFINE[4], FP7-Clommunity[5] and H2020-netCommons[6]) and half a dozen PhD dissertations.

1.2 Problem statement

1.2.1 Drawbacks and limitations of current dominant models

In western society the current main models for infrastructure development and management are (i) the public sector model, (ii) the public-private partnership (PPP) model, and (iii) the private sector model. In the public sector model, the infrastructure and related services are provided entirely by the public administration. In the PPP they are provided through (a great variety of) collaborative agreements between the public and the private sector. In the private sector model, the infrastructure and the services are entirely provided by the private sector.

Although there is no clearly defined criteria for mapping every kind of infrastructure to a specific model, some patterns can be identified. For example, in most countries, while the justice system is run by the public sector, the telecommunications sector has been fully liberalised. Moreover, in some types of infrastructures the different models coexist like, for instance, in the education system, in which, in many countries there is offering according to the three models. Coexistence of models is also possible in the same physical infrastructure. In some countries the railway network is funded and owned by the state but it is operated by one or several private companies.

These models have made an undeniable contribution to achieve the impressive level of development of western society. Nonetheless, in our view, all of them suffer from a number of drawbacks and design limitations, that we summarise in Figure 1.1 and discuss below. To begin with, in terms of participation, all of them take a strong top-down approach in practice, either by nature in the case of public intervention or due to the relentless business concentration in the liberalised private sector. As a consequence, civil society has little chance in theory and no chance in practice to effectively engage in any of the process of infrastructure development and management and, thus, citizens are limited to become mere consumers.

The public sector model, as a result of the massive liberalisations and privatisations of the past few decades, is currently limited to some particular infrastructures, all of them out of the

[4]EC Grant agreement number 288535, 09/2011-08/2015 (http://confine-project.eu/).
[5]EC Grant Agreement number 317879, 01/2013-06/2015 (http://clommunity-project.eu/).
[6]EC Grant Agreement number 688110, 01/2016-12/2018 (https://netcommons.eu/).

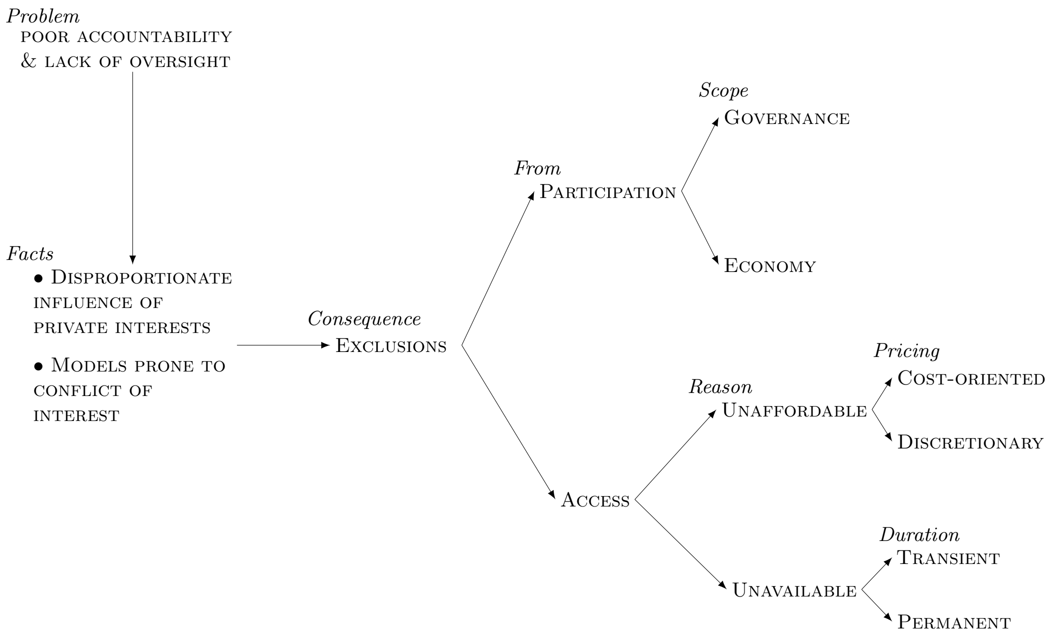

Figure 1.1: Limitations of main current infrastructure models

immediate scope of this dissertation. Moreover, probably the most efficient way to have an impact on these matters is through the political action, which is also outside the scope of our work, at least as a core activity. Therefore we stopped here its analysis.

As for the PPP and private sector models, in general, the utilisation of the PPPs is restricted either to those areas and services that the private sector would leave unattended without public backing or to those systems that are considered too critical for society to be left in the hands of private sector exclusively[7]. PPPs are also used to shape the development of a service or an infrastructure in a certain way.

Examples of the utilisation of both models in infrastructures and services that completely fall into the scope of our work abound. It is well-known that the private sector has invested a lot of money and effort to develop network and cloud computing infrastructure worldwide, thanks to which today we have high performance computer centres and high-speed wholesale networks. What is perhaps less known is contribution made by the public sector, without which the overall landscape of information and communications technology (ICT) would be totally different. Given the liberalised nature of the sector, traditionally this contributions were made through funds to private companies. However, since the direct allocation of public funds to specific private corporations jeopardises free competition, these contributions are increasingly bound to PPPs which must make available the resulting infrastructure to all the stakeholders in equal terms. Hence, we analysed both models in further detail.

PPPs have been widely criticised. In terms of efficiency, after +40 years of being massively adopted, the evidence of better performance in terms of value for money is unclear [43, 78] and, thus, the diversion of public funds to the private sector has not yet been justified. In terms of social impact, some PPPs have been blamed for being *de facto* privatisations [158] and for entailing a difficult to revert loss of know-how of the public administration [109], both leading to

[7]Like the healthcare or the education systems, although there are remarkable variance across countries in terms of which of these services are and the degree of public intervention.

social disempowerment. And in terms of risk taking and accountability, several PPPs studied have been described as riskier for the state than for the private companies involved and lacked transparency [109]. Furthermore, we can argue that, in addition to these specific problems, many of the PPPs also suffer from most of the problems inherent to the private sector model that we discuss in the following paragraphs due to poor contract arrangements.

A plausible reason behind the PPP inefficiencies can be a consequence of the fact that citizens have refrained from exercising their oversight role over the public administration due to its top-down and hermetic management. This disregard has allowed the private sector to impose a totally one-sided view at legislative level as well as at executive level. Because the PPPs are no exception, they are essentially managed as private assets, meaning that they suffer from similar drawbacks. We, henceforth, focused our efforts in the analysis of the private sector.

With regard to the private sector, it must be borne in mind that the genuine ultimate goal of any private (for-profit) initiative is to maximise the profit of the investors, and infrastructure assets are managed accordingly. Thus, when it comes to the private sector, infrastructure is highly exposed to speculative practices and speculative bubbles. Hence, the conditions under which infrastructure is made available in the market can radically change at any given time or even can become totally unavailable, regardless how critical is for society.

Shortage of private sector funding result in transient infrastructure unavailability because, the limited funding resources available are always invested in the areas with quickest return of investment (ROI). The result is that some areas are overprovisioned while others remain underserved and the constant evolution of the available technology only exacerbates the differences. Moreover, unavailability becomes endemic under certain population density without the public intervention either through public investment or through regulatory measures.

Together with the already discussed infrastructure unavailability, pricing is the other main source of exclusion from access. The maximisation of profit criterion frequently translate into product prices and service fees that are frequently higher than they would be on a cost-oriented basis, meaning that the section of the population that could afford the latest but not the first is artificially excluded from enjoying these services or products and those who can still afford them have to pay an excessive cost. Furthermore, inefficiencies, such as infrastructure duplication or transaction costs, necessarily translate into increased costs and higher prices.

Yet, not even cost-oriented pricing and inefficiencies eradication alone can avoid exclusion on the grounds of affordability due to the large amount of the world's population living in extreme poverty and distress.

1.2.2 Expected features

The limitations and drawbacks of current models for infrastructure development and management makes necessary to explore new alternatives. Here we present the features that, in our view, alternative models must meet, in whole or in part.

In terms of new models they must either entail more participatory organisational systems to allow an effective inclusion in the governance and the decision-making processes, or contribute to drastically reduce the amount of funding needs for business engagement to enable the currently excluded companies and entrepreneurs to join the economic ecosystem. Making the concept of "economy" more flexible and local to enable complementary means of business participation helps to integrate into the system small capitals that currently remain unused.

Lowering the capital requirements not only makes the system healthier from the business participation perspective but also has a direct impact on availability as there is more investment in infrastructure, specially if the model also allows investment by the citizens to promote specific deployments, like, for instance, the neighbouring community that join forces to deploy OF at their homes. The reactivation of local economies facilitate the customisation of services to better suit specific realities, offering, for instance, low-cost services for low income families, directly diminishing exclusion by price. Another field of action to bring prices down is to reduce total costs through efficiency increase. Ensuring an optimal use of the existing infrastructure before deploying a new one or to improve the business processes has a direct effect in this regard.

Finally, the candidate models must allow measures of last resort to ensure that no one is being excluded from access either due to affordability reasons in properly served regions or due to the lack of available infrastructure, because even in the most optimal situation some access problems are likely to persist. Essentially, these measures can be either based on public subsidies or on internal wealth redistribution mechanisms. The second are preferable to the first because the management is done organically and more likely to be sustainable. Resources made artificially scarce, like OF, are specially suitable for testing wealth redistribution mechanisms based on radical new approaches such as the economy of abundance theory [71]. More traditionally, wealth redistribution is frequently implemented through overpricing for those who can pay to help those who cannot. Nonetheless, these last measures must be tailored carefully to keep the total cost competitive.

1.3 Research questions

In the search of more participatory models for infrastructure development and management, the work presented in this dissertation attempts to answer the following research question (RQ):

RQ1 Does the approach followed by Guifi.net outperform the private sector model?

RQ2 Does the Guifi.net case have enough unique and beneficial features to be considered a model on its own?

RQ3 Does the Guifi.net model apply to other infrastructures?

1.4 Methodology

In our work, as the research questions as a whole suggest, we followed an overall incremental methodology. Firstly we focused our efforts on the network infrastructure and the particular case of the Guifi.net CN. Then, on one side, we extended the scope to the CNs as a whole and, on the other, we studied the case of cloud computing infrastructure. Finally we looked for more general conclusions. For the field work we mainly followed an action research approach [33, 149] in general, and network action research [51] and ethnographic action research [144] in particular.

Action research is a practical problem-solving methodology in which the research questions are not made beforehand as a result of a pure intellectual exercise but arise from the practical experience. These questions are usually either a product of abstractions from specific problems or when looking for the improvement or optimisation of a process of a community of practice. The solutions are tested by putting in practice in the community and observing their effects. The overall process is iterative because successful solutions lead to higher stages of development that, in turn, bring new challenges and, thus, new questions. Hence, it is difficult to predict accurately the final result of a certain research beyond general guidelines.

In line with the iterative nature and the constant critical reflection of the action research methodology, despite knowing since the beginning that we wanted to investigate Guifi.net to explore its potential to overcome the current dominant models for infrastructure development and management, we had only been able to formulate the research questions presented in Section 1.3 in an explicit manner after a long research work. Moreover, it is been during the writing of this dissertation that, based on our confidence on the outcomes of the RQ, we decided to add a chapter on the generalisation of the model. We believe that such chapter enriches the completeness of this work, although the model is in a propositional stage.

The main reasons to choose Guifi.net as a starting point were its exceptional results already achieved by the time of starting our research and the close relationship that the research group in general and the advisor and the candidate in particular had with the Guifi.net community and the Guifi.net foundation.

The selected methodology allowed us to gather first-hand information and to conduct experiments that would have been harder to carry out otherwise while providing an stimulant high level of feedback to the communities of practice we worked with. The interactions with the practitioners included:

- Participation in community meetings, hacklabs, and gatherings to understand the social dynamics, in the first instance, to later contribute whenever possible and to present the research results.
- Personal interviews to learn on personal perceptions and understandings, and to deepen in knowledge of complex or controversial aspects.
- Participation in mailing lists and social media to supplement the interaction with individuals and groups.
- Data collection and analysis to obtain supporting arguments. Quantitative data was preferred over qualitative data.
- Working meetings to discuss the research challenges, and later to present and discuss preliminary results, and design the coming research iteration.

RQ1 implied the evaluation and comparison of the results in terms of availability as well as in terms of engagement. The common indicators of the telecommunication sector, namely coverage, price and adoption, are limited to describe the performance in terms of access. Thus, to evaluate the performance in aspects such as opportunities for effective participation in the governance and the economic systems, diversity of stakeholder groups, diversity within the stakeholder groups, internal wealth redistribution mechanisms, etc. broadened the aforementioned quantitative indicators with other qualitative indicators. Our work confirmed the preliminary empirical evidences pointing towards a positive answer to RQ1.

To answer RQ2, we first deepened our research on Guifi.net, this time focusing on its organisational structure. The governance and economic systems deserved our special attention due to the critical role they play within the ecosystem and their complexity. Secondly, we studied the performance of other CNs (reported in [O8]) and compared the results. Our findings on the complexity and the particularity of the Guifi.net initiative as well as its contributions to extend the social value of the infrastructure put in place led us to answer RQ2 affirmative.

We tackled RQ3 on the applicability of the model to other infrastructure incrementally. We first investigated its scalability within the same infrastructure domain, i.e. Internet protocol (IP) networks. For this investigation we decided to focus our efforts on CNs because in them, not only the infrastructure is the same, but also the social conditions (bottom-up collaborative initiatives) are rather similar. The comparison with less developed cases (Guifi.net is by far the most developed and complex CN we know) let us to better define and understand the enabling factors of the Guifi.net scalability. In a second stage we addressed the question of the exportability of the model to other infrastructures. To this end, we decided to work on cloud computing infrastructure in Guifi.net. Working with the Guifi.net community allowed us to benefit from all the existing synergies and allowed us to strengthen them. The main motivations for selecting the cloud infrastructure were: (i) the affordability of the hardware involved, (ii) the fact that the community had already made some attempts to deploy cloud infrastructure but from a rather unorganised efforts and with limited success, (iii) the fact that cloud computing and network infrastructure are frequently interdependent, and (iv) that we had the required knowledge to make the technological developments needed for the research. In terms of methodology we kept the action research approach. In the first place we analysed the results, lacks and opportunities for improvement of the preexisting cloud developments. We aimed at learning about the success factors for a sustainable creation of cloud computing infrastructure through making available a GNU/Linux distribution that met the needs of the Guifi.net community members. Our experimental research involved several meetings with community members for each stage of the investigation and the deployment of tenths of instances of the software distribution. To stimulate the uptake we made available to participants three rounds of partially sponsored low cost miniPCs.

This dissertation entailed a significant amount of qualitative analysis and required a multidisciplinary approach. The solid expertise of our research group in information and communications technology in general and in networking, operating systems and programming in particular, together with our practical experience after more than a decade participating in Guifi.net allowed us to tackle problems raised in the areas of the social sciences, economics and laws that had been left unattended by the researchers of these disciplines probably because the technological components were insurmountable obstacle for them.

We concentrated our research interests in practical use cases because, according to our view, (i) as researchers cannot ignore the reality we have to meet the challenge of delivering theoretical explanations to practical situations, specially for those that perform well, (ii) the interaction with communities of practice is an valuable source of knowledge and inspiring experiences and provides unique opportunities for making experiments and tests, and because (iii) we believe that practical involvement is the most effective way to promote the social change towards a better world.

The close collaboration our research group has had with the Guifi.net community, for almost a decade, and the amount of information publicly available resulting from the model chosen and developed to deploy and operate the network infrastructures and services, in conjunction with detailed datasets provided to us by the Guifi.net foundation have enabled an uncommon depth of analysis.

The development of this dissertation dissertation has allowed us to review and update the research results and publications of the last five years.

1.5 Contributions

The main scientific contributions of this dissertation are the following:

Collection of performance indicators of Guifi.net Quantitative and qualitative impact indicators in terms of access: infrastructure put in place, conditions under which it is made available and adoption; in terms of governance participation: opportunities for effective participation, diversity of participants; and in terms of economic participation: entry barriers, type and distribution of participants.

Description of the differences between Guifi.net and the private sector model Review of the differences in the approach and the resulting consequences from an holistic perspective, ranging from the conceptual understanding of the assets managed to the resulting conditions (attributes) of the resulting infrastructure.

Formalisation of the Guifi.net organisational model This includes the identification and classification of the stakeholder groups, the description of the interaction among them, the identification and classification of the body of normative elements developed, the description of the governance and the description of the economic subsystem.

The work related with these three contributions is presented in Chapters 3 to 5, was originally reported in [P2, P3, P5] and in [O1, O6], and contributes to answer RQ1 and RQ2.

Identification of key factors in CNs scalability and related patterns This contribution includes a review of the main social, legal, economic, technological and cross-disciplinary aspects in the scalability of CNs as an example of collectively developed and managed infrastructure and a collection of the most relevant good and bad practices (patterns and anti-patterns) from the CNs we studied.

The work related with this contributions is presented in Chapter 6, was originally reported in [P4] and in [O7, O8], and contributes to answer RQ3.

Analysis of the suitability of the Guifi.net model for cloud computing infrastructure The analysis entailed the identification of the adaptations required, of the initial key enablers for a successful adoption, the development of a cloud computing software stack for experimentally testing its adoption within the Guifi.net community and theoretical viability analysis of a business case on top of the deployed infrastructure.

The work related with this contributions is presented in Chapter 7, was originally reported in [P1] and in [O4] and contribute to answer RQ3.

1.6 Dissertation organisation

Figure 1.2 presents the general structure of the dissertation, linking chapters, research questions and main scientific production. The rest of this document is organised as follows:

Background (Chapter 2) collects the literature that this dissertation builds on and presents the limitations that our research contributions intend to meet.

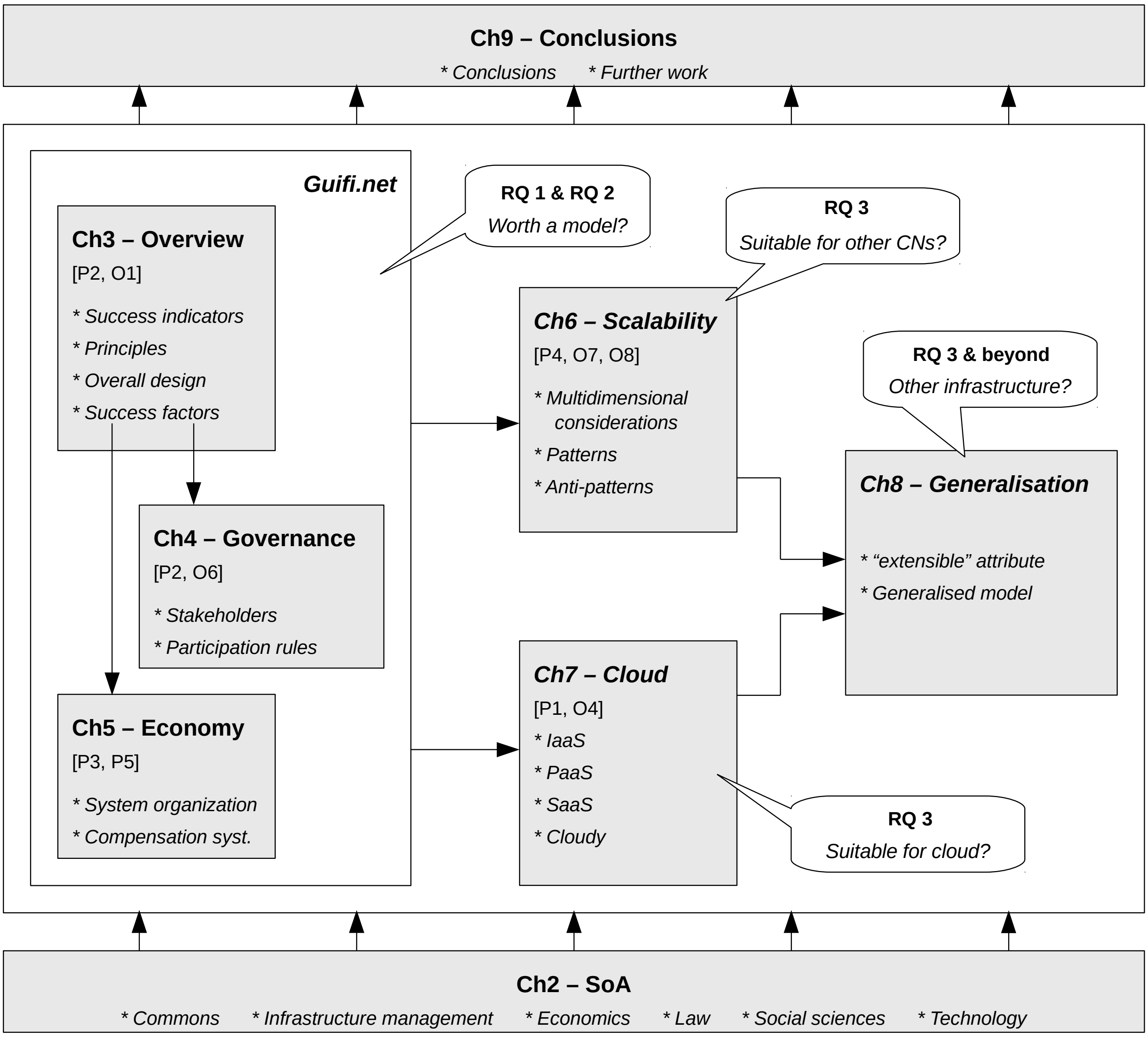

Figure 1.2: This dissertation structure.

Guifi.net – Overview (Chapter 3) presents the context and the main concepts Guifi.net builds on and its overall structure and provides evidence of uniqueness and potential of the Guifi.net as well as of the results it has already achieved.

Guifi.net – Governance (Chapter 4) addresses the governance system of Guifi.net, a central question in any organisation in general, and in particular in those aimed at being collaborative and inclusive.

Guifi.net – Economics (Chapter 5) analyses the key components of Guifi.net economy and how they are related to the fundamental principles and the governance system.

Scalability in community networks (Chapter 6) discusses the key aspects of CNs scalability from an holistic point of view and collects a set of patterns (the re-usable form of a solution to a design problem) and anti-patterns (a common response to a recurring problem that is usually ineffective and risks being highly counterproductive) extracted from the CNs we have analysed.

Applicability to cloud computing (Chapter 7) explores the applicability of the Guifi.net model in the domain of cloud computing in terms of feasibility (adoption) and economic sustainability.

Conclusions (Chapter 9) elaborates the overall conclusions of this dissertation and draws future directions that deserve further work.

Each chapter starts with a short preface that presents its contents in the overall context and briefly summarises them. After the preface, the introduction deepens on the motivation of the chapter, reviews the preliminary concepts and introduces the rest of the contents. All chapters end with a section gathering its main contributions and conclusions.

Chapters 3 to 5 form a unit describing Guifi.net, thus, it is recommended to read them in conjunction and in that sequence.

Chapter **2**

Background

Preface

This chapter collects the concepts, the literature, and the legislative and regulatory aspects that this thesis dissertation builds on, and presents the limitations that our research contributions intend to meet. Its contents are structured around the three main pillars of this work: network infrastructure, cloud computing infrastructure and the commons. Each of them is addressed in a section. The network and cloud computing infrastructure sections follow a similar structure. First they set the general context of the topic and, then they analyse the aspects related to governance and conclude with a review of existing experiences of resources sharing. The network section is significantly longer than cloud computing section because it is also provides context to ICT sector in general. The section devoted to the commons introduces the concept of common-pool resource (CPR) and how it relates to infrastructure in general an to CNs in particular. A short section compiling the most relevant legislation applicable to Guifi.net follows. The chapter concludes describing the gaps in knowledge that this dissertation intends to contribute to fill.

2.1 Introduction

The overall goal of this dissertation is to contribute in the search of new models for infrastructure development and management that overcome the limitations of the currently used. Therefore, first of all it must be clarified is the meaning of *infrastructure*, and the scope of the term *model*.

The *Cambridge dictionary* defines infrastructure as "the basic systems and services, such as transport and power supplies, that a country or organisation uses in order to work effectively" [36], and the *Investopedia* as "the term for the basic physical systems of a business or nation" [37] and mentions "transportation, communication, sewage, water, and electric systems" as examples. According to the *Wikipedia*, infrastructure "is the fundamental facilities and systems serving a country, city, or other area, including the services and facilities necessary for its economy to function" [164] and points out "improvements such as roads, railways, bridges, tunnels, water supply, sewers, electrical grids, and telecommunications (including Internet[1] connectivity and broadband speeds)". Thus, for these three sources, the term infrastructure is confined to physical systems.

[1]In this dissertation the capitalisation of *Internet* refers to the worldwide infrastructure resulting to the interconnection of numerous networks, and *internet* to the generic interconnection of networks (internets, or internetworks). In the unclear cases, we have used *internet* because we understand the *Internet* as a case of *internet*.

For *Lexico*, infrastructure is “the basic physical and organisational structures and facilities (e.g. buildings, roads, power supplies) needed for the operation of a society or enterprise” [94] and illustrates the definition with the sentence “the social and economic infrastructure of a country”, thus, it includes the organisational systems to the concept. In this dissertation, the term infrastructure is used in a broad sense, as in the definition by *Lexico*, that is to say, including the organisational improvements.

More generally, any infrastructure involve the following main business: sectors (i) planning, (ii) design, (iii) finance, (iv) procurement, (v) deployment, (vi) operation, (vii) maintenance, (viii) commercialisation, (ix) service delivery, (x) dismantling, and (xi) waste management. In this dissertation, the term *model* is used in a broad sense, from planning to service delivery, and includes all the aspects related to governance, unless otherwise indicated. The terms *development*, *management*, and *governance* are also used in wide sense. That is to say, they are not limited to a technical and narrow interpretation, but encompass, at least, the social dimension, and usually the economical and legal dimensions as well.

The rest of the chapter is structured as follows. Section 2.2 provides the necessary background knowledge in the field of network infrastructure, the first topic we have addressed in our research. It begins with a general overview and elaborates on the gaps and limitations of the current business models. Then it looks into internet exchange points (IXPs) and CNs as existing successful experiences of network infrastructure sharing. Finally, it reviews the existing literature on cost-sharing mechanisms in network infrastructure. Section 2.3 focus on cloud computing infrastructure. After a brief review of typical architecture it narrows down in scope to existing experiences of collaborative clouds. Section 2.4 is devoted to the commons. It first presents the works of E. Ostrom[2], an essential milestone in the study of the commons and also for this work, and the works of B. Frischmann, probably the author that has further investigated the translation of Ostrom’s work into infrastructure as a whole. After a general taxonomy of the commons, an analysis of CNs from the theoretical framework of the commons in general, and that of commons-based peer production in particular, follows. Next we present a modification of the social business canvas model we propose as a convenient template to capture the key external aspects of entities and enterprises interacting with commons-based infrastructure. The section ends with an analysis of the coexistence of the different rights involved in common ownership. Section 2.5 complies the most relevant applicable legislation. The chapter by describing the gaps in knowledge that this dissertation intends to contribute to fill in Section 2.6.

The netCommons.eu research project, aimed at studying the diversity in practices and methodologies related to network infrastructures as commons, and our contribution to its first work package in organisational models, has provided a solid base for this chapter, in particular [O8], with an analysis of the state of the art in governance models of network infrastructures as commons and other related aspects.

2.2 Network infrastructure

2.2.1 General overview

Computer networks, also referred as “data networks”, provide an artificial medium for digital communication and access to information across distance and time that complements our natural

[2]Elinor Ostrom and Oliver E. Williamson shared the Nobel Prize in 2009 for the analysis of economic governance, the first for the commons, and the second for the boundaries of the firm.

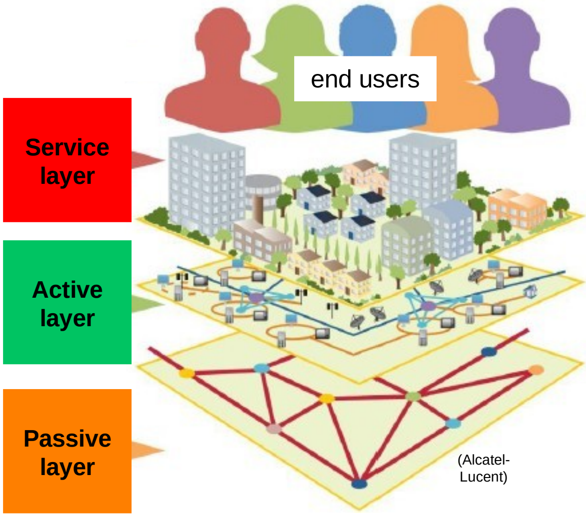

Figure 2.1: Network layers of a FTTH network.

limited capacities as evolved apes, to communicate in the acoustic space, see in a narrow frequency band of visible light, and access information in the physical space around us. Traditionally telecom services and access to the Internet were seen as an option, a luxury for corporations and the club of those citizens willing to pay premium to benefit from these artificial "superpowers".

The infrastructure that provided these commercial services was managed by national telecom monopolies and later by telecom incumbents and other commercial (for-profit) operators. In recent times, the growing adoption of data networks as the best, and sometimes the only, option to communicate with many other people and access most information, has promoted that access to an essential (sometimes called "universal") service. That requires the involvement of governments legislating and regulating various aspects to guaranteeing to the public universal access to these privately provided services.

Furthermore, the evolution of services, both private and governmental, from commerce and entertainment to tax paying and education, has in recent years relied more and more on telecommunications services, both as a means of reducing services costs and as a means to improve citizen service provision reducing the time needed to obtain the service and allowing service provision outside normal business hours.

According to the broadband[3] investment guide of the European Commission (EC) [44] and supporting research [49], the structure of a modern network service consists of three interdependent layers: (i) the passive infrastructure, (ii) the active infrastructure, and (iii) the delivery of service, as illustrated in Figure 2.1. In the Open Systems Interconnection model (OSI model) [80] the passive infrastructure corresponds to layer 1 (physical), the active infrastructure corresponds to layers 2 (data link) and 3 (network), and the delivery of services includes the remaining layers (from transport to application).

The most typical passive infrastructures are the traditional telephone copper wires, television (TV) coaxial cables, OF, wireless point-to-point or multi-point links and the corresponding dedicated (licensed) or shared (unlicensed open access) spectrum. The active infrastructure

[3]The term broadband is used to refer to fast data networks, in contrast to slow and narrowband dial-up telephone lines.

typically comprises a diversity of data-link protocols matching the associated passive infrastructure. It converges in most cases to an IP network on top and is sometimes also combined with network virtualisation techniques.

These IP networks can offer a wide range of services such as interconnection to the global Internet, telephony as Voice over IP (VOIP), access to media content (such as television, radio, cinema), and can be accessed by personal client devices or servers, typically through Ethernet cables or WiFi access point (AP).

The deployment and operation of these networks and services requires investments that feature large economies of scale in urban areas with many citizens (customers). The concentration of customers in small areas and their grouping in buildings, make it a great business for commercial telecom providers. As the population density decreases and the distance to major cities increases or the economic capacity of customers decreases, the margin for commercial exploitation decreases or becomes negative. However, there is growing consensus that it is important to provide these services to every citizen, in particular in remote areas that are generally under-served when compared to more urban areas, and even public services are sometimes provided only remotely. As a result, public administrations have devised policies that promote and try to ensure a minimum level of service for all citizens independently of their location. These policies range from subsidies to network operators in exchange for offering services in these areas, to public investment in the development of complementary network infrastructures, or definition of public (regulated) prices for key services. However, network infrastructures are in most cases under the control of former monopolies, now telecom incumbents. These entities control the offer and have strong lobbying mechanisms in place to influence regulation and discourage competitors. Except for the most developed urban areas, the typical situation is of lack of competition, defined as "market failure". The typical market structure is rather disappointing, with a very small set of large telecom providers acting as oligopolies and exercising cartel practice, which justifies public intervention [44]. This has been recognised as a critical challenge by International Telecommunication Union (ITU) in a report [87] that explores and proposes options based on the principles of separation and sharing, typically managed by governments through legislation, regulation and subsidies. The most visible recommendations are:

- Extending access to fibre backbones: open access to bottleneck or essential facilities (like fibre infrastructures), that encourages the development of multiple providers of any size and scope, and promotes investment in a high-capacity infrastructure to unserved or underserved areas;
- Mobile network sharing: an equivalent to the previous but applied to the mobile network, applicable to both passive and active elements of the network;
- Spectrum sharing: promotion of the spectrum "commons", with administrative, licensing, unlicensed bands, commercial or technical measures (like dynamic spectrum access or cognitive radio);
- International gateway liberalisation: liberalisation of international gateways, such as access to submarine cable systems, avoiding any anti-competitive control from incumbents;
- Functional separation: also known as operational separation, creating separate business divisions for retail and wholesale that act independently from each other; where a separate wholesale division to supply network access and services to competitors, along with the incumbent, on a non-discriminatory basis.

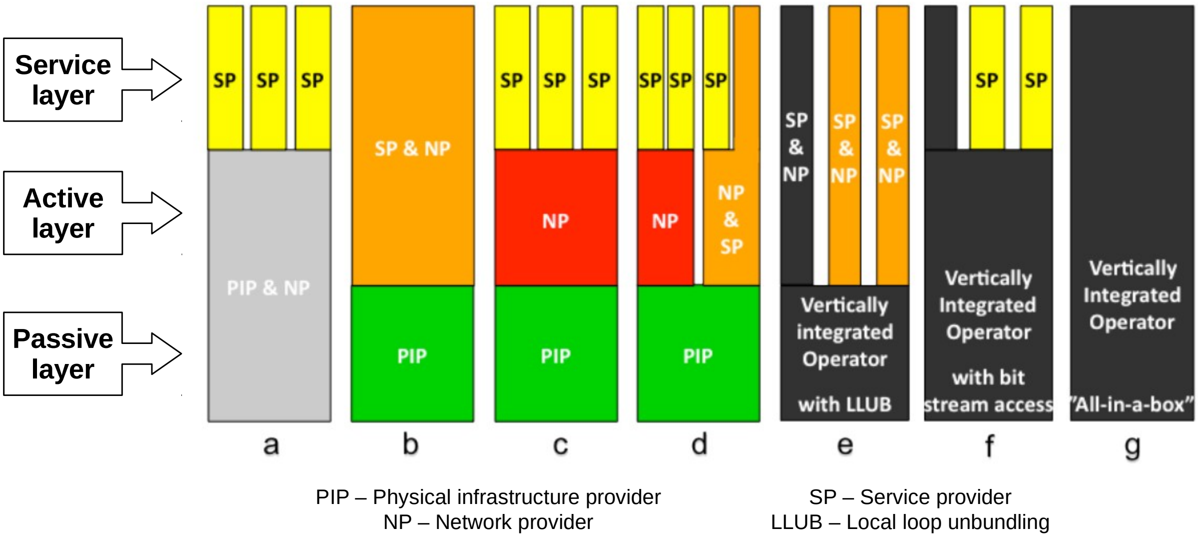

Figure 2.2: Different division and separation across service layers [49].

- Structural separation, a last resort which requires an operator to separate its network infrastructure from its units offering services using this infrastructure. Also known as 'ownership unbundling' or 'divestiture', it means that all of the network elements are placed in a separate legal entity.
- Cost sharing and user sharing: sharing of a computer, mobile, Internet link, or content, across a group of people, such is schools, libraries, public-access tele-centres or shops.

Each of these measures can help develop new business models that can make a great difference in the expansion of the coverage and usage of data networks for the socio-economic benefit of every citizen in the world [79], and community networks can benefit from changes in these directions.

In Europe, in response to these measures the EC has introduced the cost reduction directive with measures to reduce the deployment cost of high-speed electronic communication networks (2014/61/EU) [46].

The typical business models of modern data networks follow one of the structural models depicted in Figure 2.2. Nevertheless, in some cases (and countries) functional or structural separation is in place to prevent anti-competitive, discriminatory behaviour by incumbents. The ultimate goal is to promote cooperative cost sharing schemes to reduce the cost of deploying infrastructures of any kind (telecom-related and others such as roads, water, electricity that require expensive civil works), and promote competitive offerings (market) to widen the choice and reduce the cost of services to customers.

Overall, the global Internet is in danger of fragmentation [40], the risk of breaking up into loosely coupled islands of connectivity, driven by technological developments, government policies and commercial practices, but also in danger of consolidation [88], including growing forces of concentration, vertical and horizontal integration, and fewer opportunities for market entry and competition, with trends towards (i) total service environments (the "one-stop shops"), (ii) network flattening where access networks are increasingly interconnected with less need for international transit, (iii) deep dependencies with an increasing dependency on a small number of private platforms, (iv) the risk of growing societal dependencies on a handful of powerful economic actors in contrast to the "no permanent favourites" principle of the Internet, and (v) the growing number of responses to the negative effects –either real or perceived– of concentration and consolidation.

2.2.2 Cases of network infrastructure sharing

2.2.2.1 Open-access networks

According to [166] *an open access network (OAN) refers to a horizontally layered network architecture in telecommunications, and the business model that separates the physical access to the network from the delivery of services. In an OAN, the owner or manager of the network does not supply services for the network; these services must be supplied by separate retail service providers. There are two different open-access network models: the two- and three-layer models. In the two-layer OAN model, there is a network owner and operator, and multiple retail service providers that deliver services over the network. In the three-layer OAN model the physical layer –the fibre or wireless infrastructure– is owned by one company, the operations and maintenance of the network and the provision of services is run by a second company, and the retail service providers provide the third layer.*

From the business model perspective *"Open Access" refers to a specialised and focused business model, in which a network infrastructure provider limits its activities to a fixed set of value layers in order to avoid conflicts of interest. The network infrastructure provider creates an open market and a platform for internet service providers (ISPs) to add value. The Open Access provider remains neutral and independent and offers standard and transparent pricing to ISPs on its network. It never competes with the ISPs.* [166] OANs are also referred as wholesale-only networks.

In Stockholm, the public company Stokab [48] established in 1994 was one of the earliest wholesale only initiatives. Through its OF network, now it serves more than 100 operators and is having a key socio-economic impact in the region [50]. In Reykjavik, *Gagnaveita Reykjavíkur* (Reykjavik Fibre Network)[4] is already offering 100 % fibre to the home (FTTH) connectivity in the city of Reykjavik and every urban home in neighboring towns. CityFibre[5] is deploying OF in over 50 cities in United Kingdom to reach 5 million homes. Deutsche Glasfaser[6] in Germany, Open Fiber[7] in Italy, are other successful OF OANs in Europe.

In Mexico, Altán Redes[8] is a state PPP running *Red Compartida*, a wireless 4G Long-term evolution (LTE) broadband network, with low latency and high speed features, including indoor connectivity, offering services to mobile operators. With coverage of a 32 % of the population, it aims to reach 92 % by 2024.

[4] http://www.reykjavikfibrenetwork.is
[5] https://www.cityfibre.com/
[6] https://www.deutsche-glasfaser.de/
[7] https://openfiber.it/en
[8] https://www.altanredes.com/

2.2.2.2 Internet exchange points

According to [165] *"An IXP is the physical infrastructure through which ISPs and content delivery networks (CDNs) exchange internet traffic between their networks. IXPs reduce the portion of an ISP's traffic that must be delivered via their upstream transit providers, thereby reducing the average per-bit delivery cost of their service. Furthermore, the increased number of paths available through the IXP improves routing efficiency and fault-tolerance. In addition, IXPs exhibit the characteristics of what economists call the network effect.*

For ISOC, IXPs *are a key part of the Internet ecosystem and represent a vital way to increase the affordability and quality of connectivity in local communities.* According to their view, *IXPs fall roughly into five categories: not-for-profit organisation, an association of ISPs, operator-neutral for-profit company, university or gov agency, or an informal association of networks.*

Among the most relevant examples, the Brazil Internet Exchange (IX.br) accounts for almost 2,400 members and an average throughput of 4.4 Tbit/s and 31 IXPs, the most important are located in São Paulo with a traffic peak over 5 Tbit/s, and Rio de Janeiro with 1 Tbit/s. The Deutscher Commercial Internet Exchange (DE-CIX) with a peak traffic with a maximum throughput of more than 6.7 Tbit/s has 870 members in 13 IXPs in 9 countries around the world. The Amsterdam Internet Exchange (AMS-IX) and the London Internet Exchange (LINX) also account for over 800 members each.[9]

2.2.2.3 Community networks

Community networks (CN) are bottom-up initiatives aimed that building network infrastructure by pooling resources and managing it collectively. The coverage of underserved areas and the fight against the digital divide are the most frequent driving factors for their deployment, although contributors often mention doing things for experimentation, fun or the act of contributing to the development of a new telecommunications model per se as alternative motives.

The employed technologies vary significantly, ranging from very-low-cost, off-the-shelf wireless WiFi) routers to expensive OF equipment [8]. The models of participation, organisation, and funding vary broadly across these networks. For example, some networks are freely accessible, whereas others are run as a cooperative, and others are managed by federations of microISPs. A few examples follow: Broadband for Rural North (B4RN) in Lancashire, United Kingdom, and Nepal Wireless Networking Project (NWNP) in Nepal, are networks built in response to the lack of coverage of the conventional operators. B4RN deploys and operates OF in a cooperative way. NWNP [145] is a social enterprise that uses wireless technologies to provide Internet access, electronic commerce, education, telemedicine, environmental and agricultural services to a number of remote villages. French Data Network Federation (FFDN) is a federation of French Do-it-Yourself ISPs comprising Digital subscriber line (DSL) resellers, wireless internet service providers (WISPs), collocation centres, and the like. HUBS is a not-for-profit transit provider whose members are the community networks that it serves. HSLnet in the Netherlands or several members of the INCA association in the United Kingdom are examples of cooperative OF networks.[10]

[9] IX.br: `https://ix.br`, DE-CIX: `https://www.de-cix.net/`, AMS-IX: `https://www.ams-ix.net/`, LINX: `https://www.linx.net/`.

[10] B4RN: `https://b4rn.org.uk/`, NWNP: `http://www.nepalwireless.net/`, FFDN: `https://www.ffdn.org/en`, HUBS[11], HSLnet: `https://www.hslnet.nl/`

Other representative examples are Guifi.net in Catalonia, Freifunk (FF) in Germany, the Athens Wireless Metropolitan Network (AWMN) in Attica region of Greece, FunkFeuer (0xFF) in Austria, and Ninux.org in Italy.[12] All of them include thousands of links, mostly wireless[13], but gradually integrating also OF and optical wireless links.

In general, CNs have already been studied from several angles [O3, 99, 150, 12], and in particular, Guifi.net from the structural [30, 154, 102], technological [O2, 101, 11] or organisational [P2, 96] points of view. The results from the netCommons.eu project, including a survey of CNs in Europe, in particular, and in the world, in general, [O8], have been used in this dissertation for comparison with Guifi.net, together with [125].

2.2.3 Cost-sharing in network infrastructure

Sharing or working together leads to the problem of how to divide the joint costs and cost savings among participants. As [146] stated, no single absolutely best set of criteria exist, but diverse policies are aimed to treat every participant in equivalent terms, being fair, impartial, and just without favouring or discriminating any party. The policy choice depends on a number of factors, including strategic aspects of cost allocation situations and participant preferences.

The 95-percentile method [39], which is billing based on the 95th percentile of traffic volumes sampled over five-minute intervals (also known as burstable billing) [160], is the most standard measure for billing traffic in ISPs and transit providers. It is an indicator of the network usage used for the dimensioning of the network infrastructure. The Shapley value [139] is an established way to fairly distribute gains and costs among several actors working in coalition. [143, 108] uses the Shapley value to compute the fair contribution of each flow to the 95th percentile price of interconnected links. As noted in [142], internet transit is a highest cost for an ISP, and aggregating transit costs and group buying (*tuángòu*) decrease the cost due to the effect of economies of scale of typical sub-additive pricing and burstable billing because not all ISPs transit their peak traffic in the same period.

There are many experiences of cost sharing in IXPs [60] and community networks, such as B4RN [6], Guifi.net [P2, P3], or RemIX [O5], to achieve quality and affordability of backhaul connectivity in remote and underserved regions and therefore ensure the autonomy and sustainability of small ISPs. In [P3], we examined some aspects related to the last-mile economics based on the monthly records of four WiFi and optical fibre deployments of the two previous years. However, beyond the case of Guifi.net, these cooperative operators have limited or incomplete traffic and economic log data, little formal and detailed cost analyses, and therefore, a lack of cost fairness optimisation. Beyond this, commercial network providers consider the detailed traffic and pricing data to be commercially sensitive and confidential and, therefore, inaccessible for analysis.

[12] Guifi.net: https://guifi.net/, FF: https://freifunk.net/, AWMN: http://www.awmn.net/, 0xFF: https://www.funkfeuer.at/

[13] The term *wireless* was broadly used to refer to this type of community networks, so that many of these networks are referred to in literature as wireless community networks (WCN), because originally WiFi technologies were the only one cheap enough and not subject to licensing to enable their use in non commercial developments. Nevertheless, it is deliberately preferred to avoid the term, to decouple the concept of community networks from a particular technology choice.

2.3 Cloud computing infrastructure

The cloud computing field is similar in diversity and complexity as the field of computer networks. Given that we consider that the degree of complexity has already been illustrated in the previous section and that many general concepts and approaches are shared between fields, we believe that in this case the following quotes suffice to introduce the necessary general background of cloud computing and why we look at community clouds, which the according to the *Encyclopedia of Cloud Computing* are "cloud systems designed to address the needs of a community." [110] "Cloud computing is a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction. This cloud model is composed of [...] three service models" [117]: software as a service (SaaS), platform as a service (PaaS), and infrastructure as a service (IaaS). "In the SaaS model, an application is hosted by a cloud vendor and delivered as a service to users, primarily via the Internet or a dedicated network. [...] In the PaaS model, the platform and tools for application development and middleware systems are hosted by a vendor and offered to application developers, allowing them simply to code and deploy without directly interacting with the underlying infrastructure. [...] In an IaaS cloud, raw computer infrastructure, such as servers, CPU, storage, network equipment, and datacenter facilities, are delivered as a service on demand. Rather than purchasing these resources, clients get them as a fully outsourced service for the duration that they need them." [110]

"Cloud Computing is rising fast, with its data centres growing at an unprecedented rate. However, this has come with concerns over privacy, efficiency at the expense of resilience, and environmental sustainability, because of the dependence on Cloud vendors such as Google, Amazon and Microsoft." [104] Several alternative models have been proposed in response. Many of them, "utilising networked personal computers for liberation from the centralised vendor model", including "Community Cloud Computing (C3)."

2.3.1 Community clouds, infrastructure sharing in cloud computing

In terms of cloud computing paradigms, fog [24] and edge computing [61] have been proposed to enable a new type of cloud services at the network edge, combining an edge cloud infrastructure in addition to that in large data centres. Fog computing migrates cloud computing to the edge of the network, where, through edge networks, more decentralised services are expected to replace centralised cloud services [153]. Edge cloud computing is well suited to perform local data processing for the internet of things (IoT) [140]. From the peer-to-peer (P2P) cloud computing perspective [61], the users can be in the loop and participate in edge cloud computing service provision. Our approach shares the focus on decentralised infrastructures and services.

A community cloud (CC), in general, is a cloud deployment model in which a cloud infrastructure is built and provisioned for exclusive use by a specific community of consumers with shared concerns and interests, owned and managed by the community, by a third party, or a combination thereof [106]. Different examples of CCs are the ExoGENI distributed networked infrastructure for experimentation and computational tasks, the EGI federation of 350 resource providers offering computing, storage, and data infrastructure, and ELIXIR, a European intergovernmental organisation that brings together life science resources including databases, software, and computing tools for researchers.[14]

Cloud software, service, and business models abound. There are proprietary remote public cloud solutions offered by the major players [95]; closed-source CC solutions; and full stack open-source products in the market like OpenStack or OpenNebula, compared in [157], intended for rack or data-centre class computing clusters. These solutions are being used in several application areas, such as in the financial, governmental, and health sectors, fulfilling community-specific requirements (e.g., security, performance, and local content) [167, 167]. Considering the consistency, availability and partition tolerance (CAP) theorem [25], decentralisation means (i) local availability, as the network may be unreliable, (ii) eventual consistency, as data may not propagate synchronously, and (iii) partition tolerance, as geo-replicated systems in large networks tend to suffer from network partitions. Therefore, software tools come with assumptions about the centralisation of the underlying cloud computing and network infrastructure that may not apply in a community environment. To circumvent the limitations imposed by these assumptions, developed a model for managing and aggregating cloud computing resources in decentralised networks. We envisaged that the centralised stacks will interoperate and be federated to our software stack through public application programming interfaces (APIs) as hybrid clouds [106] do, combining the capabilities of in-house (private) and external (public) clouds, and designed the model accordingly.

Regarding user-oriented applications, there is a wide range of free software content management systems (CMS) [118], file sharing [97, 63], among many other web tools that are useful in a CC. However each requires a specific operating system environment, installation and configuration, so a single server host may not fit all. The need for security and resource isolation, resulted in the idea of process containers [13], that years later translated into Linux containers, an operating-system-level virtualization method for running multiple isolated Linux systems (containers) on a control host. This has evolved in products like Docker [107] or cluster managers such as Kubernetes [21] that also ease application and service management and even orchestration among complementary services. In our work, we started with containerised services. Later we added support for Docker images and Docker Compose to automate the deployment of applications in separate containers, and benefit from the wide range of pre-packaged Docker containers available that can be included and run as applications in our CCs. We found limitations in performance isolation required to avoid resource interference across containers, to be able to ensure the quality of the services provided. We developed solutions [123, 122] but these are not yet integrated.

Feasibility, the possibility of being made, has several levels of realisation. From a Technology readiness level (TRL) [45] perspective, it relates to the results from the experimentally driven research [62] in terms of the evaluation of technical alternatives, assessment of performance and cost, and optimisation of diverse aspects of the software system. Therefore, in terms of TRL, we target assessment of integration and validation (TRL 5), field demonstration (TRL 6), prototyping (TRL 7), and even complete system qualification (TRL 8) in some respects if the system is adopted by a community of users. From a market pull perspective of Demand-readiness level (DRL) [159], we seek mature understandings about local demands and governance issues to allow a matching point between technology push and demand pull. Our aim is to reach an 'adapted answer to the expressed need' (DRL 9). The results of this research can reduce start-up

[14] ExoGENI: `http://www.exogeni.net/`, EGI: `https://www.egi.eu/`, ELIXIR: `https://www.elixir-europe.org/`.

costs and help lower the risks for success of related initiatives. That connects with the concept of sustainability, the ability to maintain an initiative after feasibility is proven.

Sustainability for CCs refers to the deployment of infrastructure and services with long-term availability and production usage, governed and used by a community. To be sustainable, edge cloud services must be able to generate a positive socio-economic balance for their participants [69, 70]. Enabling economic activity through commercial providers within commons infrastructures, such as in Guifi.net, has been identified as a key element for enabling its transformation into a consolidated sustainable infrastructure [P2]. Commercial providers addressing such environments need to face different risks in providing service-level agreements (SLAs) [119]. However, edge cloud services open new business opportunities to better serve citizens with tailored and local services. These services can be related to local data processing, which may attract commercial providers. Such processing of data streams by devices at the edge was suggested in [35], with privacy as an important reason for providing local services [74]. The application scenarios for such services are diverse. Some examples are image processing [121] or sensor data processing [168]. The quality of service needs of these streams will require solutions to cope, for instance, with busy streams or real-time constraints [148, 147].

2.4 The commons

A CPR or *commons* is *a natural or man-made resource from which it is difficult to exclude or limit users once the resource is provided by nature or produced by humans [114]. One person's consumption of resource units removes those units from what is available to others. Thus, the trees or fish harvested by one user are no longer available for others. The difficulty of excluding beneficiaries is a characteristic that is shared with public goods, while the subtractability of the resource units is shared with private goods.* [115].

In fact, *exclusion*, preventability from access, and *rivalry* or *subtractability*, where consumption by one consumer prevents or reduces (subtracts) consumption by others (*when the benefits consumed by one subtract from those available to others* [114]), distinguishes CPRs from other forms of goods or resource systems. While excludable goods can be either non-rivalrous (toll or club goods) such as cinemas or satellite TV, or rivalrous (private goods) such as cars, food or parking spaces, non-excludable goods can be either non-rivalrous (public goods) such as the air or radio broadcast, or rivalrous, which correspond to goods that can be managed as CPR. In this dissertation, a CPR is a system of (artificial) resources collectively built and managed, unless otherwise indicated.

2.4.1 Common-pool Resources

The "Tragedy of the commons" problem ([72]) has been used since the seventies to support the notion that shared resources have to be either taken over by the state or privatised in order to be sustainable. However, E. Ostrom noted that some CPRs had lasted for centuries. After the study of some of them, in [113] Ostrom identified eight "design principles" of stable local CPR management and in [116] outlined five basic requirements for achieving adaptive governance. After analysing 91 additional cases, M. Cox [34] found that Ostrom's eight principals were well supported.

According to M. Bevir [22], "Governance refers, therefore, to all processes of governing, whether undertaken by a government, market, or network, whether over a family, tribe, formal or informal organisation, or territory, and whether through laws, norms, power or language.

Governance differs from government in that it focuses less on the state and its institutions and more on social practices and activities."

B. Frischmann [55] explored the applicability of commons*, a resource management principle by which a resource is shared within a community on nondiscriminatory terms to* infrastructure*, a particular set of resources defined in terms of the manner in which they create value* mainly from an economic point of view and focusing predominantly on demand-side issues because he argues that infrastructure policy is heavily influenced by economics and a supply-side approach. For him, *when reduced to a public good provisioning problem, the functional role of infrastructure is lost.* According to his view [56], infrastructures governed as commons generate positive externalities (positive effects) that benefit society by creating opportunities and facilitating many other socio-economic activities, although their benefits are sometimes hard to measure. An infrastructure that is cooperatively managed and sustained leaves a greater margin for added value activities compared to commercial network infrastructures developed competitively. Examples of infrastructure commons are the Internet, with issues about congestion and network neutrality [55] or Internet/spectrum commons [18]. A first study of CNs as commons can be found in [P2]. Chapter 7 builds upon that study, covering CCs and the value of commons in the different cloud service layers.

The commons can be fragmented into different subtypes. Ostrom developed her framework based on the analysis of case studies from local, mostly environmental, commons and extended her study with cases from knowledge commons, cultural and digital commons [75], composed by a resource, a community, legal rules, interaction (commoning), outcomes, and evaluation.

Scholars further extended this work in an attempt to systematise knowledge commons with another collective volume [57], including infrastructure commons with the example of internet congestion and network neutrality [55], and Internet/spectrum commons [18].

These adapted versions of Ostrom's framework look into the nature of the resource, of the community, the criteria of success, failure and vulnerability, and finally the political purpose such the importance of the commons for democracy and freedom.

Finally, the study of digital commons, with the major examples of free software and Wikipedia, gave rise to commons-based peer production (CBPP) [20]. The study of CPBB develops a political economy dimension to the study of a type of commons, by shedding light on the purpose and the underlying political values carried by commons as a sustainable alternative to the production by the state or the market only. The construction of such a common infrastructure will require policy action [19].

The concept of commons has been applied and extended to many domains, deviating outside the natural resource sectors: *Before 1995, few thinkers saw the connection. It was around that time that we began to see a new usage of the concept of the "commons". There appears to have been a spontaneous explosion of "ah ha" moments when multiple users on the Internet one day sat up, probably in frustration, and said, "Hey! This is a shared resource!" People started to notice behaviours and conditions on the web-congestion, free riding, conflict, overuse, and "pollution" –that had long been identified with other types of commons. They began to notice that this new conduit of distributing information was neither a private nor strictly a public resource.* [75]. There are many new commons [76] sectors beyond the traditional and beyond the scope of our work, being the most relevant to our work the knowledge commons, that includes some aspects of the Internet [77] (although others disagree [124], qualified as *nested clubs*), and infrastructure commons, that include the Internet infrastructure.

Commons, in the scope of our work, may be classified as:

Natural commons are brought by mother nature and the emphasis is in how these commons are self-managed sustainably for the benefit of a community and its preservation.

Immaterial commons of knowledge and code that follows similar principles but requires a model for its collaborative production and its collective property, that Benkler [17] called *Commons-based peer-production*. In this model, information and knowledge lie close to a non-rival resource, although the cost of finding it (requiring search engines) and accessing it (requiring content servers) consumes rival resources that can be congested (energy, digital devices as clients or servers). Moreover, knowledge and code do not constitute an exclusion barrier in developed societies, but generate exclusion in developing societies (cost of access and availability of access infrastructure such as servers, networks, client devices, energy, etc.)

Artificial material commons are complex systems where peer production is applied to build some specific, traditionally material, resource resource pool (or system) that is critical for a community as an infrastructure or as a means for development. There is no clear cut between the natural commons and the artificial material commons, but a continuous transition whereby more and more value of the commons is related not to the natural resource managed, but to the complex engineering manipulation of it.

A traditional example of artificial material commons are the woods and lumber production and commerce in north-eastern Italy, traditionally managed by the *"Magnifiche comunità"* (magnificent community) [98]. Coming to modern times, a good example of artificial material commons are the pool of digital devices deliberately shared by a community that is willing to use, reuse, repair, refurbish and recycle [53] them for the sake of a sustainable circular economy. Community network and community cloud infrastructures are also examples, that are the focus of this dissertation.

2.4.2 Network infrastructures

In the past, network infrastructures were considered as club goods (excludable and virtually non-rival as a commercial service) provided by for-profit ISPs to those fortunate to be in coverage areas and willing to pay the service fee. CNs are a social response to the wide recognition of connectivity as a basic human right, and therefore an opportunity that network infrastructures connecting people becomes non-excludable.

Modern network infrastructures are based on the packet-switching principle that provides a mode of data transmission in which a message is broken into a number of parts (packets), and transmitted via a medium that may be shared by multiple simultaneous communication sessions (multiplexing). That results in a multiple access scheme using switches and routers where packets are transferred or queued, resulting in variable latency, limited throughput, and subject to network congestion if traffic gets close to its capacity. Despite conceptually non-rival, its practical implementation in a community of people, information and network services requires careful capacity planning to cope with demand and finite capacity, and provide good quality of service and avoid network congestion that degrades the effectiveness of the network.

Under these assumptions, real (production) network infrastructures should be considered rival (networks have limited capacity, and every possible packet in a network can only transfer a specific amount of data, subtracting from its capacity, and its presence in the network delays other packets). Without a careful design and planning, a network infrastructure gets imbalanced, congested and therefore exhausted as a resource system that produces connectivity as consumable. In typical networks, this cost is subject to traffic loads and how they compare to the network capacity (over-provisioning is desirable and common practice in all networks, but too much of it is not economically efficient due to cost): additional traffic has a cost and an impact in the rest of the traffic.

Networks typically perform some kind of traffic engineering to operate efficiently (and manage rivalry), and network owners have to monitor the characteristics and volume of traffic to plan capacity and invest in its capacity when congestion starts to degrade the quality of service perceived by its users. Many Internet links tend to saturate from time to time. As network paths involve several link hops, some degree of congestion is nearly always present. In fact, Van Jacobson in the late 1980's faced the problem of Internet congestion and together with the research community came with several mechanisms for congestion control [92] in the most frequent transport protocol (TCP). Network users can generate large and virtually unlimited amounts of network traffic (e.g., each home user downloading content on a 1 Gbit/s optical fiber link) typically just limited by the speed and the cost of their link (and not by the cost of its data traffic). Internet peering disputes between "eyeball" ISPs, transit ISPs, or content ISPs, are not an exception [10], and typically capacity upgrades in network links result in elastic increases of traffic expanding and adapting very quickly to the new capacity of the link. The same principles apply to (cloud or publicly shared) computing and storage resources.

Therefore we can consider that production network and cloud computing infrastructures are subject to congestion, and therefore connectivity and computing has to be considered rival. While commercial ISPs try to maximise benefit and minimise company risk in a competitive market (therefore an excludable resource sold at the highest possible market price), a goal for CNs is to maximise social inclusion, in terms of number of participants, coverage and cost, using a cooperative model where risks, costs and management is shared among the participants. This results in a network infrastructure that produces connectivity as close as possible to the ideal of non-exclusion and collective property.

2.4.3 Community networks as common-pool resources

The theoretical framework of the commons, in general, and that of commons-based peer production, in particular, serve as references for the development, management, and scientific analysis of CNs.

The fundamental principles of most CNs, defined from the start to be fully inclusive, revolve around (i) the openness of access to the infrastructure (usage), and (ii) the openness of participation (planning, design, finance, construction, operation, governance, etc.) in the development of the infrastructure and its community.

When these fundamental principles are applied to an infrastructure, they often result in networks that are *collective goods*, *socially produced*, built and managed as *common-pool resources*.

Thus, a CN could be viewed as a *collective good* or a peer property, in which participants contribute and share their efforts and goods (routers, links, and servers) to build a computer network. The peer property emerges under the operation of different internet protocols provided that the community rules such as community licenses, are respected by all participants.

The development of a CN is an instance of both *social* and peer production. The participants work cooperatively at local scale to deploy network islands, and at global scale to share knowledge and coordinate actions to ensure the interoperability of the infrastructure that is deployed at local scale.

According to Ostrom, CPRs typically consists of a core resource that provides a limited quantity of extractable fringe units. In the case of Guifi.net, the core resource is the network, which is nurtured by the in kind or monetary contributions from the beneficiaries, and the fringe unit is the bandwidth they obtain. Resilient CPRs require effective governance institutions to keep a long-term direction and deal with the struggle to handle many actors and changes in a complex system. The long-term direction is defined as *sustainability* in remaining productive or operational under the fundamental principles of the CPR, and the short-term goal is defined as *adaptability* in reacting and adapting to change.

According to Frischmann [56], public goods and non-market goods, as network infrastructures, generate positive externalities (positive effects) that benefit society as a whole by creating opportunities and facilitating many other socio-economic activities. Therefore, open network infrastructures have great social and economic value, although their benefits are sometimes hard to measure. An infrastructure that is cooperatively managed and sustained can leave a greater margin of added value activities than commercial network infrastructure developed competitively, making a great difference in developing regions or communities.

2.4.4 The bundle of rights in commons

Rooted in the seminal work in [131][15] and adapted to community networks in general in [111], it is essential to clearly identify the interests and specific tasks of the different stakeholders, and the relevant conflicts of interest, with respect to a common property. As the community managing a commons can be divided into various sub-communities depending on their role, the bundle of rights becomes a useful additional analytical grid to further break down these tasks. [131] says that the rules of each community can specify the requirements the participants must meet in order to exercise each right. The bundle of rights distinguishes:

a) Access (at operational level[16]): The right to enter and connect to the network (contribute resources, link up).[17]

b) Withdrawal (at operational level): The right to "extract resources" from the system (obtain connectivity).[18]

c) Management (at collective-choice level[19]): The right and authority to determine the rules to use the connectivity (withdrawal) and the structure of a resource (e.g. zones).[20]

d) Exclusion (at collective-choice level): The right to determine who will have access and how this right can be transferred.

[15] Aiming to *explain outcomes achieved by joint users of a common-pool resource, particularly in-shore fisheries.*
[16] Operational level: Exercising a right.
[17] *The right to enter a defined physical property* in [131].
[18] *The right to obtain the "products" of a resource (e.g., catch fish, appropriate water, etc.)* in [131].
[19] Collective-choice level: Participating in the definition of future rights to be exercised.
[20] *The right to regulate internal use patterns and transform the resource by making improvements* in [131].

e) Alienation (at collective-choice level): The right to transfer the right to manage or exclude to others (e.g. by participants transferring decision making rights over specific network infrastructure involved in a commons to others).[21]

The commons implies common-property resources, and *within a single common-pool resource situation a conglomeration of* de jure *and* de facto *property rights may exist which overlap, complement, or even conflict with one another* [131]. The property-rights schema ranges from authorised user[22] (only access *a* and withdrawal *b*), to claimant[23] (from *a* to *c*), to proprietor[24] (from *a* to *d*), and to owner[25] (all).

Related to the case of forests, but applicable to other commons, [105] defines common property as *shared private property and should be considered alongside business partnerships, joint-stock corporations and cooperatives* and the collective nature of a resource system: *common property regimes are a way of privatising the rights to something without dividing it into pieces.* Communal forests can be built from private pieces of land, managed in commons. Similarly, a network infrastructure can be built from private devices, bought and installed by diverse participants, but incorporated into a network managed in commons. This arrangement can be formal (de jure donation or usufruct[26]) or informal (de facto), according to the rules of the community.

In the case of CPR CN, people who accept the individual participation principles[27] and link up[28] to the network are given access rights and at the same time withdrawal rights (consumption of connectivity). The enrolment process is usually implemented and automated by a software service to register, enrol and configure the new resource unit (link and router) and register and enrol a new participant. By implicitly or explicitly accepting the participation rules (licence), the collective governance principles and according to the rules of the community, these people may have some degree of collective-choice rights: the right to participate in the governance of the infrastructure (management rights). As communities become large and complex, collective-choice rights tend to concentrate in an (informal or formal) group of most committed and experienced participants. As far as we know, the right of alienation (at collective-choice, and therefore the consideration of ownership of the whole or a portion) is not transferable in the CNs we studied or in the literature. In few cases, such as B4RN [O1], the CN issues shares that are purchased by community members in exchange of an economic or volunteer effort, but the holders are not considered owners as co-owners, as these cannot be transferred to other participants.[29]

[21] *The right to sell or lease either or both of the above collective-choice rights* in [131].

[22] *Authorised users lack the authority to devise their own harvesting rules or to exclude others from gaining access to fishing grounds* in [131].

[23] *With the right of management, claimants have the collective-choice authority to devise operational-level rights of withdrawal* in [131].

[24] *Proprietors authorise who may access resources and how resources may be utilised, however, they do not have the right to alienate either of these collective-choice rights* in [131].

[25] *The fishers may transfer their rights of management and exclusion over their particular spot to other fishers* in [131], but ownership refers to these rights, and can be *de jure* (given lawful recognition by formal, legal instrumentalities) or *de facto* (originate among resource users).

[26] Usus *(use) is the right to a thing possessed, directly and without altering it*, and fructus *(fruit) is the right to derive profit from a thing possessed.*

[27] In some communities, these are formalised as a community participation licence that can be legally binding.

[28] Expanding the infrastructure commons by adding network nodes (routers) and links in new locations.

[29] B4RN says that neither *Shares cannot be sold or given to anyone else, they can only be sold back to B4RN.*, nor the organisation and its commons: *Being a "community benefit society" means that the assets are locked down and cannot be sold off to an outside interest in the way that a conventional company's could. Therefore, the time, effort and money that the community invests to get high quality broadband will be preserved for the benefit of the community and future generations, not purely to make profits for the shareholders.*

2.5 Legal basis

The European legal framework for CNs covers four main topics that are key to the activity of CNs: (i) civil liability, (ii) data protection law, (iii) data retention law, and (iv) telecommunication law. This was the subject of study in the netCommons.eu project and the results reported in [64]. For our case of study, the Guifi.net CN, the main legal documents (regulations, directives, laws, decrees) that relate to the deployment and operation of network (telecommunications) infrastructure and services, as well as commons and related legal entities, are as follows.

At present:

- European union
  - General context: The liberalisation of goods and services is at the heart of the European Union (EU) legislation
    - Treaty on the Functioning of the European Union, Title VII: Common Rules on Competition, Taxation and Approximation of Laws.
  - Telecommunications
    - Telecom package Directives: 2002/21/EC (Framework), 2002/19/EC (Access), 2002/20/EC (Authorisation), 2002/22/EC (Universal Service)
    - Further Directives such as Costs reduction directive (2014/61/EC), which imposes infrastructure sharing.
- Spain
  - Telecommunications liberalisation
    - General telecommunications laws: *Ley 9/2014*
    - Transposition of further EU regulation
  - Common goods (*Bienes comunales* in Spanish)
    - *Real Decreto 1372/1986, de 13 de junio, por el que se aprueba el Reglamento de Bienes de las Entidades Locales.*
- Catalonia
  - No competences in Telecoms
  - Common goods (*Béns comunals* in Catalan)
    - *Llei 4/2008, Codi Civil de Catalunya, Llibre cinquè, Títol IV, Capítol III -drets d'aprofitament parcial*
    - *Decret 336/1988, de 17 d'octubre, pel qual s'aprova el Reglament del patrimoni dels ens locals.*
  - Foundations
    - *Llei 4/2008, Codi civil de Catalunya, Llibre tercer, relatiu a les persones jurídiques*
    - *Llei 21/2014, del protectorat de les fundacions i de verificació de l'activitat de les associacions declarades d'utilitat pública.*

In the near future:

- European regulation: Electronic communications code (which will need to be transposed into national law by 21 December 2020) and the Body of European Regulators of Electronic Communications (BEREC) regulation (both entered into force 20 December 2018).[30]

The EU admits that the market is imperfect and, thus, imposes the creation of the National regulatory authorities (NRA). The Spanish NRA is the "*Comisión Nacional de los Mercados y la Competencia (CNMC)*".[31]

2.6 Filling gaps

In the rest of this dissertation we will focus on shared network (Chapters 3 to 6) and cloud computing (Chapter 7) infrastructures governed[32] as commons that deliver abundant and cost-effective connectivity and cloud computing resources to its participants and to the applicability of the lessons learned to other domains.

From the scientific perspective, our results extend E. Ostrom production. The first main contribution in this regard is that we report on a CPR case –Guifi.net – that has some notable differences compared to those studied by her and subsequent literature. Our CPR is an "intrinsically" artificial commons while most of the existing literature on case studies focus on natural commons, like fisheries or timber lands, on "moderately" artificial commons, like irrigation systems or arable lands, or on immaterial commons, such as code or knowledge. The main challenge of the natural commons is avoiding their depletion, which is an operational problem. The same applies to moderately artificial commons, although they also entail constructional problems to some extend. Conversely, immaterial commons mostly entail constructional problems. But, any of the previous type of commons poses major operational and constructional simultaneously, which is the case of the intrinsically artificial commons. Moreover, in most of the commons in Ostrom's studies do not exceed the tens of thousands of end-users and the dozens of participants directly involved, while our case has over a hundred thousand beneficiaries and hundreds of participants with very diverse roles and interests. The second relevant contribution in the field of the study of the commons is the confirmation that our case study fit Ostrom's design principles and adaptability requirement seamlessly.

Our results also extend the literature on infrastructure as commons. Although many authors argue that commons is a very suitable model for infrastructure development and management, to the best of our knowledge, when it comes to implementation in general, and to governance in particular, either they omit these challenges, or the scope of the solutions are limited to public administration interventions. In this regard, we believe that these solutions are more related to remunicipalisation[33] approaches than to collectively managed CPR. In this regard, our results document success case of a communications network, i.e. an intrinsically artificial infrastructure, collectively built and managed, and show that similar arrangements should work for cloud computing, another intrinsically artificial infrastructure. Furthermore, we argue that the two previous cases have the shared attribute of extensibility, and propose a generic model for deploying and managing infrastructure with this attribute.

[30] https://ec.europa.eu/digital-single-market/en/telecoms
[31] https://www.cnmc.es/ambitos-de-actuacion/telecomunicaciones
[32] i.e. planned, financed, developed, extended, managed, maintained, operated, owned, used
[33] The recovery of previously privatised services to municipal authorities.

In the context of open access infrastructure, our results contribute to mitigate the main limitation of the model based on the existence of a infrastructure manager (e.g. Stokab in the case of the Stockholm municipal fibre), that is to say, having a single player in charge of the operation of the whole infrastructure. Based on the Guifi.net experience, in which the infrastructure is effectively operated by dozens of participants, we propose a model where the infrastructure is collectively operated, and where specific players can be immediately replaced by others in case of failure.

Finally, we show how the Guifi.net community is addressing, from the legal perspective, the challenge of protecting a common good made out of a number of private property assets. The value of the solution, beyond its specific implementation of the solution that is deeply rooted in the legal framework of the project (i.e. the Catalan legislation), is in its underlying model: the combination of a license describing the CPR, and an entity oblige by its bylaws to look after the CPR. Although from a general perspective this is the same model as that of many free software projects, like for instance the GNU General public license (GPL) and the Free Software Foundation (FSF), the different nature of the good protected (i.e. an immaterial good replicable at no cost vs. a usually capital expenditure (CAPEX) intensive good) have serious implications.

Chapter 3

Guifi.net – Overview

Preface

This first chapter of the three devoted to Guifi.net provides an general vision of the project and its context. It summarises the underlying principles, the associated business model, and the benefits derived from them in comparison to the private sector model. It also reviews some of the results already achieved in terms of deployed infrastructure, the conditions under which it is made available, and the opportunities for participating in the governance and in the economic system. The ultimate goal of the chapter is to provide evidence that the Guifi.net case have enough unique and beneficial features to be considered a model on its own, and thus, it is worth to explore it in further detail.

3.1 Introduction

Guifi.net [67] (pronounced /'gɪfɪ/) is a bottom-up, citizenship-driven technological, social and economic project aiming at creating a free, open and neutral telecommunications network based on a commons model. The development of this common-pool infrastructure eases the access to quality, fair-priced telecommunications in general and broadband Internet connections in particular, for everybody. Moreover, it generates a model for collaborative economic activity based on proximity and sustainability.

Started in 2004, Guifi.net was born in Osona, a county in Catalonia, to overcome the lack of broadband Internet access provision in rural areas by traditional ISPs. There, citizens deployed their own network infrastructure to interconnect different locations (the so-called nodes) such as houses, offices, farms, public buildings, etc. This allowed them to self-provision telecommunications services and Internet access wherever they were needed: at home, at work, in the library, etc. As of January 2019, Guifi.net accounts for more than 50,000 working nodes. Through an extensive production network of OF and WiFi links, thousands of people satisfy their connectivity necessities on a daily basis.

The Guifi.net project puts in practice a disruptive economic model based on the commons model and the collaborative economy, by deploying a CPR network infrastructure and a fair and sustainable economic exploitation model. In September 2019, more than 30 small and medium-sized enterprises (SMEs) operate their services professionally on top of the commons network and, moreover, they do it simultaneously and in coordination with the individuals, volunteers and other organisations participating. This is possible thanks to the development of governance rules that define the terms and conditions in which businesses can obtain economic profit out of the exploitation of the Guifi.net network.

In July 2008 the Guifi.net community established the *Fundació Privada per a la Xarxa Oberta, Lliure i Neutral Guifi.net* (The Guifi.net foundation for the Free, Open and Neutral Network) [58]. Its mission is to work in favour of the free, open and neutral network (FONN), by developing and applying a sustainable, collaborative and commons-based economic model. It is responsible for the development of the required internal norms, the project's oversight, and the operation of the critical services. The Foundation is registered at the Catalan Government foundations registry, thus, it is ruled by the Catalan law and, accordingly, it is officially recognised as an NGO. It is a registered telecommunications operator under the Spanish regulation and a member of the Réseaux IP Européens Network Coordination Centre (RIPE-NCC)[1] and APC[2], among other international organisations. In 2015, it received the European Broadband Award from the EC as best project in the category on innovative model of financing, business and investment[3].

The rest of the chapter is structured as follows. Section 3.2 lists the principles on which Guifi.net builds on, first in a natural manner, and then in a formal manner. Section 3.3 presents the business model, discusses how it links with the principles presented in the previous section, and compares it with the private sector model. The overall benefits of this approach are presented and discussed in Section 3.4. Section 3.5 contextualises the project in the legal framework and discusses its alignment with the main goals of the European regulation. Section 3.6 presents some qualitative and quantitative results to illustrate the achievements in terms of diversity of participants involved in the project as a whole and in its governance and the economic system in particular, the size of the investment made and infrastructure put in place, etc. and analyses the impact the project already had in 2013 though official statistical data. Section 3.7 reviews the main success factors and Section 3.8 presents the conclusions of the fist chapter devoted to Guifi.net.

3.2 Principles

Guifi.net develops a comprehensive ecosystem based on the following driving principles:

- Sharing network infrastructure increases the efficiency (i.e., better performance or wider coverage for the same investment) of the network infrastructure because it stimulates cooperation, preventing duplication of efforts and facilitating economies of scale; this is particularly true in the case of OF because, once in place and operated, it can become a non-rivalrous asset (zero marginal production costs) due to its virtually unlimited bandwidth.

- Network participants have the right to satisfy their connectivity needs through their own as well as through the procurement of professional services in a fair competition market.

- The existence of a fully developed and healthy economic activity, rooted in good practices such as the collaborative economy and fair trade, creates a virtuous circle of dependency and reinvestment which has a very positive impact on the project's sustainability and vice versa, the presence of few "just for profit" participants can ravage the collective production of the whole community.

- The professionals (i.e., individuals or enterprises that deliver services in return for an economic remuneration) who work to operate, maintain or extend the network deserve

[1] https://www.ripe.net/
[2] https://www.apc.org/
[3] https://ec.europa.eu/digital-single-market/en/news/five-projects-got-first-ever-european-broadband-award

a fair reward for their work, but speculation with network assets or any other harmful practice is totally forbidden.

- The network must remain open, free, and neutral.

Or more formally and summarised:

- A single infrastructure is collectively built and managed in a non-discriminatory manner,
- The resulting infrastructure is made available to everyone on equal and non-discretionary terms for any purpose, including, but not limited to, the commercial exploitation, and
- The participation in the construction and maintenance of the infrastructure is made according to its usage.

The spirit of sharing, social justice and freedom is well captured by the two main mottos of the community:

- "*Xarxa oberta, lliure i neutral*" in Catalan, "neutral, free and open network".
- "*Una Internet justa per a tothom*" in Catalan, "A fair Internet for everyone".

3.3 Business model: infrastructure as a commons

As shown in Figure 3.1, in contrast to other existing business models, in Guifi.net the infrastructure is considered a CPR in which the participants can (i) extend the infrastructure where necessary, and (ii) actively participate in the governance system, i.e. to influence on the policy, actions, and affairs, and in the economic system. The network infrastructure growths through the contribution of the participants, who can be fairly compensated for their contributions if they are used by other participants.

The Guifi.net business model tackles from the foundations the two drawbacks of the existing models, namely restrictions to access to infrastructure and to participate in its deployment and operation. The private model only enables two *domains of direct action*[4], i.e. fields where people take action straightforwardly. The first refers to participation in the infrastructure management, either in the decision-making area or in the economic system. As already discussed in previous chapters, nowadays, this domain is restricted to very few people, that is to say, the vast majority of the population is effectively excluded from it. The second domain is the usage of the infrastructure provided which, in this case, is limited by the availability of infrastructure and by the conditions it is provided, deriving in exclusions due to unavailability or affordability (see Section 1.2.1). Conversely, the Guifi.net approach (i) enables the additional domain of self-provisioning, (ii) extends the domain of participation to everyone, (iii) eliminates uncertainty, and (iv) improves the conditions under which the infrastructure is made available. As a consequence, we find a mix of for-profit and not-for-profit participants. Moreover, in addition to the inclusion of new type of participants, and contrary to the traditional business models, in Guifi.net all for-profit participants collaborate in the construction and maintenance of the single shared infrastructure.

[4] We use the term *direct* in contrast to indirect procedures such as the pursuit of legal changes through the political participation.

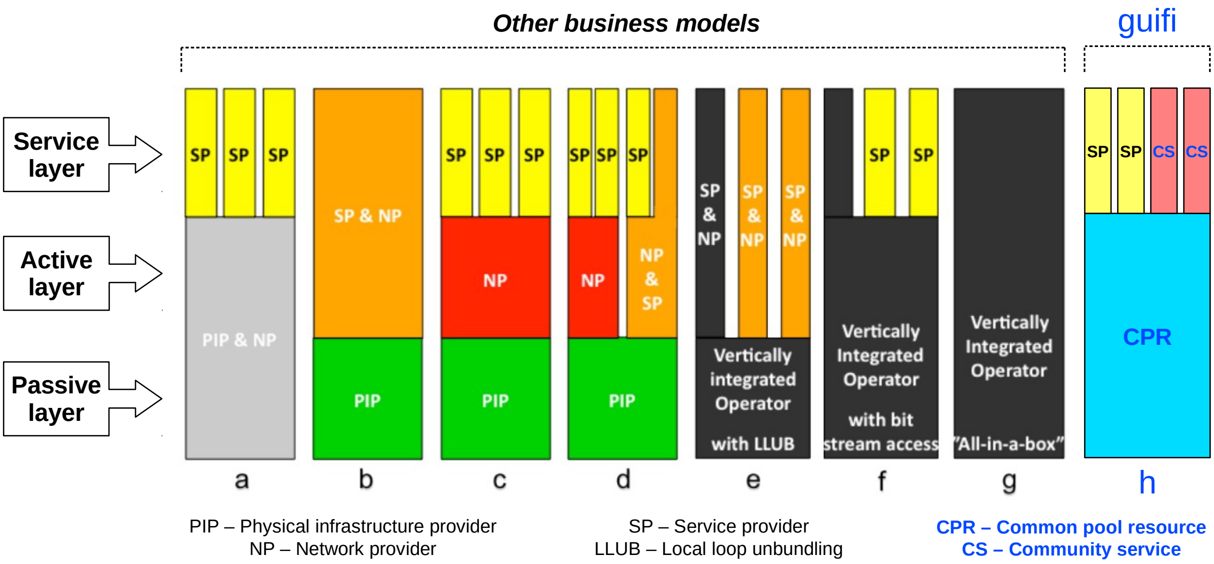

Figure 3.1: Network business model of Guifi.net. Passive and active layers as CPR (based on [49] (see Figure 2.2)).

In this approach, the control over the assets is no longer a competitive factor among for-profit participants, that is, network assets cannot be traded on a discretionary basis. Thus, the resulting ecosystem becomes a true *single market* and, hence, it gets close to the perfect competition conditions (i.e. the perfect market ideal) because any company in the project has exactly the same opportunities to reach any potential customers. With the removal of the control over infrastructure as a competitive factor, these become essentially limited to the increase of quality of services or price reduction. Consequently, we can state that the Guifi.net approach not only makes the collaborative and the free market economies compatible, but brings out the best of each. The restriction of the capacity of influence of the private sector to technical an operational matters has also proven key in the sanitisation of the ecosystem as a whole.

Table 3.1 summarises the major differences between the Guifi.net and the current private sector approaches. As the table shows, there are significant divergences in almost all the fields. To begin with, while Guifi.net main objective is to seek a social benefit by maximising the of the extension and use of a shared good which is seen as indispensable in the modern world, in the private sector it can only be assumed that the underling motivation is the maximisation of the profit of the investors, which has very little or nothing to do with the social benefit. The conception of what are the productive assets and the associated rights, the strategies to achieve the goals, and the investment periods are also radically different. In the first case the assets are conceived as a long-enduring CPR. Hence, the strategy relies on the of cooperation among the participants and long-term investment. In the second the productive assets are conceived as private goods which are traded which are bought and sold on the basis of profit opportunity and the investment periods are becoming sorter. Private sector needs constant external regulatory oversight because the purpose of the infrastructure and the objectives of the promoters are not bound. Conversely in Guifi.net the economic activity directly depends on the proper operation of the infrastructure and on the number of participants served, thus, the professionals have strong incentives to look after the CPR. Moreover, the active implication of a number of other stakeholder groups, including the Foundation, strengthens substantially the internal oversight, making nearly unnecessary the external intervention. Such a number of divergences can only lead to totally different, if not incompatible, results. While Guifi.net can

	Guifi.net	Private sector
Objective	Maximisation of the size and use of the shared good (social benefit)	Maximisation of the profit of the investors
Manages	Common-pool resources	Private goods & exclusive rights
Strategy	Optimisation of cooperation	Maximisation of the market-share (become a monopoly, ideally)
Investment	Long-term, collective	Short-term, speculative
Governance	Self-governance, self-regulation	Needs external legislation and regulation
Features	Cost-oriented, inclusive, sustainable, redistributive, local	Directional pricing, extractive, market failures, speculative, transnational

Table 3.1: Comparison of Guifi.net and private sector approaches.

be described as cost-oriented, inclusive, sustainable, redistributive, and local ecosystems, the globalised private sector is directional in pricing, extractive and speculative, and market failures are intrinsic to it.

3.4 Main benefits

Environmental impact

Reduces resources consumption The existence of one single infrastructure minimises the resources required to deliver the same level of service. The reduction is obvious in deployments where a single physical link –a pair of antennas in WiFi, or a cable in OF– suffice. In these scenarios, which are the most common by far, specially in OF deployments due to the high performance of this technology, adding additional infrastructure only increases the total bandwidth surplus, which is totally superfluous but obviously has a negative impact on the environment. Optimisation of surpluses also occur in the network segments where a single link does not suffice. In OF in most of the cases an upgrade of the active equipment of the edges suffices. Thus, extra cable deployments are only needed occasionally. Similarly, in WiFi in many cases the upgrade to newer technology is enough. But, in any case, the management of multiple parallel links is more efficient if it is done in a coordinated fashion that if is done independently, and these kind of inefficiencies frequently end up in additional infrastructure deployed.

Supply side

Stimulates cooperation The retailers compete with each other for customers, but they all depend on the same infrastructure. Thus, they all share similar incentives to keep it in pristine condition.

Boosts economies of scale The joint management not only avoids the duplication of infrastructure, but also allows the optimisation of the human resources and enables their specialisation. Joint procurement is also more efficient and facilitates access to types and prices of offerings hardly attainable otherwise. For instance the transition from the access to Internet from retailers to the wholesale market brought an extraordinary increase of the quality of the service and a substantial reduction of the price.

Eliminates entry barriers In practice, the entry barriers for new professionals have been reduced close to the capital needed to extend the network to the areas where the economic activity is intended to develop if it does not preexist. The backbone network and its associated services, as well as the Internet access and a bunch of administrative proceedings are already in place. Thus, in practice, a new company can immediately start trading after joining the community.

Equalises business opportunities Due to the access to the infrastructure is not a competitive factor any longer, the massive reduction in production costs, and the access to a market with tens of thousands of potential customers on equal terms.

Increases competition and diversifies supply as a result of the previous points. There are about 30 participants including size companies, cooperatives, self-employed entrepreneurs and associations offering a variety of options and services such as Internet connection, tailored support, telephony services, etc.

Demand side

Delivers a true single market The single shared infrastructure allows almost any customer to consume from any professional regardless of the geographic location of any of them.

Increases the quality of service and reduces prices In a close to the perfect competition conditions, the reduction in production costs always ends up translating into the reduction of service price.

Prosumers

Enables the do-it-yourself option The mere existence of the do-it-yourself (DIY) option enriches the whole ecosystem because it contributes to increase competition –if the professionals do not fulfil the customers expectations, the customers always can self-supply their need or even bring new providers into the system, and its realisation raises the cultural level.

Social impact

Implements an inclusive and sustainable local economy in which the wealth generated is real and stays local.

Empowers people As any other participatory system, the implementation of Guifi.net increases the general awareness, which eventually translates into more a demanding society.

Puts in practice effective means for participation and oversight Increases the chances that the built infrastructure meet the people needs.

Integrates internal wealth redistribution by design by making the economic system accessible to the local population, reducing services prices, and, addressing the unaffordability challenges through mutual support at local scale.

Creates a fairer society Due to the removal of privileges as a result of the real competition environment developed.

3.5 Legal approach

There is a widespread view among the Guifi.net community that creating an environment of trust is a main goal –because trust is key for investment, among other reasons. As a consequence, the community has made a great effort to understand the legal framework, which is complex and involves several sources of law. It can be stated that Guifi.net community's general will is to observe the laws, either its members like them or not, and that just very occasionally the rules have been breached. In the last case, when it has been done consciously, it has always been done as a mean of protest –never to achieve anything illegally– and, in general, the actions have been widely published.[5] The community's positive attitudes towards the respect for the rule of law has led to participate in several consultation process and policy and regulation discussions, specially at the EU level, and frequently together with other CNs and related groups.[6] At local level, the Guifi.net community has worked hand in hand with local administrations to address several legal challenges, most of them derived from the legal impediments to contribute to the construction of a decent telecommunications network for their citizens and the associated administrative burden.[7] [59]

As to the telecommunications regulatory framework, it has to be said that, as a result of its liberal inspiration, the European regulation is very favourable towards the development of CNs as it ensures equal treatment for any telecommunications initiative. Furthermore, the contributions to extending the telecommunications infrastructure, increasing the offer, and bringing new players in the economy that CNs entail are totally aligned with the European strategic objectives.

The alignment between CNs models and the regulatory framework and its underlying principles is even more marked when compared to the EU Electronic communications code. This new regulation, which is already coming into effect, looks for further efficiency through co-investment and imposes further obligations on publicly funded infrastructure towards sharing and open access. Both, co-investment and open access, are common traits in CNs and are central in the Guifi.net initiative.

In practice, the truth is rather different, however. According to the EU rules, the transposition of the directives must be done by the member states. In Spain transpositions frequently happen late and inefficiently. In the telecommunications sector, these failures commonly benefit the big

[5] For instance, in some OF deployments, the poles by the incumbent have been used without an explicit consent after a long waiting time.

[6] For instance, in 2017 the Guifi.net foundation took part in the campaign led by La Quadrature du Net (https://www.laquadrature.net to defend the CNs interest during the drafting process of the Electronic communications code), which led to the release of the following public statement: https://www.laquadrature.net/en/2017/03/16/netcommons-open-letter-EU-policy-makers-on-community-networks/.

[7] For instance, since the very beginning a system based on the use and federation of proxies connected to public DSLs was developed. The objective was two fold. On the one hand it contributed to manage the scarce Internet access existing at that time. And on the other hand, it provided a convenient way to the mayors to share with their neighbours the very limited Internet access they had in the town council buildings –because in most of the rural areas those Internet connections were the only available– without having to deal with the unattainable legal obligations if they wanted to do it by their own means. A more recent example is the model has been developed as a template for a municipal ordinance by the Foundation. The purpose of this ordinance is to serve as a basis for municipalities to regulate the deployment of infrastructure that could be used for advanced networks, which is the responsibility of the city council.

telecoms, which always push to strengthen the barriers to newcomers. As an example, they are very hostile against others investing in unreserved areas, specially if they are new players. The rationale for their belligerence is two fold. Firstly, new player success would provide evidence that, contrary to what they say, others can also deploy and operate network infrastructure, and, probably in a more efficient manner. Secondly, it would cut their potential market, because deploying first gives a clear competitive edge and in many areas there is just market for a single operator. The emergence of CNs have a positive impact because they increase the number of agents interested in the timely and effectively transposition of the EU regulation.

3.6 Success indicators

This section presents some qualitative and quantitative results to illustrate the achievements in terms of diversity of participants involved in the project as a whole and in its governance and the economic system in particular, the size of the investment made and infrastructure put in place, etc. and analyses the impact the project already had in 2013 though official statistical data.

In summary, Guifi.net is currently a strongly horizontal organisation with hundreds of people involved and widely geographically distributed. Given its organisation and size must of the overall indicators can only be either qualitative or quantitative estimates. However, these overall indicators can be backed with other very accurate indicators such as precise quantification of the investment in some significant areas, the number of participants in the economic ecosystem or the traffic in the network operation centre (NOC).

3.6.1 Participation – Community building and governance

Scientific quantitative data of such a diverse and spread project can only be achieved indirectly. In terms of participation, [155] in 2014 found 13,407 registered users in the Guifi.net portal and 55 mailing lists. A qualitative description of the current state of the most relevant stakeholder groups follows.

Volunteers The Guifi.net community of volunteers is healthy. Volunteers contribute in many tasks such as bootstrapping new areas, assisting newcomers, improving the software tools, doing maintenance, etc. Thanks to their locality and their commitment to the project, they are a key component in the task of ensuring that the rules are fulfilled, especially in areas where the presence of the Foundation is limited.

The Foundation Established to provide legal entity to the project and act as the system operator. As such, it has led the process of defining and implementing the governance system.

From the legal viewpoint, through the corresponding notification to the Spanish NRA, the CNMC, it is the operator of the network infrastructure by default (i.e. of those parts of the network which are not operated by anyone else) which is very convenient for participants who are not familiar with these specific legal and administrative details of the telecommunication sector, such as volunteers or public administrations.

As part of its actions to stimulate the economic activity, it promotes network projects (e.g. an optical fibre deployment in a neighbourhood) which afterwards are executed by the professionals (project allocations are made according to pre-established rules, and the Foundation always keeps the role of project supervisor). In addition, the Foundation helps these professionals by sharing its resources, especially when they start, and accompanies them during their growth process.

Its dissemination activities include promotion in public administrations, with politicians, private companies, and citizens, dialogue with the regulator and in response to any public call that may affect the commons network, etc.

Its research activities are mostly tied to collaborations with universities. The Foundation has participated several research projects funded by the EC.

Other Guifi.net organisations A diversity of not-for-profit organisations complement the activity of the Guifi.net foundation. This include associations of users, coops and local delegations of the Foundation. This type of organisation is a typical entry point for newcomers because they do a lot of dissemination activities and provide support to beginners. Associations and informal groups are preferred by technical skilled people, while cooperatives are preferred by people who supports Guifi.net's principles and ideas, but either they do not have the required skills or the time to put them into practice.

Public administrations Collaboration agreements have been signed by Guifi.net with many of them, mostly small- to middle-size municipalities (e.g. with almost all of the Osona county), but also with counties (e.g. *Consell Comarcal d'Osona*). A correlation between the size of municipalities and the level of commitment with the commons network can easily be identified; the smaller and less served by conventional telcos, the stronger the commitment and the bigger the contributions. At the moment, more than one hundred councils are actively collaborating with Guifi.net, most of them through the Foundation but also through local installers and service providers.

Universities The Foundation has signed collaboration agreements with almost all Catalan universities. Collaboration activities include infrastructure deployment, research projects, students mentoring, dissemination, etc.

Other third parties The following are examples of the many cases of successful collaborations with third parties to contribute to the network commons. These cases show that almost any entity or organisation can contribute. Since 2008 the Catalan top level domain (.cat) has most of its hardware in the Guifi.net facilities; their contribution was crucial to launch the first territorial exchange point. The Hospital de Vic[8] and the Hospital d'Olot[9] self-supplies their connectivity needs through OF held in common.

Professionals Over 30 SME deliver professional services in the Guifi.net ecosystem (see next section for further information).Guifi.net[10]

3.6.2 Participation – Economic system

The description of the current state key indicators of the health of the economic system follows.

Professionals As already indicated in the previous section, over 30 SME deliver professional services in the Guifi.net ecosystem. They range from self-employed entrepreneurs to companies accounting for tens of employees. The key activities are deployments of new

[8] The capital of the Osona county.
[9] The capital of the Garrotxa county.
[10] https://guifi.net/en/node/3671/suppliers

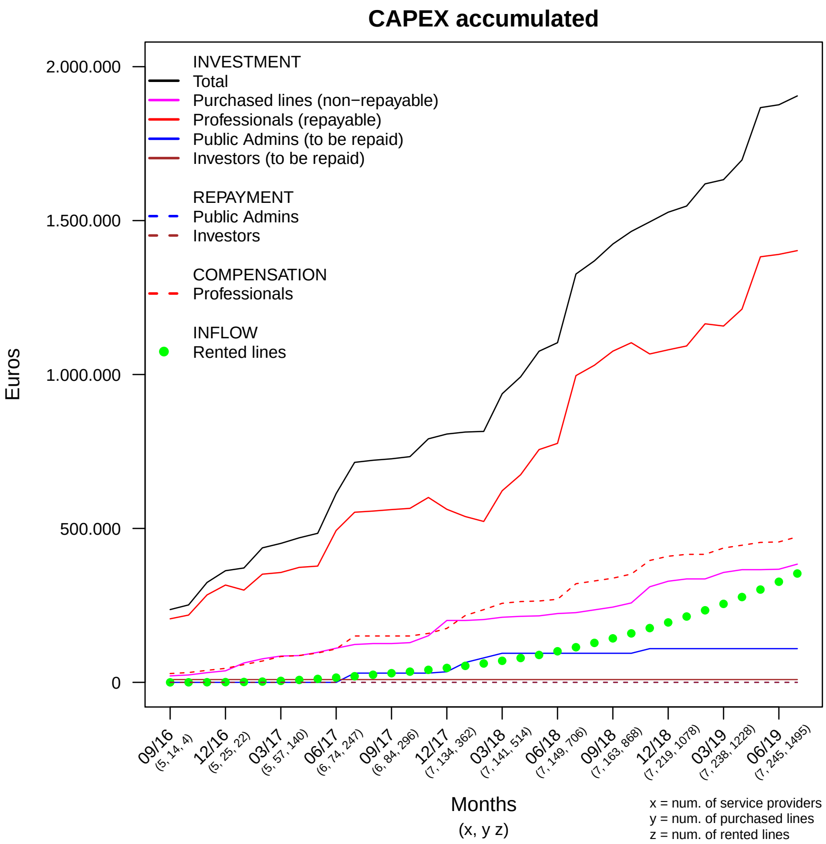

Figure 3.2: Accumulated investment in OF in Xarxa de fibra òptica de la Garrotxa (XAFOGAR) (Source: Guifi.net foundation).

infrastructure, maintenance and operation of the existing infrastructure, and the provision of services to end-customers over the network.

End-user services The Internet access is the most popular service. Nonetheless, others such as VoIP and remote backups have also been offered for quite some time, and new services such as video streaming and video on-demand are becoming popular, especially in the areas with optical fibre.

Turnover The great economic activity in conjunction with the number of participants makes difficult to estimate the total turnover of the whole project. However, precise data on some partial indicators exist. As an example, total annual cost of the NOC (see Section 3.6.3) is around 400,000 € (see Table 5.2).

Investment In [P2] it was estimated the total investment to be near 7.5 M€. Since then, the investment, specially in OF has grown tremendously. As in the case of the total turnover, the total investment could only be roughly estimated. But, in this case, precise data on some partial indicators exist. For instance, from the XAFOGAR project[11], which is a flagship project in the Garrotxa county for deploying OF across the region to every single home led by the county's *Consorci de medi ambient i salut pública (Consorci SIGMA)* (Consortium for the environment and public health) and the Guifi.net foundation. Started by mid

[11]Web site (catalan): http://www.xafogar.cat/

2016, with a total estimated budget of 10 M€, as Figure 3.2[12] shows, the accumulated investment by July 2019 was close to 2 M€. Although it is not possible to make a such precise quantification of the total investment because in in the rest of the regions the accounting is no yet as systematic as in XAFOGAR, the fact that the exterior traffic of XAFOGAR is less than one tenth of the total (see Section 3.6.3), permits us to consider that the total investment in last mile deployments must be over 20 M€[13].

In Figure 3.2, the evolution of the purchased lines, i.e. contributions made by the participants who want to have access to a specific deployment and avoid the line rental fees (see *for-fee reduction contributions* in Section 5.2.3) illustrates the potential of the system to activate direct investment by the beneficiaries, which, in this case, accounts for 25 % of the total investment.

It is also worth noting that the total investment made by the public administrations is less than 10 % of the total. However, the presence of public funds, together with the firm commitment of SIGMA, has been key to create the climate of confidence to activate the rest of the investment.

Inflow In July 2019 the monthly inflow from rented lines (see *line rental fees* in Section 5.2.5) is close to 27,000,€ and the total accumulated represents around 25 % of the total current investment made by the professionals. This rate (i.e. without new subscribers) means a ROI period of less than 5.66 years, considering an annual interest rate of 5 %.

Compensation among professionals As Figure 3.2 shows, the total amount compensated among the professionals operating in XAFOGAR accounts for around one third of their total investment, which is an indicator of the high degree of infrastructure sharing among them.

3.6.3 Access – Infrastructure deployment and adoption

Figure 3.3 shows the network architecture of Guifi.net in general. Currently, almost all the traffic between Guifi.net and the rest of the Internet (the external traffic) is exchanged at the premises of Equinix [42], the main collocation centre in Barcelona, where Guifi.net has its NOC. The traffic is exchanged preferably through peering in the local IXP, the Catalan neutral internet exchange point (CATNIX) in our case, and otherwise through network service providerss (NSPs), also referred to as carriers. At the time of this writing, Guifi.net has five NSPs, two for general purpose Internet connectivity, which account for over 99% of the NSP traffic, and three for special operations, such as specific peering or operations related to mobile and fixed telephony services. The setting of two general purpose Internet connectivity providers ensures basic redundancy. Figure 3.4 shows the traffic exchanged by Guifi.net community with other CATNIX members and

[12] Figure 3.2, summarises the monthly evolution of the main indicators of XAFOGAR. All are accumulated values. The number of professionals, purchased lines and rented lines are shown in the abscissa. The black curve is the total investment, which is the sum of the coloured solid curves. The red solid curve corresponds to the investment by the professionals; this curve can decrease because the investment made by the participants is refunded through the purchased lines (magenta solid) and the contributions of the public administrations (blue solid) and of the investors (brown solid). The purchased lines are non-refundable and together with inflow from the rented lines (green dotted) are the total net income to the system (see Chapter 5). Although the contributions by the public administrations and the investors are refundable, as the dashed blue and brown curves show, there has not been yet any repayment because the lenders have so provided. The red dashed curve shows the total amount compensated among the professionals (see Chapter 4).

[13] This is a very conservative because many deployments started using WiFi technologies, and that, after several upgrades and expansion of the WiFi equipment, they have been migrated to OF.

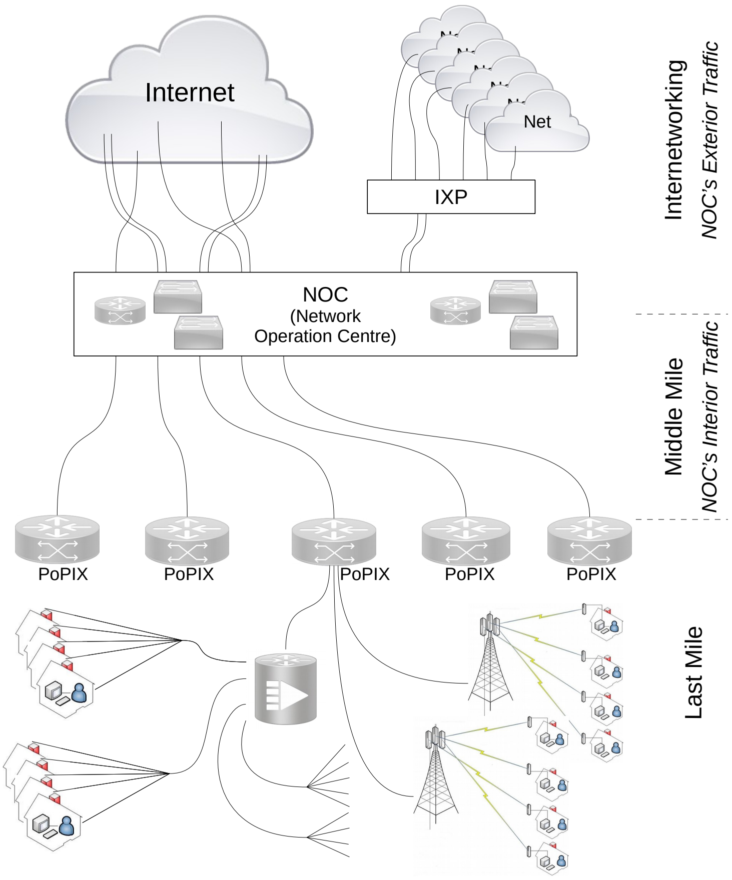

Figure 3.3: The Guifi.net network architecture.

the two main carriers at the NOC during the second week of April 2019. Guifi.net is currently the ISP member –i.e. excluding the content providers– with the largest traffic in the CATNIX. The Foundation is the official member of CATNIX on behalf of the Guifi.net community. It has been assigned ASN 49835, IPv4 109.69.8.0/21, 5.10.200.0/21 and 185.32.16.0/22, IPv6 2a00:1508::/32 by the RIPE-NCC and also operates other ASN and IPv4 and IPv6 ranges from the some of the Guifi.net professionals.

The external traffic is distributed through the middle-mile network to the territorial points of presence, the PoPIX in Guifi.net's jargon, and from there to the end users through the last-mile networks. At the time of writing there are 25 active PoPIXs, about the of them connected through 10 Gbps OF links and the rest through 1 Gbps OF links. All the middle-mile network links are rented from third-party providers.[14]

The last mile comprises a combination of owned WiFi and OF, with the last replacing the first in existing deployments and is dominant in new deployments. Figure 3.5 shows the WiFi network and Figure 3.6 the number of active nodes over time. In some rural areas the adoption is remarkably high. For instance, in Perafita, a village of 412 inhabitants, 159 main family

[14]Most of them are active Ethernet circuits traditionally rented from Xarxa Oberta de Catalunya (`https://www.xarxaoberta.cat/`), almost the only territorial connectivity provider in Catalunya until recently. However, the number of providers has increased significantly in the last years and, as a consequence, the supply has improved significantly. Nowadays the links are rented from several providers.

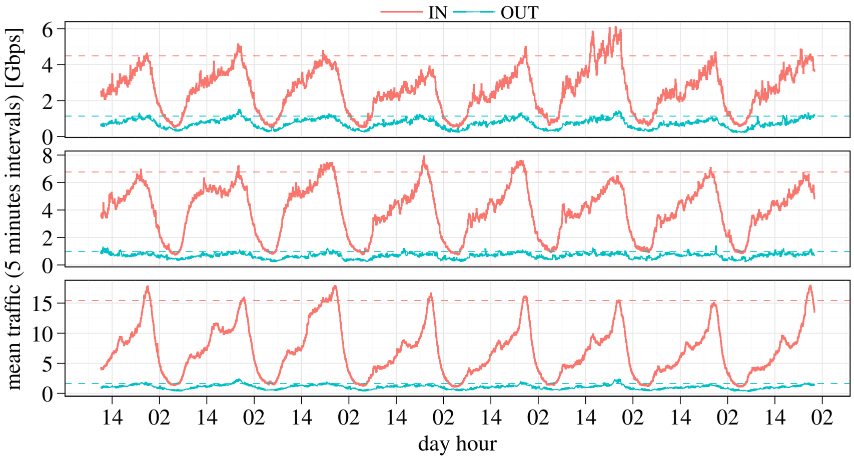

Figure 3.4: Traffic exchanged by Guifi.net community with other CATNIX members (top) and the two main carriers (middle and bottom) at the NOC (Source: Guifi.net foundation, April 2019).

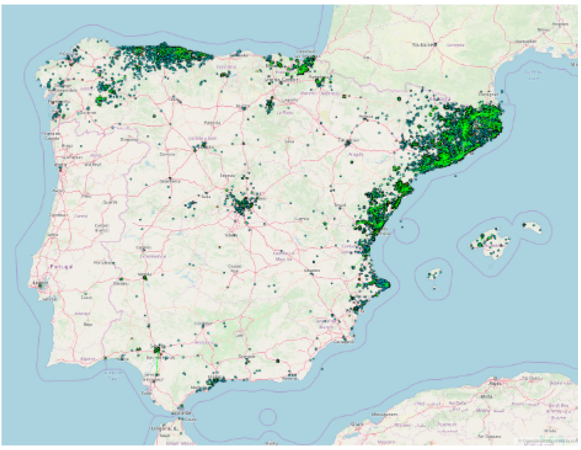

Figure 3.5: Guifi.net WiFi network (July 2019, source: `https://guifi.net/maps`, ©OpenStreetMap contributors).

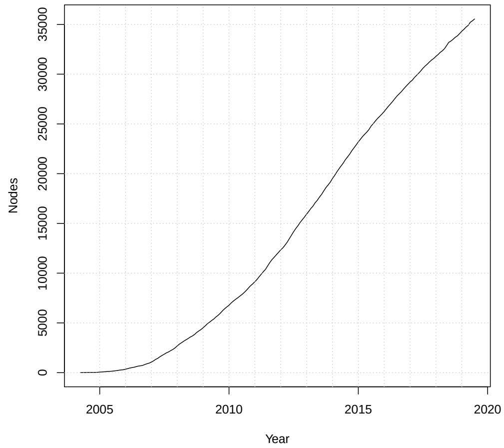

Figure 3.6: Guifi.net active WiFi nodes (source: `https://guifi.net/guifi/menu/stats/nodes`).

dwellings, and 76 secondary family dwellings, 240 in total [86],[15] accounts for 91 active WiFi nodes, that is, a penetration of 40 % in a village with good coverage of LTE and DSL.

Figure 3.7 shows the OF backbone of XAFOGAR. The Garrotxa county has 55,579 inhabitants [83] and 23,560 non-empty family dwellings [85]. Olot, the capital, has 34,486 inhabitants and 13,439 [85]. The other 21,093 inhabitants are distributed among 20 municipalities, ranging from 200 to 3,000 each in 10,121 non-empty buildings. Before the launch of XAFOGAR Olot was the only municipality with OF available. Shortly after the project was publicly announced the incumbent started deploying outside Olot.[16] Nonetheless, XAFOGAR is progressing satisfactorily. In July 2019 there were 256 purchased lines and 1572 rented lines (245 and 1495 in June 2019 as shown in fig. 3.2), meaning 18 % of the total non-empty dwellings. It must be taken into account that OF roll-outs are made per neighbourhood at least and that it is an on-going project. The penetration rate in covered municipalities is up to 90 % (e.g. Tortellá). It is also worth noting

[15] According to the Local government the garbage collection service in August 2019 issued 277 bills in total, 253 family dwellings and 22 enterprises.

[16] This pattern has been observed in many other OF deployments.

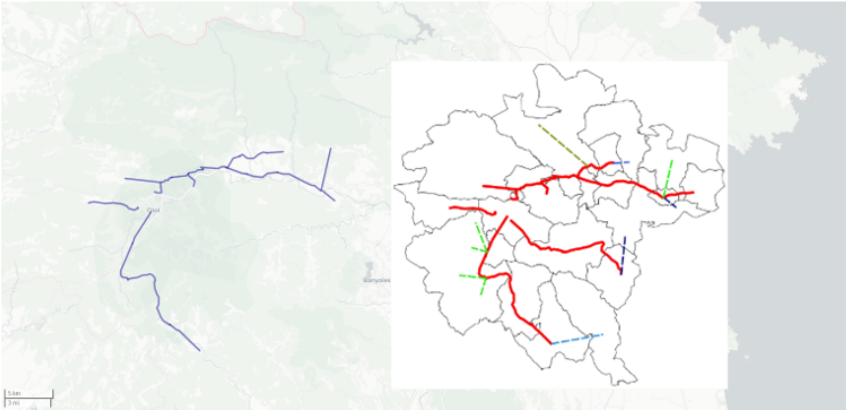

Figure 3.7: Planned (background) and executed (inner square) OF backbone network of XAFOGAR (July 2019, Source: Consorci SIGMA, ©OpenStreetMap contributors).

that, Olot, which did not join the project at the beginning, also joined recently and the initial OF deployment are expected by the last quarter of 2019.

3.6.4 Access – Affordability

The main offerings (prices per month) by the four largest service providers in September 2019 are the following (in alphabetical order)[17]:

Delinternet

OF up to 800 Mbps 27.71 €; up to 800 Mbps + fix-line (metering) 31.34 €; up to 800 Mbps + 1 mobile (3 GB, unlimited) + 1 fix-line (metering) 43,09 €.

WiFi 19.01 €; + fix-line 22,64 €; + 1 mobile (3 GB, unlimited) + 1 fix-line (metering) 34,39 €.

Goufone

OF 300 Mbps 36.20 €; 1 Gbps 39.95 €; 1 Gbps + 1 mobile (4 GB, unlimited) + 1 fix-line (unlimited) 47.95 €; 1 Gbps + TV 49.95 €.

WiFi 8 Mbps 36.20 €; 8 Mbps + 1 mobile (4 GB, unlimited) + 1 fix-line (unlimited) 44.95 €.

Iguana

OF 1 Gbps/300 Mbps 46.00 €; 1 Gbps/300 Mbps + 1 mobile (7 GB, unlimited) + 1 fix-line (unlimited) 58.00 €.

WiFi 3 Mbps/3 Mbps 25.50 €; 4 Mbps/4 Mbps 29.50 €; 6 Mbps/6 Mbps 37.50 €; 10 Mbps/10 Mbps 54.50 €.

XTA

[17] Delinternet: `https://delinternet.com/`, Goufone: `https://goufone.com/`, Iguana: `https://www.iguana.cat/`, XTA: `https://www.xta.cat/`.

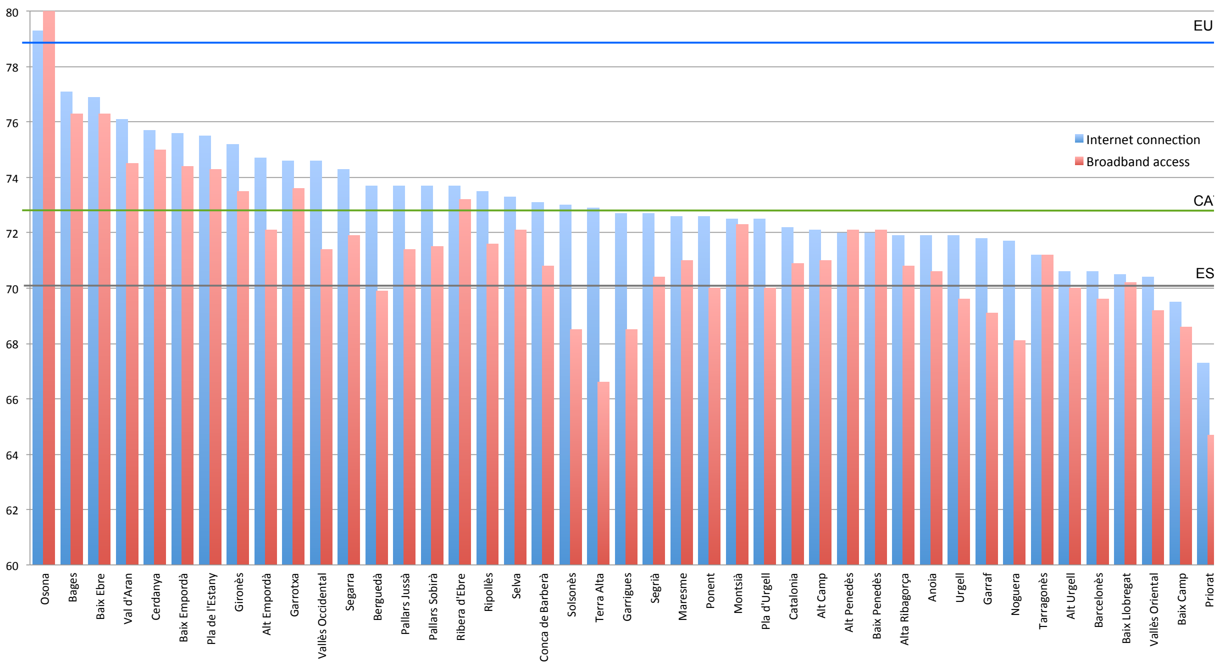

Figure 3.8: Households bandwidth and Internet access in Catalonia per county (2013, source: IDESCAT [84]).

OF 50 Mbps/50 Mbps 29.00 €; 300 Mbps/30 Mbps 39.00 €; 300 Mbps/30 Mbps + 1 mobile (3 GB, unlimited) + 1 fix-line (500 minutes) 49.00 €.

WiFi 3 Mbps/0.5 Mbps 18.00 €; 6 Mbps/1 Mbps 23.99 €

All of the above offerings are free of acquisition cost; for-free reduction contributions have 17 € monthly discount.

The Associació expansió de la xarxa oberta (EXO) associations of user has a monthly membership fee of 10 € plus 2 €/month for the WiFi Internet access. Users must contribute their own links.

3.6.5 Impact

Methodologically speaking, we believe that impact impact must be supported by data from third parties, where possible. Based on this assumption, in 2015 in [P2] we assessed the Guifi.net project impact based on information from 2013 by the public Catalan Statistics Institute (*Institut Català d'Estadística* (IDESCAT)[18]). Unfortunately, to the best of our knowledge, those statistics have never been updated[19], which has prevented us from being able to update our research. Thus, it must be noted that the quantitative information of this section is more than six years old and outdated considering the significant changes in the telecommunications industry in the last years. Nonetheless, we have opted for including the work we presented in 2015 because we believe that is still valid to provide evidence about the capacity of CNs to produce real impact.

[18] http://www.idescat.cat

[19] IDESCAT has been updating every two years, but in the following iteration of the questionnaire the questions of our interest were eliminated and were never reintroduced.

Figure 3.8 presents the data about penetration of the bandwidth and Internet access in the households of Catalonia in 2013, released by IDESCAT per county [84]. It also contains the average rate of Internet access of the European Union, Spain, and Catalonia. The first thing to notice is that, despite the fact that Catalonia is about three points above the Spanish average, it is still seven points below the European average. Second, and most relevant point regarding Guifi.net impact, the Catalan county with the best results and the only one above the EU average, is Osona, where Guifi.net was born. Moreover, it is the only county where broadband access is above Internet access. The indicators of other counties where Guifi.net presence is significant, such as Bages and Baix Ebre, are also larger when compared to similar counties but where Guifi.net presence is irrelevant.

At that time, Osona had about 9,000 nodes[20]. Combining this number with others coming from IDESCAT[21]. We conclude that about 22.4 % of the Osona inhabitants had Guifi.net access: around 30,500 people.

3.7 Success factors

This section discusses what, to our understanding, are the key success factors of Guifi.net based on our active participation and research on Guifi.net, and in comparison to other CNs.

Clear and simple principles and scope, and firm commitment to them In general, simplicity and clarity in the fundamental questions eases the consensus and sets the basis for focusing the efforts, which, in turn, in conjunction to firm commitment to them and avoiding distractions, are key for effectiveness. In the particular case of Guifi.net, the principles are openness and non-discrimination and the scope is the network. Any other issues such as, for instance, commitment to free software or dislike towards profit are left outside of the project.

Development and early adoption of a network license The license is an instrument to formally establish the principles and the scope, which are the basis to deliver legal certainty. Thus, it must be drafted to be law enforceable. To be so, the terms and conditions must be very well defined, severely restricting them in scope and in range of interpretation. The more precise the definitions and narrower the ranges of interpretation, the less likely to find consensus. Thus, from a pragmatic perspective, the less people involved, the more likely the process to be successful. In Guifi.net, the time of drafting the license there were no more than a few dozens of participants involved. Inspired by the example and good results of Guifi.net, other CN have tried to draft a license, but most of them have failed due to the excessive number of participants already involved.

The infrastructure as CPR The CPR model has proved to be a very suitable and effective resource management principle and is probably the only one that really compatible with the project's fundamental principles.

Adequate legal architecture and law compliance The legal tools developed, starting from the ground rules –the license and the Foundation's bylaws– has proved to successfully

[20] `http://guifi.net/ca/Catalunya`, 8,958 adding Osona and Lluçnęs and substracting Santa Maria de Marlès and Sant Feliu Sasserra, as they belong to other counties (*comarques*).

[21] (2013) Osona has 71,597 households, Catalunya 2,944,944 [82]; in Osona 38,029 buildings have at least a household, 75.6 % of the households are single family houses [81]; Osona population (2013): 153,563 [83]; thus, 4.08 inhabitants/building. The rate supernodes to nodes is 0.1; estimates are that half of them are not installed in homes.

withstand exogenous and endogenous attacks without relinquishing the private property right. Any breach of law puts the project at risk.

Activation of a flourishing economic ecosystem The incorporation of professional activity as an organic component of the system has contributed to drastically reduce the dependency on volunteering work and has enabled an unprecedented growth.

Early identification and sound management of conflicts of interest The Guifi.net community has combined the fact of starting a new project, thus not to bear the burden of inherited dynamics, with the knowledge extracted from the traditional telecoms industry and from its own experience to early detect those practices that lead to bad practices and vicious circle, and act accordingly. As a result, Guifi.net has defined and put into practice a complete governance system, including a well defined stakeholder group system and a clear attribution of roles and incompatibilities. These arrangements effectively protect the community against bad practices, and stimulates competition.

Diverse and well-balanced participation As a result of the governance system, which has been developed incrementally based on new challenges and lessons learnt, the system is very divers.

Effective tools for participation and coordination The tools developed around open data, procedures, automation, and coordination tools help to lower the barrier to access the infrastructure and to participate in its social production. They reduce the cost of decision-making and of action, and are imperative for transparency and accountability.

Leadership and stewardship The entire process is very innovative and therefore, due to its open nature, susceptible to deviations. Clear ideas and strong leadership have been key to stop useless discussions and isolate disturbing attitudes. At the same time, the stewardship is reasonable, inclusive, and accountable enough to maintain community's the engagement

Balanced effort between development of support tools and network deployment The main goal and the way to keep the project alive is to deploy infrastructure and to maintain it operationally. Obviously, to accomplish it, a full set of tools, many of them discussed in this dissertation, must be in place. In Guifi.net the efforts spent in building this enabling set of tools and those spent in fieldwork are well-balanced. Unfortunately, we have witnessed many projects that have failed due to excessive efforts in one of the two aspects, leaving the other unattended.

Society engagement Reasons to start a CN project vary. The most frequent ones are experimentation and research by a group of highly skilled technical enthusiasts. However, the CNs of this type that we are familiar with have not been able to engage the society because these motivations are not appealing to the public in general, and thus, these networks have remained as marginal projects. On the contrary, Guifi.net has been envisaged as a production network since the beginning, and thus, it has attracted the attention of many people who have found in it an opportunity to solve their connectivity problems. Once they have understood the social value of the proposition, some of them have become very active contributors.

3.8 Conclusions

In this chapter we have provided a general overview of Guifi.net, by analysing its traits and benefits, and presenting a collection of impact and performance indicators. The review of the fundamental principles, the ultimate objectives and the business models, already reveals remarkable differences. The innovative conception of the passive and active layers as a participatory CPR shapes the development of the project in a singular and inclusive manner. This conception does not preclude the development of economic activities and commercial offerings, but enables a number of additional alternatives such as coops or DIY. Furthermore, in terms of business opportunities, the virtual elimination of entry barriers together with equalisation of opportunities in terms of use to the existing infrastructure translates into a thriving and competitive local economy as a number of the quantitative and qualitative indicators here presented demonstrate. Part of this economical success is due to capability of the system to activate and aggregate small financial and funding players, and the lack of significant public funds prove that from the economical perspective the system is healthy and self-sustainable. The commercial offerings are, in general, similar to the average [41, 152], but the it is should be noticed that, contrary to the traditional ISPs, the service providers within Guifi.net offer the 1 Gbps (OF) to the domestic market at domestic prices (~40 €). It also is worth noting that several self-sustainable mechanisms to include socio-economic groups that cannot afford the standard prices exist.

In terms of social involvement the results are also noteworthy. To the best of our knowledge, an unprecedented amount of information is publicly available on this scale (tens of thousands of households connected) and the opportunities, number and diversity of participants in the governance affairs is also unique. As regard the infrastructure put in place there are irrefutable facts: next generation access network (NGA) technologies (essentially OF) are being deployed on a daily basis in areas traditionally deemed as unprofitable areas.

Based on the aforementioned results and the evident singularity and potential of the Guifi.net approach, we conclude that it deserves a deeper analysis. Hence, in Chapter 4 we investigate the governance and economic systems, which, in our opinion, are the two main components of Guifi.net. Due to their complexity, we address them in two separate chapters. In our analysis we paid special attention to understand the way of conflicts of interest and sustainability challenges are addressed, because, in our opinion, these are the two most relevant traits and with highest potential impact.

Chapter **4**

Guifi.net – Governance

Preface

This second chapter devoted to Guifi.net is the first aimed at providing a systematised description and analysis. Specifically, it focuses on the study of its governance system and how the project is protected from the legal perspective. It starts with a classification of the different stakeholder groups. Then it presents a structured analysis and description of the internal governance regulation principles, agreements, and instruments. The cost-compensation concept and how it is implemented is carefully analysed because it is a central component in the coordination of transactions among participants. The chapters also addresses the source of legitimacy of the project and the standard three branches of power (the legislative, the executive and the judicial) and how they relate to each other an to the overall context in which the project is developed. After that, it examines the legal construction aimed at the preservation of its core resource (the network infrastructure) and the associated activities. A short overview of the historical evolution seeks to provide a minimum understanding of the incremental process followed and the relevance that the combination of practical experience and theoretical approach has had in it. This is an continuous process as next chapter illustrates with an analysis of the discussions now are taking place. The chapter concludes with a comparative analysis of the design principles and requirements proposed by Elinor Ostrom of the long-enduring CPR institutions with Guifi.net. As described in greater detail, ensuring a proper management of the conflicts of interest by design has a primary role in the whole governance architecture.

4.1 Introduction

As already introduced in the previous chapter, the Guifi.net network infrastructure is considered a commons, and therefore managed as an open CPR, with the network infrastructure as the core resource. Treating the infrastructure as an open CPR has some immediate positive effects, such as the avoidance of redundant infrastructure because all participants operate on the same infrastructure and the increase of efficiency of the infrastructure in terms of cost savings and ease of participation. The CPR grows by the contributions that the participants make to expand or improve the network. In exchange, the contributors get network connectivity [P2]. Participants can benefit from pooling with lower individual investments since resources are shared. The knowledge on the network is open, and the network is neutral; no barriers artificially limit the extent of contributions, such as expansion, content, or service creations. For commercial services, Guifi.net as a CPR translates into a reduced entry barrier.

Nonetheless, Guifi.net, as any other CPR, is fragile. More precisely, since it is (intentionally) non-excludable and the fringe unit (the connectivity)[1] is subtractable (rivalrous)[2], it is prone to congestion and exhaustion. In this chapter we present the governance tools developed and put into practice by the Guifi.net community to protect the core resource –the network infrastructure– from depletion and ensure the maximisation of the production and its fair distribution.

The rest of the chapter is structured as follows. Section 4.2 identifies and classifies the existing stakeholder groups. Section 4.3 describes the stack of internal regulation that has been developed and put into practice, which ranges from ground rules to a number of sectorial rules and practices. Section 4.4 introduces the cost-compensation system, a central component in the realisation of the Guifi.net principles that links its governance to its economic system. Once the key governance building blocks have been already introduced, Section 4.5 elaborates on how the source of legitimisation of the system and on how the separation of powers is implemented. Section 4.6 analyses the legal architecture of the project, with special focus on the mechanisms used to shield the shared resources from privatisation attempts. Section 4.7 briefly outlines the project history. Section 4.8 discusses the relationship between Guifi.net and the main works of E. Ostrom, the academic reference in the study of the CPR institutions. Finally, the conclusions of the chapter are presented in Section 4.9.

4.2 Stakeholders

The Guifi.net ecosystem accounts for thousands of participants. Accordingly, the motivations for engaging in it vary widely as well as the degree of implication of the participants. As an example, some people just contribute occasionally on a purely volunteer basis while others fully develop in it their professional career. Moreover, quite frequently the participants have several motivations to participate and diverse kind of participation. For instance, many professionals make not-for-profit contributions in addition to their paid jobs. As a result, the interactions within the community are complex and their underlying reasons –the interests– may be classified according to different criteria.

We identify three primary motivations for participation and, based on this criterion, we define the three sets of stakeholder groups we describe below and depict in Figure 4.1. We define the elements of each set, i.e. the stakeholder groups, by the roles they play and the goals they pursue.

In-return This set is formed by the stakeholder groups whose members expect some return from their participation. In some of the stakeholder groups the members of are bound by SLAs.

CPR professionals Are the professionals whose activities fall under the scope of the CPR.

Installers Expand or upgrade the network by adding new hardware.

Maintainers Keep the infrastructure in good condition.

Network operators Operate the network infrastructure.

[1] As explained in Section 2.4.3, CPRs typically consists of a core resource that provides a limited quantity of extractable fringe units. In the case of Guifi.net, the core resource is the network, which is nurtured by the in kind or monetary contributions from the beneficiaries, and the fringe unit is the bandwidth they obtain.

[2] OF in practice is non-rivalrous, but (i) the implications of this fact have not yet been translated into different procedures in the community of practice, and (ii) for our analysis it is convenient to preserve the rivalry condition because a governance system able to deal with a resource with this constrain is likely to also work for a resource without it, but the reverse is not true.

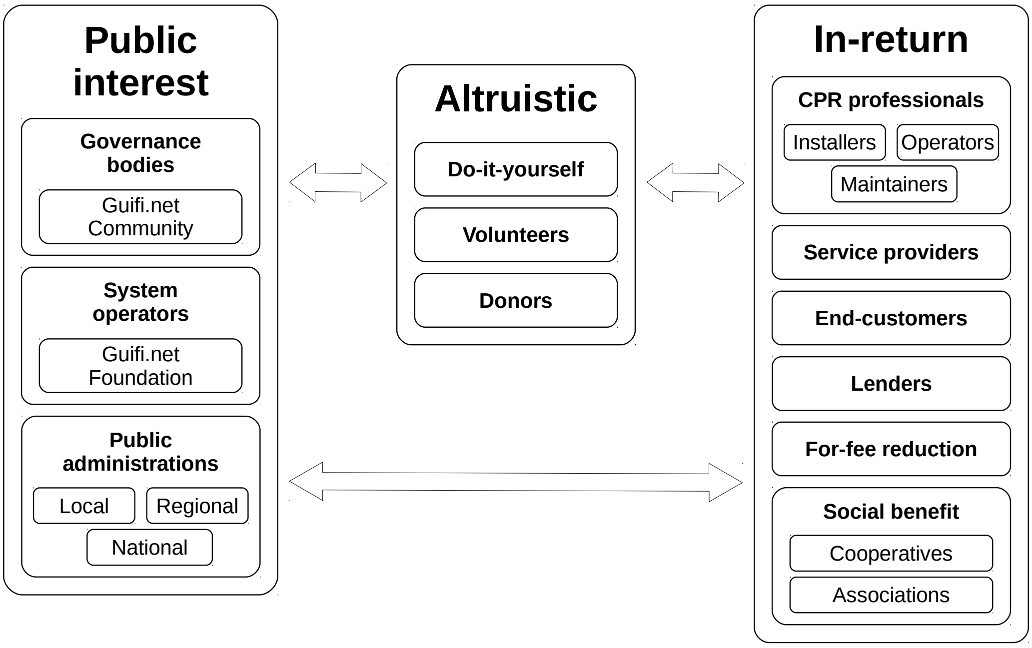

Figure 4.1: Stakeholders.

Service providers Market services on top of the existing infrastructure.[3]

End-customers Buy services from the service providers and the professionals.

Lenders Lend money that must be repaid, optionally with an interest.

For-fee reduction contributors Make contributions in exchange of a reduction of the service bill once the infrastructure they contributed to fund is put in production.

Social benefit Organisations that, despite being a not-for-profit, have some sort of service obligation towards their members.

Cooperatives Cooperatives of consumers.

Associations Association of participants.

The professionals and the end-customers stakeholders are well-established groups as well as coops and associations, although they are fewer in number. The for-fee reduction and lenders are stakeholder groups that are now actively promoted by the Guifi.net foundation, as part of its current efforts to harmonise the CAPEX investment because, for the time being, most of these sources of investment are handled by the professionals without any kind of record or oversight, thus, without the guarantee that they respect the Guifi.net spirit and rules.

Contrary to what one may expect, there is no *borrowers* stakeholder group as such to counterbalance the for-interest or for-fee reduction lenders because in the Foundation's borrowing model, the loans are taken by the Foundation on behalf of the whole community, and not individually by the beneficiaries or the installers of each specific loan. Thus, it is the Foundation who is en charge of counterbalancing the for-interest lenders. Furthermore,

[3] In Guifi.net the term operator is frequently used to refer to the CPR professionals and the service providers, which, as explained in this section, play total different roles, and, as discussed in Chapter 5, the economic operation of the firsts is regulated while of the seconds is unrestricted. In this dissertation we refrained from using term as much as possible to avoid misleading the reader.

frequently it is the Foundation who has to defend these two stakeholder groups interests against other stakeholder groups like the installers or the operators.

Altruistic This set comprises the individuals and organisations whose motivation for participating is to furthering the project without pursuing any specific material reward.

Volunteers Contribute time and knowledge to set up infrastructure and services, help other people to join, etc.

DIY Contribute the time and hardware needed to satisfy their own connectivity needs.[4]

Donors Make economic or in kind contributions beyond what is strictly required to satisfy their connectivity needs or even completely independent from these needs.

The cooperatives and association of participants which do not entail SLAs to their members can be included in this set of stakeholder groups.

In the not-for-profit set of stakeholder groups, labour and knowledge are always contributed in a volunteer basis, hence, they cannot be remunerated. Material costs, like hardware or accommodation costs, can be economically compensated. The non-remunerated labour policy does not apply to the staff of the ruling bodies and of the system operators because these costs are considered operational costs. In these cases, the employees are paid fair salaries, in line with the guiding principles of collaborative economy and fair trade. The professionalisation of these tasks, which increases as the project grows, has been shown to be indispensable to meet the needs of the development of the project as a whole, both in terms of the services offered and their quality. The best effort groups play a critical role in counterbalancing the for-profit stakeholders. The cooperatives and associations of users have traditionally joint this counterbalancing role regardless of whether or not they entail SLAs.

Public interest The motivation for participation is to contribute to the social welfare

Ruling bodies Are responsible for policy-making and strategic decision-making. Guifi.net is a direct democracy system, thus, the ruling body is the whole community. The rule-making process is conducted through participatory meetings and always seeking the greatest possible consensus.

System operators Are responsible for running the critical services of the system. Unlike usual practice in Western countries, in Guifi.net, in order to prevent collusion or conflict of interest by design, thus, to avoid having constantly to resort to ad hoc policies and regulations, the tasks of the system operators cannot be performed by for-profit participants. The Foundation is the system operator of Guifi.net. As such, it performs most of the system operation tasks, although there are some interesting experiences in which other not-for-profit participants are actively participating in the

[4] Although it can be argued that the stakeholder group of pure DIYs participants, i.e. the group of participants that only contribute what is strictly necessary to join the network, can also be included in the for-profit stakeholder groups set, we have chosen to keep it the not-for-profit set due to the following reasons. First to limit the for-profit set to contributions based on economic exchanges. Secondly, we argue that a DIY contribution implies a substantially higher degree of commitment with the project than the simple economic contribution of the for fee-reduction contributors. Finally, in practice the number of pure DIYs participants is currently negligible because nearly all former pure DIYs became customers as operators became ubiquitous, and because the vast majority of those who are currently DIY are also making other not-for-profit contributions as donors or as volunteers.

implementation of some of these tasks[5] (see Section 3.6.1 for additional information on tasks of the Foundation).

Public administrations Are responsible for regulating the interactions between the network deployment and *public interest*, such as public domain occupation. Thus, at least, they must treat Guifi.net as any other participant of the telecommunications sector. Beyond their legal obligations, they can take action either by satisfying their telecommunications needs in the Guifi.net marketplace or subordinating their funds and subsidies to the contribution of the corresponding infrastructure in the CPR.

Participants are defined as natural and legal persons. Nowadays, there are around 40 SMEs doing business activity within the Guifi.net ecosystem, with at least four of them accounting for over 20 employees, serving tenths of thousands of customers.[6] Despite the emergence of the professional activity and for-fee reduction investors, the DIY contributions are still a substantial amount of the overall investment. The DIY is still a usual approach to start deploying in new areas, specially those that are far away from the areas with intense economic activity and is still in a good shape in many of these last areas. The experience shows that many of the SMEs as well as more active volunteers in other matters such as governance, capacity building, project acquisitions etc. started as DIY volunteers. There are half a dozen of self-provisioning associations and cooperatives, some of which are also remarkably involved in the overall governance. The Guifi.net foundation has a five-members Board of directors and six full-time employees in addition to some volunteers. There are over 200 local public administrations directly involved in the project.

It is important to notice that the fact that the stakeholder groups belong to the same set of stakeholder groups set does not imply that they must necessary share the same goals. Quite the contrary, frequently they have conflicting goals. Pricing is an obvious example in the case of the professionals and the customers stakeholder groups, although both belong to the for-profit set. Nonetheless, the grouping of the stakeholders based on the primary motivations for participation has proved to be very useful in identifying and handling of potential conflicts of interest, specially in an intricate collaborative environment as Guifi.net, in which it is not uncommon that a same participant plays several roles. For instance, often the operators also invest in new infrastructure to reach new markets. In this case, contrary to their common wishes to bundle infrastructure and services, the investment must be treated according to the procedures of investment acceptance and repayment –which essentially stipulate a repayment period and a financial interest– and the services provided through the network utilisation procedures –that is, to participate in the cost-compensation system.

If a participant plays more than a role, in the case of conflict of interests among them, the most restrictive exclusion prevails. For instance, a professional who also does voluntary contributions can participate as a professional in the deliberative processes affecting the relations between volunteers and professionals but not as a volunteer.

[5] For example, in XAFOGAR a county's agency is actively contributing to the implementation of the cost-compensation system in the area.

[6] The number of enterprises doing harmonised activity can be obtained from the registry of economic activity of the Foundation. The number of customers can only be estimated because the reports that the professionals are delivering to the Foundation are still very incomplete, although the Foundation is struggling to get better records because it would like to integrate the number of customers served as a metric for the cost-sharing mechanism.

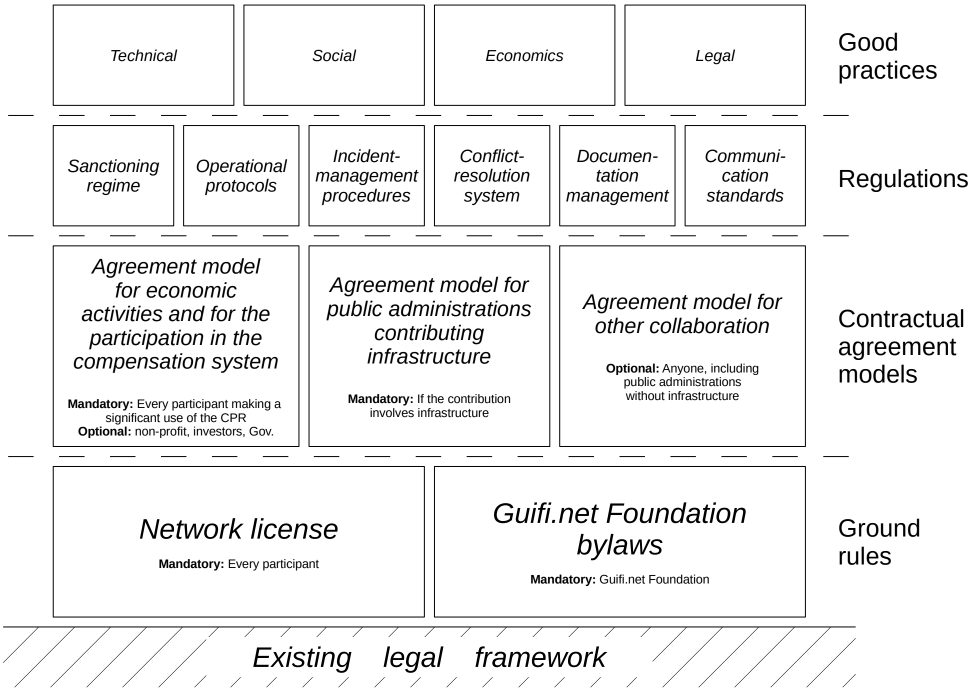

Figure 4.2: Internal regulation.

4.3 Internal regulation

Figure 4.2 presents the internal regulation developed by the Guifi.net community. It is intended to be law enforceable, thus, all the components and in particular those of the lower layers have been carefully written and are kept under constant review to guarantee their compliance with the existing legal framework.

Ground rules These include the role of every participant (license) and the role of the governing body (bylaws).

Network license[7]**.** It is called “*Llicència de comuns per a la xarxa oberta, lliure i neutral (CXOLN)*” in Catalan, “Free, open and neutral network commons license”. Is the basic standard on which the rest of the internal regulation is built. The preamble establishes the founding principles[8].

The articles establish, among others, (i) the scope of the project, i.e. the network infrastructure and the necessary services to build and maintain it and nothing else –software or contents licensing is out of the scope of the project, thus, nothing is imposed

[7] https://guifi.net/ca/CXOLN (content in Catalan). [68] is a not proofread English translation.

[8] The founding principles are:

1. You have the freedom to use the network for any purpose as long as you don’t harm the operation of the network itself, the rights of other users, or the principles of neutrality that allow contents and services to flow without deliberate interference.
2. You have the right to understand the network and its components, and to share knowledge of its mechanisms and principles.
3. You have the right to offer services and content to the network on your own terms.
4. You have the right to join the network, and the obligation to extend this set of rights to anyone according to these same terms.

to the participants with this regard, (ii) who are the participants and their rights and duties –for instance the duty to contribute to the development and maintenance of the infrastructure, (iii) the Foundation and its mission, (iv) the management of the ownership of the assets contributed –essentially, the participants keep the ownership rights on the infrastructure assets in proportion to their contribution to build and maintain them, and (v) the procedures for making changes to it. The acceptance of the license is compulsory to join Guifi.net. Any activity done in the network implies the acceptance of the license by the participant responsible for the activity.

Guifi.net bylaws[9]**.** The bylaws develop the competences of the Foundation as the governing body and the operator of the system critical resources and establishes the incompatibilities of the board members and of the employees. They define the Foundation as a not-for-profit non-partisan organisation and mandates it to promote the FONN and to look after it, conferring on it the legal capacity to represent the community and to rule over it. They specify the procedure for changing their content.

Contractual agreement models. With the network license and the Foundation's bylaws in place, the Foundation, on behalf of the Guifi.net community, signs legally binding agreements with participants who need additional specifications to create trust to enable further development of the infrastructure and the associated activities.

Agreement model for economic activities and for the participation in the compensation system[10]**.** This agreement model develops which participants are obliged to participate in the construction and maintenance of the infrastructure and how they must do it. It is mandatory for the professionals and for those who "make significant use of the network, such as to be convenient to compensate or to ensure the proper operation of the network or its sustainability" –the clause is wide enough to avoid having to deal with thresholds and particularities, which is left for more specific tools, but at the same time is precise enough to not leave room for the free-riders to put the system at stake. It is optional for investors and donors who want to track their contributions. It is the key document of the cost-compensation system.

URL no func

Agreement model for public administrations contributing infrastructure[11]**.** This specific agreement model is meant for public administrations which contribute network infrastructure to the project. It is a technical template that deals with the particularities that the legal framework imposes to public administrations in order to be allowed to participate in the telecommunications market. Although it is not mandatory, the Guifi.net foundation strongly recommends it because it has been accurately developed with legal experts. It is of special interest to small local administrations who, otherwise, just have the option to follow the guidance of the big telecoms because they have insufficient means to deal with the legal and administrative burdens.

Agreement model for other collaboration[12]**.** This is a generic collaboration agreement model for any third party interested in developing any activity that requires further specification.

[9] https://fundacio.guifi.net/page/estatutos (content in Catalan).

[10] https://fundacio.guifi.net/web/content/3960?unique=4d5fa7c30022af21b1a8deed53d462574fe6999&download=true (content in Catalan).

[11] https://fundacio.guifi.net/web/content/7411?unique=0c4ed55fb790861d82225b13165d422bd59aa734&download=true (content in Catalan).

[12] https://fundacio.guifi.net/web/content/2154?unique=b22e50a5fd9be62ee41a5eee5e951c842f67f02f&download=true (content in Catalan).

Regulations. These specific regulations develop specific areas that deserve special attention. Some play a dissuasive role and rarely are put in practice, such as the sectioning regime, while others aim at making the whole project more efficient and are used on a daily basis, like the operational protocols or the communication standards. The regulations are built on the ground rules, specially on the network license and, thus, the participants are obliged to observe them.

Sanctioning regime. It establishes a graduated sanctioning system aimed at stopping a misbehaviour in the first place, secondly, at demonstrating that misconduct of participants does not go unpunished and, finally, at redressing the damage, where possible. The sanctioning regime is maintained an operated by the Foundation, hence, it is the responsible for imposing and enforcing the penalties.[13]

Operational protocols. This group of regulations involve a wide variety of protocols of different fields. They establish common ways of addressing recurring situations or tasks to reduce uncertainty and make the operational activities more efficient, specially in terms of time and costs savings.

Incident-management procedures. They are of the similar nature of the operational protocols, but their scope is constrained to unforeseen circumstances in which downtime is critical. The management of incidents may involve the modification of operational protocols, either to reduce the probability of further similar incidents or to be better prepared to address them. Most of the operational protocols as well as the incident-management procedures are developed and implemented almost autonomously by the interested parties, thus, usually the Foundation only plays a moderator role at most.

funciona

Conflict-resolution system[14]**.** It is a systematic and clear procedure for resolution of conflicts in a quick and standard way. It consists of three stages, conciliation, mediation and arbitration. The conciliation and mediation consist mostly in voluntary rounds of meetings among the conflicting parties, with the intervention of a mediator in the last case. The arbitration is mandatory and driven by a lawyer chosen from a set of volunteers whose arbitral award is binding. The cost of the procedures is charged to the responsible party or to both parties in case of a tie. It was developed together with the sanctioning regime at a time when the flame wars between a few participants threatened the entire project. In this case the Foundation is only in charge of the maintenance of the ruling system and the set of volunteer lawyers. Charging the cost to the responsible parties had an immediate effect on stimulating direct settlements between the conflicting parties.

Documentation management. Effective data and documentation management is critical for sharing resources. The current state of development of the Guifi.net project involves a wide range of data sources, repositories, etc. One of the key factors of the initial massive adoption were the tools available at the website. For a long period of time the extensive use of the website allowed to have the records of the relevant data of that time –a registry of the participants and a database with technical information of the network including the position of the nodes, assigned IPs, links, etc.– in a remarkable good shape. However, the current situation is less satisfying due to several factors most of them linked to the increasing reluctance of the professionals to share data.

[13] Currently it is being extended to make it also applicable to the Foundation, i.e. to sanction the Foundation in the case of default.

[14] http://social.guifi.net/groups/guifi-legal/reglament-dels-procediments-de-resoluci%C3%B3-de-conflictes

First, many of them stopped reporting technical data at the website systematically long time ago claiming business confidentiality. Despite the changes introduced to make publicly inaccessible the sensible data and the efforts made by the Foundation, the restoration is still incomplete. In addition, the technical reporting tools were not updated in a timely manner to integrate the emergence of OF deployments. The professionals took advantage of this absence to start using their own closed solutions. The Foundation is also making a great deal of effort to reverse this situation –including the development of a software solution for OF management, the reactivation of the sanctioning procedures, etc.), but it is not yet clear if it is not to late to do so.[15] This reluctance to share information also extends to the economic matters, which has become a critical part of the information system because this data is critical for the cost-compensation system.

Communication standards. They establish the ways and the channels for communication among participants. General and specific mailing lists used to be the standard but with the advent of social networks and instant communication tools they have declined.

Good practices. They cover a heterogeneous set of specific norms and conduct codes developed through the experience in which compliance is desirable but not obligatory in general.

4.4 Cost-compensation system

The cost-compensation concept and its generalisation and formalisation through the cost-compensation system, which orchestrates the transactions among the participants, have been key to overcome serious threats along the Guifi.net's history and typifies the paradigm shift the whole project embodies. As in the private model, in Guifi.net the contributors not only have the right to get their contributions recognised, i.e. to keep the ownership of their contributions, but also to be compensated for their contributions if they are used by other participants. However, and contrary to the private model, (i) the cost-compensation is made according to objective and non-exclusionary rules, and (ii) the compensation always implies the proportional transfer of the ownership of the assets involved in the compensation.[16]

As discussed in Section 4.3, the main document which lays down the operation of the cost-compensation system and establishes for whom it is mandatory and for whom it is optional is the Agreement model for economic activities and for the participation in the compensation system. Figure 4.3 shows the functional block diagram of the system. The objective of the system is to periodically correct imbalances between investment (top left) and usage of the commons infrastructure (top right) among participants in a systematic manner. As shown in the figure, the system is strongly dependent on information systems and on up-to-date data because the functional blocks communicate with each other through databases. Overall, the system works as follows. On the one hand, to claim any cost-compensation, after having effectively made the contribution, which can be either CAPEX or operational expenditure (OPEX), i.e. integrating new infrastructure or carrying out any operation on the existing assets such as maintenance, operation, or upgrade, the applicant must (i) declare the contribution, and (ii) express the

[15] As a consequence of these lack of information, for instance, nowadays the exact number of households served cannot be known.

[16] The debate within the community to whom the ownership is transferred is still open. The two main options are (i) proportionally to those who have participated in the compensation, or (ii) to the Guifi.net foundation. But what is clear is that the participant who receives the compensation looses the exclusivity of rights.

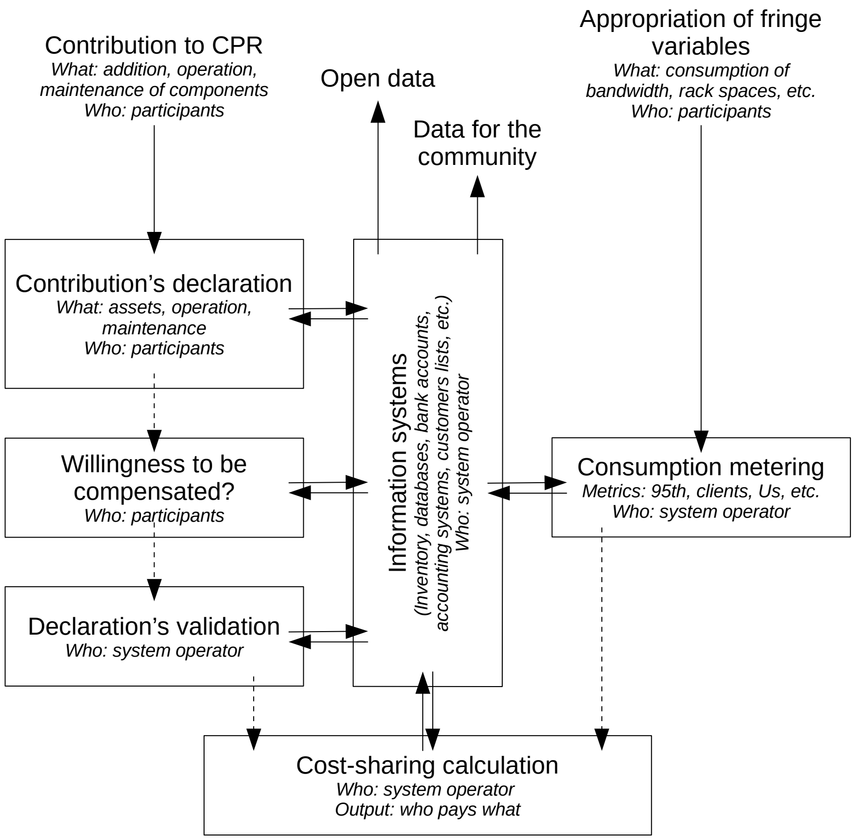

Figure 4.3: Generalised architecture for a cost-compensation system for CPRs.

willingness to be compensated and provide evidence of its execution. All declarations are reviewed by the system operator. On the other hand, the consumption of resources of each participant is measured through the appropriate metrics. At this point, it is worth noting that, although the system operator is the responsible for this task, its implementation is likely to rely on information that can only be provided by third parties, such as, for example, the number of customers an ISP has. This information dependency also happens in other areas such as the registry of contributions. Nonetheless, in this case, those who have the information may have strong temptations not to deliver the information to avoid having to compensate for the usage of the resources they have made. Thus, measures to enforce the delivery of the needed information and avoid fraud are likely to be required. Finally, costs assignment is calculated collating the registries of contributions and consumption.

The declaration of contributions and of the claim for compensation are done through the website in a single form. In order to avoid obsolete claims and to encourage to keep the information systems up to date, cut-off dates have been set. All system operations, i.e. validation of declarations, maintenance of the information systems, consumption measurements, and cost-sharing calculation, are made by the Guifi.net foundation.

4.4.1 Cost classification

Any cost to be compensated is assigned to a *clearing house*[17] or split into two or more of them. A clearing house is a functional aggregation of network components or services. At present,

[17] *Taula de compensació* in Catalan.

there are two categories of clearing houses in Guifi.net: the NOC, which includes all the services and infrastructure from the exterior traffic to the links connecting the NOC to the territorial exchange points (see Section 3.6.3), and the territorial, which encompass the last-mile services and infrastructure, that is, the infrastructure and its related services from the PoPIX to the final points of consumption. The costs of a cabinet (hardware, electricity bills, etc.) to distribute the fibre in a district is an example of a cost to be allocated to a single clearinghouse, the corresponding territorial clearing house in this case. In contrast, some of the human resource costs of the Guifi.net foundation are distributed among several clearinghouses because the workers perform tasks in them.

The cost-compensation system is implemented through a set of clearing houses. Hence, each clearing house has its own cost-compensation instance and its own compensation cycles.

In the clearing houses, the costs are assigned to *cost centres*. The cost centres are defined based on finance and accounting criteria. A typical criterion is the CAPEX and OPEX distinction. In practical terms, the crucial difference is that while the settlement of costs classified as CAPEX can be fractioned among several compensation periods, those classified as OPEX must be cleared entirely in the next compensation settlement. Recurrent costs, such as utility bills, are always OPEX. On the contrary, capital intensive investments for hardware renewal or infrastructure deployment are CAPEX costs which repayment is usually fractioned over time.[18] Single payment fees, like registration fees, can also be repaid over several compensation cycles.

CAPEX and OPEX redistributions are calculated separately due to their different nature. In the territorial clearing houses both CAPEX and OPEX costs are usually significant. Thus, there are two cost-compensation calculations for each of them. Conversely, in the NOC, given that, OPEX costs are generally much higher than CAPEX costs, the CAPEX is subsumed as OPEX through periodic charges for a given number of months. Furthermore, the NOC has a different kind of cost centres defined and some costs are split between two or three cost centres (see Section 5.3).

In terms of implementation, costs are classified through two main processes. The first is for the costs incurred by the participants, which are topically costs of new deployments, maintenance and upgrades, thus, they are usually assigned to a single clearing house. In this case, the selection of the clearing house is made by each participant through the web form for declaring the contributions and is checked, and amended where necessary, by the Foundation as part of the process of contributions validation. The second is for the costs incurred by the Foundation. These bulk of these costs are for staff, hardware and services. These costs are assigned to the clearing houses by the Foundation. As already discussed, staff costs are usually split among several clearing houses and centre costs.

4.4.2 Cost-compensation meetings

As already explained, the cost-compensation system is implemented through cycles and through clearing houses. Each of these cycles always comprises a meeting open to all the participants of the given clearing house. These meetings are aimed at discussing and approving the cost-sharing assignments in the previous cycle, which is presented in advance by the Foundation, and discuss any operational issue affecting the scope of the clearing house, such as doubtful cost classifications, new deployments or updates, or rules affecting the development of the cost-compensation instance

[18]The amortisation period must always be shorter than the life time of the asset.

itself. This is why, for instance, cost-compensation periods may vary from one clearing house to another.

4.4.3 Cost-sharing fundamentals

The total cost borne by a participant of a clearinghouse is the result of a fixed charge equal for each participant, the *membership fee*, plus a charge for consumption for each cost centre from which the participant uses resources, the *consumption fees*. Consumption fees are usually calculated by proportionally allocating the costs of the cost centres among the resource usage of the participants.

The rationale behind this cost-sharing mechanism is two-fold. On one hand, the membership fees, which are equivalent to equally weighting part of the costs, act as a filter against opportunistic participants to keep the costs related to the number of participants under control by establishing an entry barrier. On the other hand, proportionally assigning most of the costs to each participant's usage not only avoids negative externalisations from big consumers towards the smaller consumers but also has a wealth redistributive role because it makes technologies available that smaller consumers could afford neither separately nor though coalitions without big consumers.

4.5 Separation of powers

The source of legitimisation is the Guifi.net community,[19] which through two acts of legitimisation, the drafting of the first version of the network license in January 2005[20] and the establishment of the Guifi.net foundation in July 2008, set the ground rules of two branches of power within the project, the legislative, hold by the community, and executive, hold by the Foundation.

By default the policy-making process, i.e. the legislative branch in the internal organisation of a state, is open to all the community and made by consensus. Occasionally, the deliberations are kept confidential or restricted in participation for confidentiality reasons.[21] If consensus is not reached, decisions are made by taking a vote –sometimes by weighted vote. The natural places for the discussion of operational issues are the cost-compensation meetings and the working groups, while the discussion of proposals affecting the ground rules take place in specific public meetings open to all the community. In addition, questions of common interest can also be addressed during the general meeting the community holds once a year.

The Foundation, as the head of executive branch, has the duty to veto any decision made by the legislative power contravening the fundamental principles of Guifi.net expressed in the network license. In addition to this inescapable duty, it may provide guidance and steer the deliberation process, but does not have the right to intervene in the decision-making. As the executive power, it is also responsible for the implementation of the regulations enacted, including the system operation tasks.

[19] Before the drafting of the first network license, it was a member of the community anyone who wished so, which implied to embrace the principles of sharing and mutual support. With a network license in place, it belongs to the community anyone who accepts its terms.

[20] It was called *Comuns sensefils* in Catalan (`https://guifi.net/ca/ComunsSensefils`), Wireless commons license (`https://guifi.net/en/WCL_EN`). In December 2009 it was replaced by the present CXOLN.

[21] Mostly because either some of the information involved is confidential by law or for strategic reasons (e.g. to avoid providing commercially sensitive information to competitors outside of the ecosystem such as infrastructure deployment plans).

The *duty to veto only* solution has proven to be a very practical solution to create a common ground for the active collaboration among the stakeholder groups in general and of the professionals in particular.

In terms of law interpretation, which is in the field of the competence of the judicial branch, the internal tools developed are limited to the conflict-resolution system, which is aimed at dealing with conflicts among participants, the most likely to happen. In the pursuit of an effective powers separation, the rest of conflicts, specially those involving the Foundation, are intentionally left to settled though the external legal mechanisms.

4.6 Legal armour

The maximisation of the growth of the project and the assurance of its endurance over time are key design criteria of almost any tool in Guifi.net. The overall legal structure of the project in general, and of its bases in particular, play a specially critical role in the achievement of these goals. Any mistake in their design or implementation can jeopardise the whole project at any time. The legal framework was analysed under these premises. As a result, it was chosen an structure entailing the definition of a good –an IP network, with a specific legal form –the commons, described by a legally valid instrument –a license, and a legal entity obliged to protect the good –a private foundation.

Hence, the legal bases of Guifi.net are composed by the pairing license/private foundation, in which the license determines the legal good of the project, making explicit its scope and its conditions of existence, and the Guifi.net foundation, through its mission, obliges itself to ensure compliance with the license. The endurance of the mission of the Foundation over time is guaranteed by the private foundations Catalan law, which prevents the private foundations from changing their mission under any circumstances. In the case of Guifi.net, due to the link between the license and the Foundation, this legal impediment translates into the impossibility of changing the operation or exploitation conditions of neither the existing assets nor the future assets.

The assets of the Guifi.net CPR are owned either by the Foundation or by the participants. The Catalan legislation allows the dissolution of the private foundations. However, under no circumstances should the dissolution of the Guifi.net foundation affect the CPR because, according to this legislation, in the case of the dissolution of a private foundation all the remaining assets are placed under guardianship of the Catalan government, which must preserve them according to the purpose for which they had been donated or bought by the Foundation.

As regards the of assets owned by the participants, although the contribution does not alter the ownership rights, thus, the assets can still be freely traded. However, it does entail a servitude which obliges to hold the operation and exploitation conditions, that is to say, the existing assets must remain in the CPR regardless although they change hands.

In relation to the concept of common property and the bundle of rights outlined in Section 2.4.4, the Foundation is the *de jure* institution in charge of representing and effectively protect the common property, as shared private property, from abuse at collective-choice level of management, exclusion or alienation (such as privatisation). As such, the members of its governing bodies –the Board, in normal operation, or the Foundations' protectorate of the Catalan Government, in case of dissolution of the Foundation– must be independent, free from any conflict of interest as regards the telecommunications sector, and must be unquestionably committed to serve the public interest in general, and the Guifi.net CPR in particular.

4.7 Historical development

Generally, the improvements in the governance system have been introduced in response to specific challenges as they appeared. Thus, the governance system development is inseparable from the technical, economical and social evolution of the project. From the design criteria perspective, it is doubtless that a success factor of Guifi.net has been to find a well-balanced compromise between the scaling factor aimed of the changes introduced –not so small to make the changes simple but non-reusable patches and not so large to make them effectively unimplementable. Informally speaking, we can put the intended scaling factor of the sought solution between one and two orders of magnitude higher than the problem addressed. Systematisation, automation and autonomy have been the guiding principles of all of them. It has also been key to keep an appropriate balance between hands-on and conceptual work.

Figure 4.4 presents the most relevant threats and needs faced over time, their context, and the governance tools developed in response to them. The initial meetings among inhabitant of neighbouring villages of the county of Osona took place in the first quarter of 2004. The initial wireless links were set up in mid May by the villagers and in few months several villages were already connected to the backbone. Although the initiative was very well received by the local authorities because it offered an affordable and immediate solution to the generalised problem of lack of Internet access in a familiar way to them –the collaborative approach, most them looked forward for further legal development, thus, very few dared to invest in such incipient and innovative project. The development of the concept of federated proxies network not only contributed to make the use of the very few existing and limited in bandwidth DSL connections more efficient and resilient, but contributed to circumvent the legal challenges of Internet access liability as the service required personal credentials. The democratisation of the access to these few DSL, mostly from the few local administrations that had already joined the network, brought an exponential increase of the inhabitants' attention and interest of the surrounding villages. This explosion of interest, in turn caused more councils to join the project an the appearance of the initial for-profit participants, the installers. The installers made an invaluable contribution to the democratisation of the access to the network because they eliminated the need to have technical expertise to join the network or the dependency on volunteer contributors. The development and integration in the web of a set of tools aimed at easing the participation and reducing the required technical knowledge such as the maps and the *unsolclic*[22] also proved very useful in the democratisation of the participation.

The release of the first network license marked a real turning point in terms of certainty both conceptually and legally since it made clear the scope of the project –to develop a telecommunications network– and the implementation conditions –it should be and remain open to everybody for any (legal) purpose. The drafting process of the network license settled most of the controversies such as the legitimacy of economic activity and its approval enabled the integration of many other councils, the consolidation of the installers stakeholder group, and the significant increase of the investment in network assets.

[22] A software solution that automatically generates the configuration setup of the devices to be connected to the network.

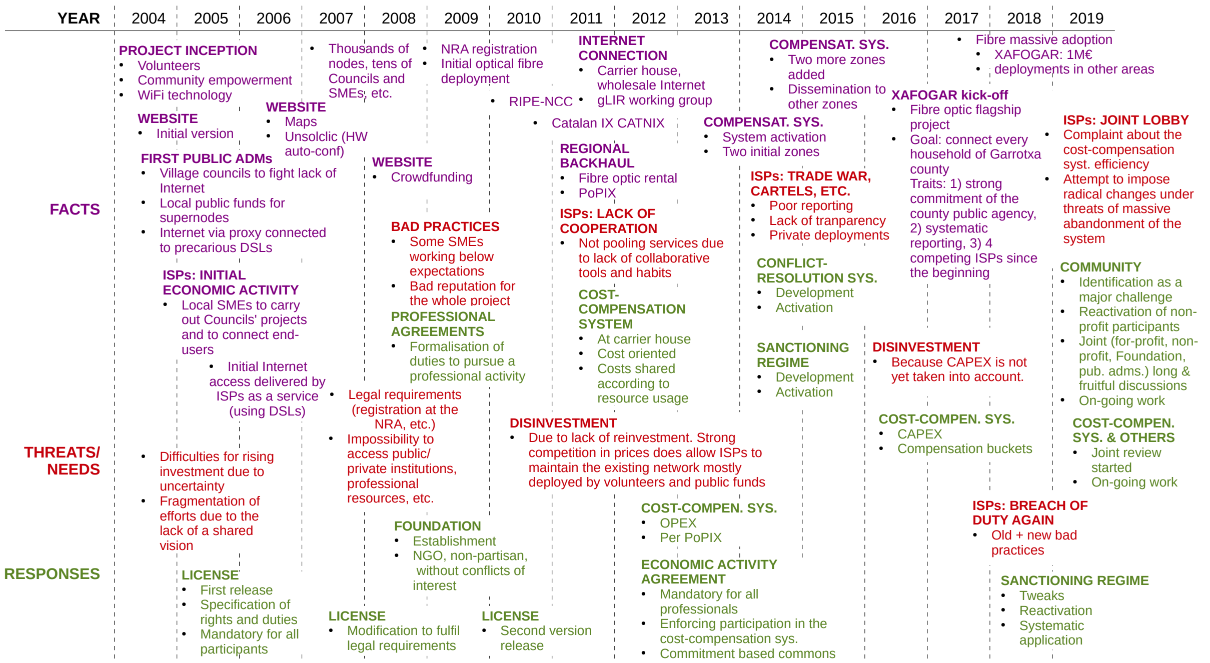

Figure 4.4: Historical development. Purple text indicates facts, red threads or needs, and green the responses to threads or needs.

Nonetheless, the development of a for-profit activity also involved the appearance of a number of bad practices that have put the whole project at stake several times and that has triggered –at least partially– some of the major improvements in the governance system, including the establishment of the Guifi.net foundation and the development of most of the governance tools such as the cost-compensation and conflict-resolution systems, the sanctioning regime, the second version of the network license, the professional agreements, etc.

4.8 Relation to E. Ostrom research

As discussed in Section 2.4.1, CPRs were studied in depth by E. Ostrom. In [113] Ostrom presented the eight *design principles* of the long-enduring CPR institutions she studied held in common and in [116] proposed five *basic protocol requirements* for achieving adaptive governance. According to Ostrom, local adaptability is indispensable for the sustainability of CPRs because their management is highly dependent upon the type of resource involved and the local conditions meaning that an effective strategy at one location, or of one particular resource, may not be necessarily suitable for another.

Ostrom focused on natural resource management. Nevertheless, her design principles and basic requirements fit admirably with a such artificial resource as a computer network as we discuss below. To the best of our knowledge, Ostrom's works remained unknown by the Guifi.net community until 2011. Although by that time the Guifi.net community was pretty well-established and had developed the vast majority of its governance tools, the discovery of her works contributed decisively to strengthen the community's confidence because, interestingly, the tools already developed fit very well to her findings, and to consolidate the theoretical framework, and provided invaluable guidance in identifying and developing the remaining tools.

4.8.1 Design principles of long-enduring CPR institutions

In this section we discuss the degree of applicability of each of the eight design principles of [113] for stable local CPR management to Guifi.net.[23]

1. ***Clearly defined boundaries:*** *Individuals or households who have rights to withdraw resource units from the CPR must be dearly defined, as must the boundaries of the CPR itself.*
    - The term *participant* is used instead of *Individuals or households* to better accommodate the diversity of stakeholder groups.
    - There is a clear criterion to establish the participants *who have rights to withdraw resource units from the CPR*: the acceptance of the network license, which is mandatory to use any CPR resource. The fact that in this case the CPR is mostly artificial and that the current legislation allows the deployment of telecommunications infrastructure in private domains virtually nullifies the risk of legitimate rights of individuals who have not subscribed the network license.
    - *The boundaries of CPR* are *clearly defined* by the license and the professional agreements, and the existing resources –only– are those that are listed in the inventory of the information systems.[24]

2. ***Congruence between appropriation and provision rules and local conditions:*** *Appropriation rules restricting time, place, technology, and/or quantity of resource units are related to local conditions and to provisioning rules requiring labour, material, and/or money.*
    - *Appropriation rules [...] are related to provisioning rules requiring labour, material, and/or money*: The obligation to contribute the CPR based on the appropriation –mostly proportionally– is one of the fundamental principles of Guifi.net as a whole and of the cost-compensation system in particular.
    - *Appropriation rules [...] are related to local conditions*: The cost-compensation system is implemented through local autonomous instances –the *clearing houses*. In each of them the participants are able to tailor the implementation particularities that better suit their needs –as long as they are not contrary to the network license, in which case they would automatically be vetoed by the Foundation.

3. ***Collective-choice arrangements:*** *Most individuals affected by the operational rules can participate in modifying the operational rules.*
    - Inclusion, also in the governance affairs, is another of the fundamental principles of Guifi.net. More precisely, the decision-making and the policy-making processes are by default open to every participant and are only kept confidential or restricted in participation for confidentiality reasons. However, in case, confidentiality claims are accepted to exclude from the deliberations or the vote any of the participants directly

[23] Ostrom's quotations, in italics, are extracted from Table 3.1 of [113].

[24] To have an up-to-date inventory of the CPR assets is a must for the implementation of a truly participatory institution –in Ostrom's words. In order to highlight the strategic importance of the inventory, in Guifi.net there is a saying that what is not listed in the inventory it does not exist.

affected by the rules under discussion. Any exclusion of this kind would be considered arbitrary, thus, it would automatically activate the Foundation's veto power.

4. ***Monitoring:*** *Monitors, who actively audit CPR conditions and appropriators behaviour, are accountable to the appropriators or are the appropriators.*
   - *Appropriators behaviour* is monitored by the participants, who report to the Foundation, but also by the Foundation, to prevent, *inter alia*, cartel behaviour.
   - The *audit CPR conditions* mainly includes the monitoring of the network and the appropriation metering. The monitoring of the core network components is done by the Foundation as a task of the operation of these resources. The edge components are monitored by the participants, specially by the operators and the maintainers. The appropriation metering is done by the Foundation where possible. The rest of the information required must be delivered by the affected participants. The breach of this duty activates automatic sanctions.
   - The Guifi.net foundation is accountable to all Guifi.net participants and, by law, also to the Catalan Government.

5. ***Graduated sanctions:*** *Appropriators who violate operational rules are likely to be assessed graduated sanctions (depending on the seriousness and context of the offence) by other appropriators, by officials accountable to these appropriators, or by both.*
   - It is implemented through the sanctioning regime. As most of the system operation tasks, it is applied by the Guifi.net foundation. It is one of the tools that, although it had already been considered, it was not yet developed when the E. Ostrom works were discovered by the Guifi.net community.
   - The extension of sanctioning regime to make it also applicable to the officials is being considered.

6. ***Conflict-resolution mechanisms:*** *Appropriators and their officials have rapid access to low-cost local arenas to resolve conflicts among appropriators or between appropriators and officials.*
   - It is implemented through the conflict-resolution system which consists of three stages, all of them seeking the encouraging dialogue between. The last includes the drafting of a binding resolution.
   - Any conflict involving the Guifi.net foundation is intentionally excluded of the conflict-resolution system as power distribution measure. Any participant, at any time, can submit a case to the external competent authority, although the sought agreed solutions are always preferred.

7. ***Minimal recognition of rights to organise:*** *The rights of appropriators to devise their own institutions are not challenged by external governmental authorities.*
   - All the activity within the project is intended to be compatible with the legal framework. Thus, the project should not be *challenged by external governmental authorities* due to legal reasons unless unintended unlawfulness, in which case, a collaborative attitude of the authorities is expected, as it has been the case in general.

- In the European Union the telecommunications sector is liberalised, thus, any public administration should discriminate CNs. Moreover, given the social value of the project, even a more proactive attitude of the public authorities is desirable. This has been the case for many municipalities. Nonetheless, very hostile –even illegal– attitudes from larger administrations have also been observed.

(For CPRs that are parts of larger systems)

8. Nested enterprises: *Appropriation, provision, monitoring, enforcement, conflict-resolution, and governance activities are organised in multiple layers of nested enterprises.*

- Decentralisation and local autonomy has been key for scaling-up and it is generally accepted that current and future strategies must proceed further along this path.

4.8.2 Adaptive governance

In this section we discuss the suitability of each of the basic protocol requirements for achieving adaptive governance of [116] to Guifi.net, [25]

1. Achieving accurate and relevant information*, by focusing on the creation and use of timely scientific knowledge on the part of both the managers and the users of the resource.*

- There is a strong interaction of the Foundation and of the participants with universities and research centres. The Foundation has over a dozen research agreements signed and has participated as a partner in five European research projects. The result main of these collaborations is a remarkable work of conceptualisation and optimisation of diverse governance tools.
- The literature review has been very inspirational. The fact of learning about other initiatives working around the commons has contributed in creating confidence in the project.
- The Foundation's endeavour to convince the participants –specially the professionals– to base their decisions on objective data, not on mere beliefs.

2. Dealing with conflict*, acknowledging the fact that conflicts will occur, and having systems in place to discover and resolve them as quickly as possible.*

- The conflict is part of the Guifi.net history and has triggered major changes which have made the system more resilient. This includes the development of a number of channels to deal with conflict.

3. Enhancing rule compliance*, by creating responsibility for the users of a resource to monitor usage.*

- Although responsibility for the users is always welcome, the conviction is that resiliency cannot depend on participants will –which may change over time. The strategy adopted revolves around establishing protocols, automation and enforcement.

[25] Italics and bold typesetting denotes quotations from Ostrom [116]. Italics denote quotations from Wikipedia [163].

4. ***Providing infrastructure****, that is flexible over time, both to aid internal operations and create links to other regimes.*

- The Guifi.net community has kept an infrastructure to support internal operation that has evolved continuously and incrementally to address its growing complexity, scale and needs, and facilitate participation while keeping it effective for all. The community maintains links with external organisations and other regimes in other locations and other topic areas.[26]

5. ***Encouraging adaption and change****, to address errors and cope with new developments.*

- Adaptation to change is also part of the Guifi.net history. From the techno-economy point of view, some of the major changes faced include the integration of OF and the evolution from retail Internet access to the whole sale. In social terms, the way people communicate is constantly changing due to technological innovation. The community has also to deal with the radical changes in the legal framework provoked by technological and social progress.

4.9 Conclusions

In this chapter, we have described in detail the design of a governance model for Guifi.net that implements its principles under a governance framework that allows structured participation and cost sharing. The system has developed organically to address the evolution, expansion and professionalisation of the community. Our investigations deepen knowledge and understanding of the critical role the proper management of the conflicts of interest has in the whole Guifi.net project. They also shed light on the legal architecture aimed at the preservation of the network and the associated activities, which is deeply shaped by the concern for deterring conflicts of interest. Our understanding these legal and organisational structures, to which we refer as the governance system, been the basis for the successful development of the economic system, studied in Chapter 5.

In the field of the research in the commons, we can state that, the Guifi.net is a case that extends the CBPP model to capital intense resources, a (material) network infrastructure in this case. The analysis of the governance model from the perspective of the Ostrom's design principles and requirements shows that the model complies as a CPR. It is not necessary that all governance systems have the same elements, but we do believe that it is important that these fit well because, as shown in Chapter 5 and Chapter 6, misalignments lead to conflict. The complexity and uncertainty of the issues to face as a bottom-up project develops, with changing requirements and growing scale and complexity, confirms that an issue-based or reactive design and development approach works better than *a priori* top-down design, more adequate for scenarios with well-predefined requirements, uniform structures, and no changes expected. In addition, as Ostrom says in her principles and requirements, the complexity of mechanisms has to be proportional and adaptive to the complexity of the problem at hand, otherwise we will be under or over regulating, with potentially catastrophic effects.

[26] The eReuse.org initiative inspired by the Guifi.net model [53, 52]

Chapter 5

Guifi.net – Economics

Preface

This second chapter aimed at providing a systematised description and analysis of Guifi.net focuses on the economic matters. It is structured in two main parts. The addresses the topic from the general perspective. It first analyses the financial flows as a whole to then discuss on the sizing of the territorial clearing houses and examine the CAPEX and OPEX financial instruments. Next it presents and discusses how CAPEX and OPEX sustainability is ensured. The first part concludes with an analysis of the current open issues and how they are being currently addressed by the community in general and by the Foundation in particular. The second part elaborates in detail on the cost-sharing mechanism that Guifi.net has developed as part of its cost-compensation system through the accurate analysis of its implementation of in the specific case of the distribution of the interconnection costs of the NOC. In addition to provide detailed information on the implementation aspects, it investigates on the sensitivity of the system to alterations in the set of participants, compares the results to a widely known cost-sharing mechanism (the Shapley value). This chapter is the last of the three devoted to the study of Guifi.net.

5.1 Introduction

Guifi.net started in 2004 as a grass-roots movement with the objective to provide Internet access to rural areas using WiFi. However, over time, Guifi.net experienced an enormous growth, offering novel models of participation and new business opportunities. This environment has stimulated the development of a number of companies and entities that offer professional services inside the network and make investments to improve and extend the infrastructure and services. At the time of writing, the investment in WiFi deployments has been clearly exceeded by the investment in OF, which is much more capital intensive, and it is expected that the OF roll-outs in the middle term will have replaced almost all WiFi deployments.

The capacity to enable economic local and regional ecosystems with professionals offering services has proved to be one of the essential factors for making Guifi.net sustainable and scalable beyond voluntary efforts and non-refundable contributions. The other has been the ability to create a context of sufficient trust to enable a size of the investment that conservative estimates put over 10 million euro. Underlying this environment of confidence economic success are the governance system as a whole, analysed in Section 5.3, and the economic subsystem in particular, which is discussed in this chapter.

The rest of the chapter is structured in two main sections, Section 5.2, which on the economic system of Guifi.net in general, and Section 5.3, which elaborates in detail a case study of cost-sharing. Section 5.2 presents and discusses the main financial flows withing the Guifi.net ecosystem, making special emphasis on two particular facts. The first is the distinction between the professional activity in the CPR itself, which is regulated, and the professional activity developed on top of the CPR, which is liberalised. The second is the fact that all CAPEX investments –and OPEX costs– must always be compensated regardless the source of funding. Section 5.2.1 discusses the key aspects taken into account in the investment strategy identifying three main zones based on the ROI period and Section 5.2.2 elaborates on the influence these zones on the sizing of the clearing houses. Sections 5.2.3 and 5.2.4 analyses the main sources of funding of CAPEX and of OPEX respectively. The template for billing the subscribers of the service providers that the Guifi.net foundation is promoting as a tool for improving the collection of CAPEX and OPEX fees is presented in Section 5.2.5. Finally sections 5.2.6 and 5.2.7 concludes with a discussion of the open issues that remain open add how are they being currently addressed by the community in general and by the Foundation in particular.

In Section 5.3 we discuss the cost-sharing calculation through studying the specific case of the cost-distribution of the interconnection between Guifi.net and the rest of the Internet, which is the network service with the largest number of participants. We analyse this case in sufficient depth to show the traits and operational details of a real working example. Sections 5.3.1 to 5.3.3 provide a detailed description of the use case of the cost-compensation system developed by the Guifi.net community of practice. Section 5.3.4 presents and elaborates on the datasets used. Section 5.3.5 elaborates on of a mathematical model of the characteristic cost function and Section 5.3.6 on the cost-sharing mechanism. Section 5.3.7 analyses the senistivity of the mechanism to participants with high usage. The results obtained are compared with the Shapley value in Section 5.3.8 and Section 5.3.9 presents a proposal for improving the system currently used. The section concludes with an analisys of the against ceasing cooperation in Section 5.3.10. The conclusions of the chapter are presented in Section 5.4.

5.2 General approach

From the economic operation perspective, the Guifi.net project seeks the creation of virtuous circles towards sustainability and expansion of network infrastructure based on the efficient use of the funds available and the connection of as many users as possible. Figure 5.1 shows the current state of the general economic organisation that the community is developing and implementing.

However, before proceeding to the analysis of the economic organisation in further details it must be made clear that its proper implementation is highly dependant of the governance system because neither the objectives nor the strategies of the project as a whole do necessary match the objectives and strategies of the participants in general, and of the professionals in particular. Thus, in the economic operation regard, the objectives of the Guifi.net governance system are to ensure that:[1] (i) The funds made available are effectively used for building network infrastructure. (ii) The infrastructure is effectively made available to all the population. (iii) The infrastructure is built, operated, and remains according the Guifi.net fundamental principles. Before any further analysis, it is also worth remembering that the scope of the CPR is limited to the network construction and its operation. Thus, it is outside of the scope of the project to rule over the profit of the professionals that use the network to deliver their services[2], but that

[1]The typical forms of fraud in the telecommunications sector include the diversion of funds to other purposes, the change of the conditions under the infrastructure is built or kept, and the lack of interest in connecting end-users because the doing so reduces the overall profit.

[2]As already discussed in chapter 3 the construction and maintenance of a single common infrastructure use by all the competitors under the same conditions delivers a true single market close to perfect competition. As a

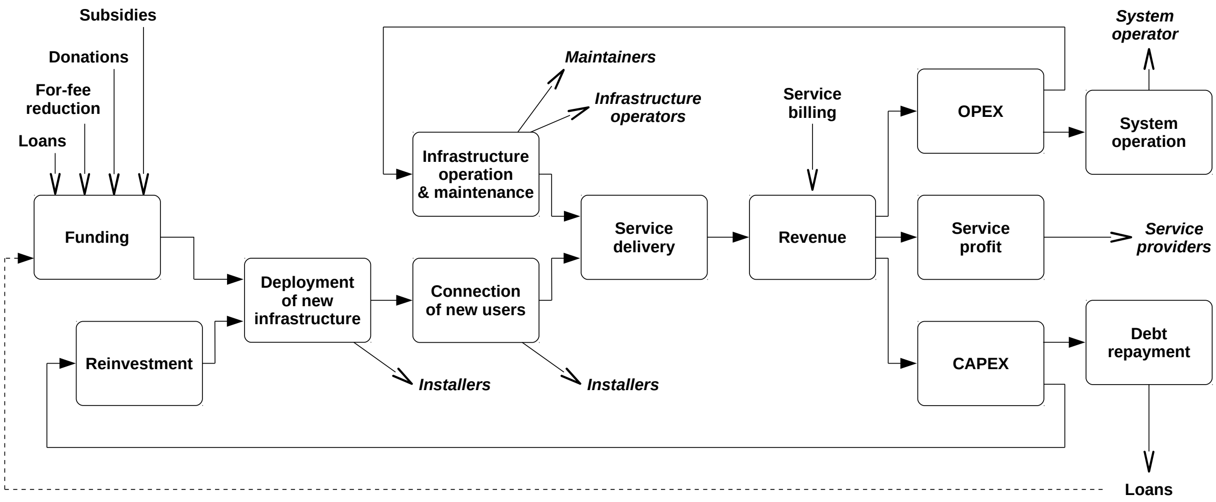

Figure 5.1: Global financial flowchart.

speculative and extractive practices are not allowed in the construction, operation or access to the CPR. Accordingly, the only three sources of profit within the CPR are labour remuneration and interests on loans. All of them are collectively established. The labour remuneration is set on the basis of fair salaries[3]. The interests on loans are set seeking a compromise between being so high for being competitive with similar investment opportunities outside the Guifi.net system and excessive benefit, which also prevents over abuse of the lending facilities.

As Figure 5.1 shows, the cycle starts with the presence of one or more external funding sources. The funds, which may be subject to a repayment obligation, are used to put some initial infrastructure in place by the installers and connect the initial users to it. Once the infrastructure is in place and is operated, the service providers start acquiring customers, delivering services, and generating revenue through the corresponding service fees. This revenue is used to cover the OPEX, to repay any debt, and to fund new infrastructure where possible, closing the virtuous circle in this way. In addition to this first reinvestment loop, which entirely depends on the internal management, a second one is possible on the basis of debt repayment. The realisation of this second loop does not depend on internal factors exclusively but also on external circumstances including investors' will, investment alternatives, etc. Nonetheless, the timely repayment and attractive interest rates certainly have a positively impact on investors' decision to keep their capital within the system.

5.2.1 Investment strategy

The investment plans are defined taking into account the ROI periods and the influence of competitors. Three main types of areas can be defined based on these to factors. The *unprofitable areas* are the areas with ROI periods longer than the infrastructure amortisation periods. The *single deployment areas* are the areas with a market able to stand a single deployment. The *multiple deployment areas* are the areas capable to stand more than one infrastructure deployment. Very remote areas, rural areas and cities are common examples of each of them. The classification is traditionally related to the population density and its purchasing power, that is, non-business

result, as the free market theory predicts, the commercial offer within Guifi.net has cheaper prices and better services than the external competitors.

[3] Standardised labour prices are necessary to avoid conflicts in the cost-compensation system (introduced in later in this chapter and further analysed in the next one).

parameters. However, business related parameters like lower business costs and the capacity to activate alternate or complementary sources of funding such as contributions coming from the beneficiaries can make a difference in converting an unprofitable area to profitable.

In practice, most of the existing Guifi.net deployments have started taking advantage of the window of opportunity left by the traditional operators. In WiFi, given its low CAPEX, the deployments have been usually developed through a number of small investment cycles, deploying first in most profitable areas and extending to the rest later on according to the funds available. A significant part of the funds for the iterations come from the neighbours of the uncovered areas who, following the example of their fellow citizens, want to extend the infrastructure to their homes. In OF the scale of investment rounds have increased to accommodate the CAPEX needs and the specialisation of the sector.[4]

Contrary to the sharing spirit of the community and what was done in the past, nowadays the deployment plans and the associate marketing campaigns to gather investment from the beneficiaries are handled discreetly to counterbalance the overbuilding and other bad practices noted by traditional operators. As a result of these bad practices many very promising projects have been torpedoed.[5]

5.2.2 Clearing houses sizing

The sizing of the clearing houses (defined in Section 4.4.1) must seek a balanced compromise between operability –too large clearing houses become inefficient in the fulfilment of wealth redistribution objectives. Deployments in unprofitable areas are only viable by compensating the losses with gains from profitable areas.[6] Given that the territorial clearing houses are the natural place for local wealth redistribution, they are the ideal place for levelling the differences between neighbouring profitable and unprofitable areas. Thus, their geographical scope must seek a balance between these types of areas and never be limited to unprofitable areas unless a mechanism for wealth distribution between them is put in place, which is not yet the case for the time being in Guifi.net, although it is planned for the future.

5.2.3 CAPEX

The two sources to finance new infrastructure are the external resources and the reinvestment. The main sources of external funding are the following.

Donations They are contributions made without return consideration. The contributions can be in kind, monetary, in labour, in knowledge, and others including the DIY contributions. They can be made to the community, in which case are essentially protected by the network license, or to the Foundation, in which case they are also protected by the law applicable to the foundations and the Guifi.net foundation bylaws. Although the irrevocable notion is implicit in the concept of donation, according to the network license the contributions

[4]The specialisation index of the WiFi installers is very low, meaning that a single installer is able to perform most of the tasks involved in a deployment if not all. However, in OF this index has increased up to the point that there are installers specialised a single job such as cable deployment, fibre splicing, etc.

[5]There are well-founded suspicions that confidential administrative information have been leaked by public administrations to the competitors.

[6]The viability of these deployments outside Guifi.net is frequently based on subsidies, and thus, it always depends on the continuity of the subsidies. In Guifi.net these type of solutions are unaccepted due to their dependency on third parties and because they are unsustainable. So far, the occasional subsidies received have been integrated into the financial flows as another source of funding.

to the community could be reverted. On the contrary, the donations to the Foundation are legally irreversible. In addition, the donations to the Guifi.net foundation are tax deductible. The motivations for donating range from supporting the community and the project in general to promoting very specific actions, including the initial deployments of an area, the test of new technologies, etc. Some of the funding instruments explained below are donations, to the Foundation in some cases.

For-fee reduction contributions These are contributions made by the participants who want to have access to a specific deployment and avoid the line rental fees. The donation is made in exchange of a reduction of the service fee once the infrastructure is put in production. It is a stipulated amount corresponding to the estimated average CAPEX per household connected. Currently the amount for OF[7] deployments is 1,500.00 €.[8] Formally, these are donations to the Foundation, which has the task of guaranteeing the proper execution of the projects.[9] This is a very interesting funding instrument because it provides up-front non-repayable capital in a highly replicable fashion. Despite the obstacles from service providers (see Section 5.2.6), it is very successful in some areas and the Foundation is highly promoting it.

Loans Are cash contributions that must be repaid, frequently in addition to an interest. They are typically five to seven year loans, i.e they are medium term loans. The fact that the borrowed capital must be repaid brings additional certainty towards their efficient use. The most common type of loans are the following.

From public administrations Commonly they are used for strategic deployments aimed at sparking further investment from other agents by showing commitment and financing the first pieces of infrastructure to show the potential. They are usually interest-free. Although the total contribution in the overall financial capital is currently rather low, this type of funding has been key to activate very successful deployments.

From private lenders They are private loans frequently with a financial interest. In order to attract lenders the interest rate is usually higher than the interests offered by banks. The Foundation is promoting this type of loans to counterbalance the loans by banks. Although nominally this option is open to everybody, so far, in most of the existing cases the lender has been a for-fee reduction contributor who, in order to accelerate the execution of the project, has contributed additional capital. A typical case is an industry that incurs the total cost of the deployment in its industrial park to ensure a rapid execution. The immediate repayment, where possible[10], in addition to the corresponding interests, was agreed for these cases. However, for the time being, almost none of these lenders has expressed the desire of getting neither the capital nor the interests back.[11]

From retail and commercial banks These loans have become the most common source of finance of OF deployments.

[7] This funding instrument is not common in WiFi deployments.

[8] The resulting lines are referred as *purchased lines* in contrast to the *rented lines* or *financed lines*, which are financed by a third-party investor.

[9] This kind of contributors can also be referred as crowdfunders because they receive a reward –the fee reduction– in exchange of having paid some money upfront.

[10] For instance when, with the necessary budget is already in place, when additional for-fee reduction contributions are made.

[11] But it is also true that very few of them have formalised their contributions as donations. In some cases the contributors have explicitly stated that the reasons to do so are that they prefer to keep the capital invested in exchange to have the right to track the development of the project.

- **From investment banks** These loans have started being explored as an alternative to the loans from retail and commercial banks.

Subsidies They are non-repayable contributions by public administrations. Although small in amount because they basically came form small local administrations, they contributed to the expansion of the WiFi network in the past. But beyond these local contributions, Guifi.net has been traditionally excluded from the major sources of this type of funding.

According to the Guifi.net principles, any user of the network must participate in the recovery of CAPEX and OPEX of the network regardless the source of funding. Conceptually, this rule prevents from dumping practices (see Section 6.4.19), in addition to recapitalise the system. At implementation level, the redistribution of these costs is made within the scope of the clearing houses through objective prefixed amounts per compensation period and per participant in the clearing house or per service providers' customer.[12] These amounts are referred as fees. The only participants that are exempt from CAPEX fees are those who have made the for-fee reduction contribution or have incurred the total cost of a deployment. The for-fee reduction contribution can be made at any time, but in any case, the recurrent fees that may have been incurred before can be recovered or deduced.

For the time being, the only reinvestment has come from the CAPEX recovery of deployments funded through donations and non-refundable subsidies because all of the projects funded through loans are still in the stage of investment recovery, i.e. the break even point has not yet reached in any of them. It is in the power of each clearing house to decide on the reinvestment strategies, but in any case they must always be reinvested in network infrastructure and cannot be used for any other purpose.

The CAPEX contributions of the Guifi.net foundation to the CPR are assigned to the corresponding clearing house and are settled as any cost of any other participant.

5.2.4 OPEX

Like in CAPEX, in OPEX there cannot be profit because the operational activities are part of the CPR. The cost of the interventions of the installers, maintainers and operators (labour, hardware, travelling costs, etc.) are preestablished through objective estimations. The standard operations are also predetermined in duration, thus, their total cost too. All these costs are reported to the respective clearing houses for their settlement.

The recurrent costs of the Guifi.net foundation activity, as the system operator are also CPR OPEX costs, thus, are distributed among the different clearing houses.[13]

5.2.5 Revenue streams and service detailed billing

The two main sources of net income in the project are the non-repayable contributions –project revenue– and the service billing from the services providers to their subscribers –service revenue. The non-repayable contributions are essentially devoted to infrastructure deployment, and they only cover a fraction of the total CAPEX costs. Therefore the rest of CAPEX and the entire

[12]There are very few participants but thousands of customers. For simplicity, just customers will be mentioned henceforth.

[13]In order to reduce costs, the Foundation prioritises the collaborations based on exchange and other win-win agreements.

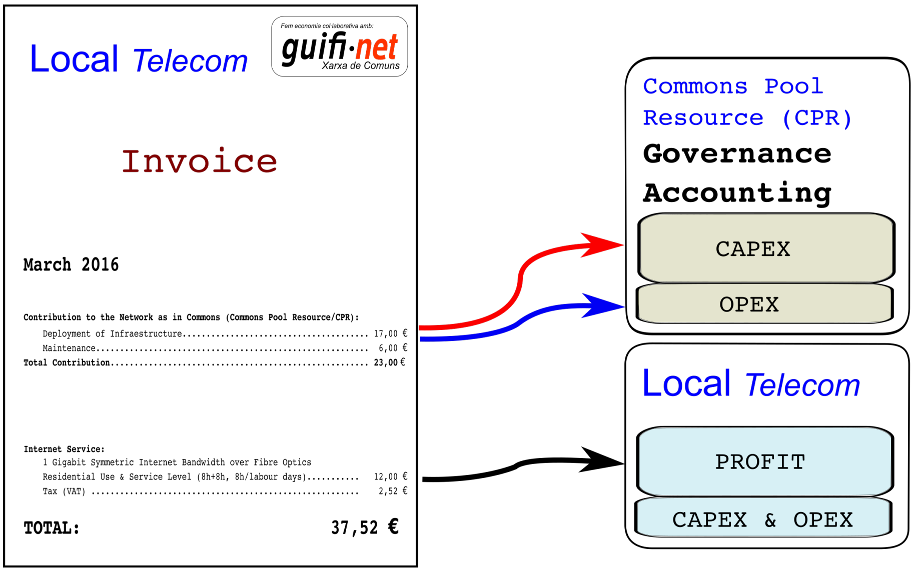

Figure 5.2: The template to be used by the operators for invoicing their service subscribers and destination of its items.

OPEX must be obtained from the service bills the service provider issues to their customers. From a business as usual (BAU) perspective, the service providers have a business-to-customer (B2C) relation with end-customers and a business-to-business (B2B) with the CPR professionals. Of the CPR professionals only the installers have B2C with end-customers and only when the end-customers contract the installations directly to them and not through a service provider, which is them most common case.[14]

In order to harmonise and secure the fees collection as well as to increase the transparency towards the customers, the Foundation developed the template to be used by the operators for invoicing their service subscribers presented in Figure 5.2. As the figure shows, the invoices must include the following items at least.

Line rental fees They are the total CPR CAPEX amount. They are standardised. The current amounts are: 17 € for OF, and 4 € for WiFi per month and per customer. It is only charged to the customers who have not made the for-fee reduction contribution.

Network operation fees They are the total CPR OPEX. They are standardised. The current amounts are: 6 € for OF, and 4 € for WiFi per month and per customer.

Service fees They are the additional charges set by each service provider. It must include the service provider's CAPEX and OPEX that are not part of the CPR and, optionally, the desired profit.

The proper implementation of this billing system also requires the service providers to provide updated data to the corresponding clearing houses through the Foundation. For the time being, the billing template has not yet been adopted by any of the service providers. However, in the active clearing houses the fees are already accounted to the greatest possible extent (see Figure 3.2).

[14]The BAU is no suited for describing the complexity of Guifi.net as a whole, but it is adequate to highlight the most relevant traits of the relations between end-customers, service providers, and CPR professionals.

5.2.6 Open issues

At the time of writing, some of the companies operating within Guifi.net, lead by the largest ones, are putting a lot of pressure to gain control over the infrastructure to manage it at their will under the pretext of lack of viability of the current setting. They have openly expressed their intention to leave the project unless the community accepts to implement a set of changes they propose. Many other participants, including volunteers, coops, associations, other companies, etc. and the Foundation have expressed serious doubts about the compatibility of these changes and the spirit of the project.

Much of professionals' strategy is based on claiming the ownership rights over the infrastructure on the assumption that they have funded the vast majority of it. The controversy, which has a profound legal background, specially in terms of a bundle of rights (see Section 2.4.4), must be tackled by the community at some point. But the sudden outbreak and the intensity of the professionals' claims may also shed light on the real motivations behind many of their actions contrary to the general interest such as declaring as less expenses as possible to the compensation system, the misattribution of contributions made by others and their preference to start deployments in new areas instead of extending the coverage of the already started.

The set of changes proposed by the professionals has triggered an intensive discussion which is still going on at the time of writing this dissertation. Due to the fact that there are still most of the central points to be clarified, and that there are different opinions including who must be considered the debtor and the ownership rights of the resulting infrastructure of some of the funding instruments presented above, these two questions have been intentionally left neglected in the previous sections and will be addressed as part of the discussion that follows.

For the professionals a central question in the debate is the delimitation of the assets that can be classified as *funded* by them. Although in the Foundation's opinion this is not such a critical question, the views about the amount of assets that can be classified as funded by the professionals differ radically. First, the professionals tend to consider as funded by them all the projects they have executed regardless the sources of the capital involved. In this regard, the Foundation allege that the donations, the for-fee reduction donations and the contributions by the public administrations and other participants by default belong to the commons or, at least, it must be asked to each contributor individually if they want to transfer their rights to the professionals. Secondly there is also controversy concerning the infrastructure funded through bank loans. For although the professionals are the debtors, it is equally true that, beyond the opportunities that Guifi.net project gave them to learn and grow in the past, their current creditworthiness are directly bound the size of Guifi.net, and probably their collateral are also bound to the network, meaning that they have put at stake other participants interest. From this point of view, the ownership rights cannot go entirely to the professionals.

A more important question for the Foundation is to clarify the impact on the infrastructure in the case of withdrawal of a professional. The Foundation argues that, according to the network license and the agreements for developing an economic activity signed by the professionals with it, under any circumstance the professional could retrieve any infrastructure if it has been co-financed by others, which includes any received cost-compensation. Thus, the definition of the scope of *an infrastructure* becomes a crucial point. In the Foundation's view, the term is to be interpreted widely, that is to say, any physical infrastructure reachable without the need of crossing assets outside Guifi.net form one single infrastructure. Thus, the lack of co-investment can happen at most in isolated deployments and only if the party which wants to retrieve infrastructure proves that it has effectively made the entire investment.

Another key point is the definition of the rights of the service providers' customers, specially of those who have not made the for-fee reduction contribution. The Foundation assumes that all the participants, including the service providers' customers have the right to enjoy the CPR rights unless explicitly waived by them. Thus, even in the case of the assumption of the lack of investment, the change of the conditions under which the infrastructure is exploited would require the explicit consent of each customer to whom the proper information is to be provided first.

Finally, there is also opposite points of view on the destination of the CAPEX fraction of the customers' bill after debt repayment. For similar reasons to the ownership dispute, the professionals argue that they have the right to decide what to do with this money, including using it as a profit. On the contrary, the Foundation and the volunteers claim that they can only be reinvested in the CPR.

5.2.7 Mitigation measures promoted by the Guifi.net foundation

According to the Guifi.net foundation rationale, although currently it is not possible to provide complete quantitative information due to the lack of information from the professionals to the Foundation, there are strong evidences that both the infrastructure and the professionals making activity in it have not only lasted over a long period of time, but experienced substantial growths, meaning that the overall approach is wise. Correspondingly, contrary to some of the professional claims in favour of internal deregulation and weakening of the commons, the Guifi.net foundation deliberately opts for keeping developing and putting into practice methodologies to strengthen the collaboration among the participants and the resources sharing through the CPR model. To this end, it is fostering the following measures.

Multilateral meetings and working groups The Foundation is coordinating a round of participatory meetings to discuss the proposal made by the professionals and other solutions or improvements. The round is not yet finished but for the time being the meetings have contributed to defuse tensions and restore confidence. Some working groups have been created to address specific issues.

Reinforcement of the systematic data reporting Update data is essential for many tasks such as cost-compensation calculations, cost estimation refinement, etc. Currently, the professionals on the one hand complain about the poor performance of the governance tools including the cost-compensation and the conflict-resolution systems, but on the other hand they usually report their data belatedly and it is frequently uncompleted.

Clarification of professional roles The professionals systematically oppose any measure which implies the revelation of any information about them. There is a widespread feeling that this is a strategy to hide their profits, which are suspected to be higher than they say and than it would be acceptable by the community. To clarify which part of their activity is for the CPR (thus, is must be transparently reported and it is regulated by the community rules), and which is related to service provisioning (thus, it is a liberalised activity) is a central issue to move forward.

Revision of cost estimates There is also the feeling that current costs are too conservative, which is favourable for the professionals, which is another incentive for them not to report to the clearing houses.

Adoption of the detailed billing template Although the template is available since in 2016, just very few participants has adopted it and, to the best of our knowledge, no professional has done so.

Implementation of new clearing houses and strengthening of the existing In the Foundations view, the clearing houses play a key role in the whole governance system as they are the most direct way for mutual supervision and coordinate. Thus, it not only opposes the reduction of the activity in the existing ones, but wants to foster their full implementation and activate newer ones in other areas.[15]

Recovery of the communication through shared channels The professionals have stopped using the community's communication channels for some time and are only communicating to each other through parallel channels. Again, there is the general feeling that this is part of the general strategy of excluding the rest of the participants. However, because they have a point on the need to update the existing channels to meet their needs, the Foundation is updating the communication systems.

Transparency in the loans management that the participants inform the others about these initiatives and that the periodic and occasional repayments are part of the cost of the cost-compensation cycles of the clearing houses.

Search of lines of credit The Foundation is working with investment banks on the design of funding instruments that under the technical supervision of the Foundation and the investment bank would entail standardised lines of credit. Such financial instrument can substantially contribute to harmonise the procedures and the guarantees are to reduce the administrative burden, reduce the financial risk and to ensure that the infrastructure is developed and will remain in commons.

Information campaign The Foundation is leading an information campaign to inform about the current tensions addressed to specific participants who although being directly affected by the professional intentions might not be aware of them, and invite them to have a say.

5.3 Analysis of a case of cost-sharing

Cost sharing allows the development and operation of a few common resources among multiple parties instead of building and maintaining multiple separate facilities. The potential for efficiency and sustainability in sharing comes with the overhead of coordinating the participation, contribution, and output allocation among multiple participants with widely different possible capacities and needs. Thus, efficient cost allocation methods are required.

In this section, we address the challenge of advancing the development of such methods in the particular case of network services and infrastructure because the potential for savings due to cooperation in this field has been well described in [142]. Nonetheless, the lack of case studies

[15] Mainly the professionals proposed to stop running the clearing houses and let them settle any unbalance through private negotiations among them. The general opinion is that the acceptance of this proposal would imply *de facto* the death of the overall project.

seems to be a major barrier for the uptake of resources and service-sharing practices beyond IXPs or some community networks. To contribute to filling this gap, we analyse in detail the mechanisms developed and put in practice by the community of practice of Guifi.net [P2] to jointly enable the provisioning of a critical service, such as the transit service, and to share its costs.

5.3.1 Carriers setup

The general configuration of the NOC is discussed in Section 3.6.3. Hereafter we focus our attention on the two main carriers, which we refer to as C_1 and C_2. To ensure a certain quality of service in the case of failure, the hired capacities of C_1 and C_2 are required to be always the same.

The pricing scheme of C_1 is a strict flat rate for its entire capacity, and the pricing for C_2 is a flat rate for the traffic below 10 % of its capacity plus a per traffic fee for the traffic exceeding this. The flat rate part of C_2 is around two-thirds the cost of C_1. The routing policy is to maximise the use of the capacity of C_1 within a safety margin, and the rest of the traffic is diverted to C_2. The hired capacities are extended when the cost of the per traffic fee of C_2 becomes greater than the cost of the capacity expansion of C_1. On average, the contracts are being renegotiated every year or year and a half to accommodate the growth in demand. In May 2019, C_1 and C_2 have been upgraded from 2×10 Gbps to 3× 10Gbps, and the IXP connection is 1× 10Gbps, but it will be soon upgraded to 2× 10Gbps. The costs of the additional NSPs for specific operations is less than 4 % of the total external connectivity costs.

5.3.2 Cost classification

As explained in section 4.4.1, in the clearing houses, the costs are grouped according to the CAPEX and OPEX criterion except for the NOC, in which case the grouping is made by *cost centres*. The current cost centres are *exterior traffic*, *interior traffic*, and *rack spaces*. The exterior traffic costs include the NSPs and IXP, and the interior traffic includes the middle-mile links. Rack space costs are those that refer to the housing facilities. Table 5.1 shows the NOC's most significant costs, how these are distributed among cost centres, and the maximum amortisation period (MAP) in months, if any.

5.3.3 Available resources

Two resources (flow variables or *finge units*) can be consumed at the NOC: network bandwidth and rack space. The metric used to measure the usage of network assets is the sum of the 95th percentile of five-minute time averages of the inbound and outbound traffic of the given link per participant. Rack space is measured through the standard *rack unit*, which is half the minimum size. To ensure liquidity, the cost-sharing calculations, the *compensations* in Guifi.net's terms, are done periodically. In the case of the NOC, they are done on a monthly basis.

5.3.4 Datasets

The Guifi.net foundation has given us access to a traffic dataset and to some of the spreadsheets generated on a monthly basis to calculate the cost sharing and has provided some additional information on carrier offerings. To maintain confidentiality, the names of the participants and carriers have been kept anonymous.

Item	Cost centre			MAP [months]
	Exterior t.	Interior t.	Rack s.	
Hardware (routers, switches, etc.)	✓	✓	–	36
Insurance (annual fees)	✓	✓	✓	12
Administration	✓	✓	✓	–
Management	✓	✓	–	–
Technical support	✓	✓	–	–
Legal support (outsourced – monthly fee)	✓	✓	✓	–
Housing – acquisition cost	–	–	✓	36
Housing – monthly fee (including electricity)	–	–	✓	–
Housing – shared hardware slots	✓	✓	–	–
IXP – monthly fee	✓	–	–	–
carriers – monthly fee	✓	–	–	–
Middle-mile circuit – acquisition cost	–	–	✓	36
Middle-mile circuit – interconnection costs	–	–	✓	36
Middle-mile circuit – monthly fee	–	–	✓	–

Table 5.1: Most significant network operation centre costs, cost centre assignment (✓: assignment applies, –: assignment does not apply) and maximum amortisation period.

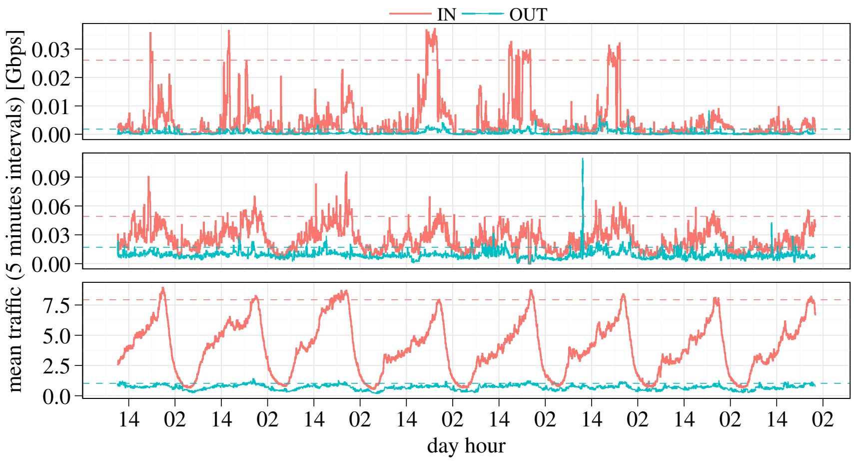

Figure 5.3: Exterior traffic of three participants. The dashed lines correspond to the 95th percentiles.

5.3.4.1 Traffic

The traffic dataset contains(i) the inbound and outbound aggregated traffic of each participant (i.e. the traffic exchanged by each participant in both directions with the IXP and the carriers and the other participants all together), and (ii) the inbound and outbound traffic of each carrier and the IXP. The dataset we have evaluated in this section consists of the mean traffic of five-minute samples, recorded during the second week of April 2019, from Saturday the 6th to Friday the 12th. The data files are in comma-separated value (CSV) format and can be found in the public repository [29]. As an example of this data, Figure 5.3 shows the *inbound* and *outbound* traffic of three participants. The dashed lines correspond to their 95th percentiles. Throughout the section, we sorted the participants in ascending order by the addition of the *inbound* and *outbound* 95th percentiles. Accordingly, the graph on the top corresponds to the participant with the least usage (26 Mbps), the one in the middle to medium usage (49 Mbps), and the one on the bottom to the highest usage (7.9 Gbps). As Figure 5.3 shows, the traffic patterns become more evident as the traffic of the participants increase.

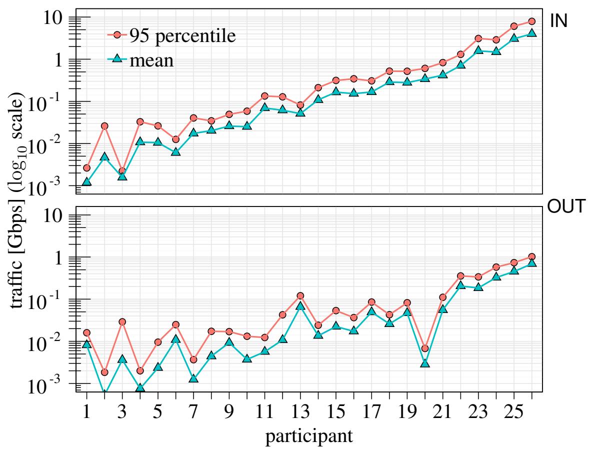

Figure 5.4: In and out traffic: mean and 95th percentile.

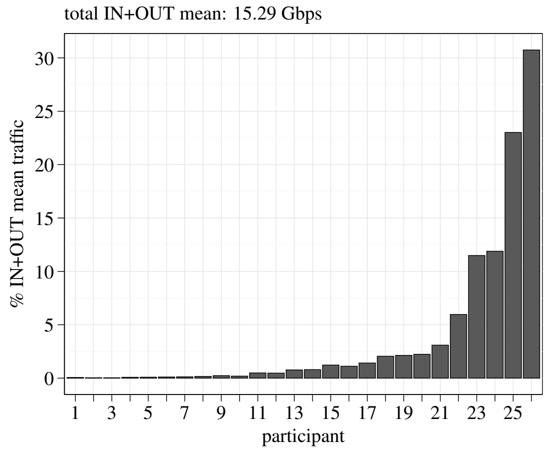

Figure 5.5: Percentage of mean of inbound and outbound traffic.

During the recorded period, 26 participants had traffic activity in the NOC. Figure 5.4 shows their mean traffic and 95th percentiles in the log scale sorted according to the aforementioned criterion. It is interesting to note that nearly a constant distance exists between the mean and 95th percentiles in the log scale, especially for participants with higher traffic. For instance, let q_p^{in} and m_p^{in} be the *in* traffic at the 95th percentile and the mean, respectively, of participant p. There are 13 participants using $m_p^{in} > 0.1$ Gpbs. For these participants, the mean of q_p^{in}/m_p^{in} is 1.93 with a standard deviation of only 0.11. Thus, if only the mean traffic is known, a rule of thumb for the five-minute sampling at the 95th percentile is taking twice the mean.

Outbound traffic that is higher than the inbound traffic corresponds to content providers, whereas the opposite indicates that the participant is either an end user or an access network provider. To appreciate the large difference between participants in terms of traffic exchanged, Figure 5.5 shows the percentage of mean inbound and outbound traffic exchanged by each participant. The participant with the highest usage exchanges 30.74 % of all traffic, and the four participants with the highest usage account for the 77.12 %. Indeed, all of them are service providers, and together, they have over 25,000 subscribers. Conversely, the 10 participants with the least usage together exchange only 1.10 % of the traffic. Among these participants, there are associations, self-provisioning participants, micro-service providers, etc., that account for less than a thousand end users each.

5.3.4.2 Costs

The NOC's cost-compensation spreadsheet has numerous data and formulae because it is used to calculate the dues of all participants for the exterior traffic and the middle mile and racks. As already explained, for simplicity, we focus on the distribution of the costs associated with external traffic. To this end, we recalculated the cost assignments because, for historical reasons, in Guifi.net's spreadsheets, the labour and other costs are entirely charged to the exterior traffic cost centre, whereas, as shown in Table 5.1, they should also be partially incurred by the internal traffic and, in some cases, by the rack spaces as well. To address this anomaly, we proportionally distributed the costs that should be incurred by more than one cost centre to the total amount of exclusive costs of each cost centre of the previous month. We used the data of the previous iteration because some of the exclusive costs, such as the cost per slot of housing, depend on the

	Cost centre			
	Exterior t. [€]	Interior t. [€]	Rack s. [€]	Total [€]
Exclusive	6,362.00	14,501.00	2,558.00	23,421.00
Shared	2,963.00	6,754.00	339.00	10,056.00
Total	9,325.00	21,255.00	2,897.00	33,477.00

Table 5.2: Considered costs per cost centre (April 2019).

		Cost function category	
Item	Cost [€]	NSPs & IXP	Other
C_1 (2×10 Gbps)	2,800.00	✓	–
C_2 flat rate (2×10 Gbps)	1,500.00	✓	–
C_2 excess	317.00	–	–
Additional NSPs	356.00	–	*equally split*
IXP (1×10 Gbps)	650.00	✓	–
RIPE-NCC	87.00	✓	*constant*
Cabling	652.00	–	*participants*
total	6,263.00		

Table 5.3: Exterior traffic cost breakdown (April 2019) and assignment to cost function categories (✓: assignment applies, –: assignment does not apply).

proportionality factors. Hence, they cannot be obtained from the data of the current iteration due to indeterminate problems.

Table 5.2 shows the exclusive costs per each cost centre and our redistribution of the costs to be incurred by more than one cost centre and the corresponding totals. Table 5.3 shows the costs of the external traffic cost centre. Given that the deals with the carriers are private and subject to non-disclosure agreements, in this table and hereafter, we use approximations for the actual costs by rounding the values with deviations below 1 %. The membership fee is 154.00 €.

5.3.5 Cost estimation model

In this section, we derive a function to estimate the total cost of the external traffic on Guifi.net for an arbitrary coalition (i.e. a subset of participants) and traffic consumption. This will be the baseline cost function that we use in the cost-sharing analysis we perform later in Section 5.3.6. For ease of reference, Table 5.4 summarises the parameters and values defined in our model cost, and Table 5.5 displays the main variables of this section.

In line with the classification in Table 5.3, we propose a cost function with components that can be grouped into two main categories: the *NSP and IXP costs*, which exclusively depend on the port capacities contracted to the NSPs and the IXP, and the *other costs*, such as housing, electricity, exceeding traffic, insurance, manpower, amortisations, etc., that is, costs that depend on several factors, with the number of participants and traffic volume being the most significant. Roughly, each of them represents one-half of the total cost. These categories must not be confused with the exclusive and shared cost classification criterion from Section 5.3.4.

Parameter	Value	Unit	Description
P	26	part.	Number of participants
A_P	$\{1, 2, \cdots P\}$	part.	Grand coalition
α_{C_1}	0.58	–	Proportion of traffic exchanged at C_1
α_{C_2}	0.17	–	Proportion of traffic exchanged at C_2
α_{IXP}	0.25	–	Proportion of traffic exchanged at IXP
K_{C_1}	1.25	–	C_1 overprovisioning factor
K_{C_2}	1.25	–	C_2 overprovisioning factor
K_{IXP}	1.50	–	IXP overprovisioning factor
$q(A_P)$	25.06	Gbps	95th-perc. of traffic exchanged by A_P, Eq. (5.3)
$m(A_P)$	15.29	Gbps	Mean traffic exchanged by A_P, Eq. (5.7)
c_T	$8,575.00$	€	Total cost of A_P
H_f	$1,193.33$	€	Other costs parameter, Eq. (5.6)
H_d	$\frac{1,423.33}{m(A_P)}$	€/Gbps	Other cost parameters, Eq. (5.6)
H_p	$\frac{1,758.33}{P}$	€/part.	Other cost parameters, Eq. (5.6)

Table 5.4: Parameters of the cost model.

Variable	Description
i	External connectivity provider, $i \in \{C_1, C_2, \text{IXP}\}$
p	Participant, $p \in \{1, 2, \cdots P\}$
A	Coalition of participants, $A \subseteq \{1, 2, \cdots P\}$
q_i^{in}, q_i^{out}	95th percentile of *in* and *out* traffic of provider i
q_p^{in}, q_p^{out}	95th percentile of *in* and *out* traffic of participant p
m_p^{in}, m_p^{out}	Mean of *in* and *out* traffic of participant p
$q_{in}(A)$, $q_{out}(A)$	95th percentile of *in* and *out* aggregated external traffic exchanged by A
$m_{in}(A)$, $m_{out}(A)$	Mean of *in* and *out* aggregated external traffic exchanged by A
g_p	Guifi.net cost assigned to participant p
s_p	Shapley value cost assigned to participant p

Table 5.5: Main variables used in this section.

5.3.5.1 NSPs and IXP costs

The total cost of this category is the sum of the cheapest combinations of links offered by the NSPs and the IXP that are able to satisfy the respective capacity demands. Since the links are symmetric, each provider demand is established based on the maximum of its inbound and outbound traffic of the previous iteration, that is, of the traffic consumption of the previous month. For dimensioning purposes, the traffic to be considered is given by the following:

$$q_i = \max(q_i^{in}, q_i^{out}), \quad i \in \{C_1, C_2, \text{IXP}\}, \tag{5.1}$$

where q_i^{in} and q_i^{out} are respectively the 95th percentile of the *in* and *out* traffic of provider i.

Using Equation (5.1), we can compute q_i of the coalition containing all participants, the grand coalition of all participants. However, for smaller groups of participants (coalitions), we assume that the NSPs and IXP traffic proportions remain the same because the dataset only encompasses aggregate traffic records but not which proportion of the traffic of each participant is exchanged at NSPs and the IXP. That is, we let P be the number of participants, and $A \subseteq \{1, 2, \cdots, P\}$

	Monthly fees [€]		
Capacity	C_1	C_2	IXP
1 Gbps	*430.77	*276.92	200.00
10 Gbps	*1,400.00	*750.00	650.00
20 Gbps	2,800.00	1500.00	–
30 Gbps	4,200.00	1800.00	–
100 Gbps	*20,000.00	–	3,900.00

Table 5.6: Monthly fees of the NSPs and the IXP (May 2019; * estimated values; – indicates no data available for that configuration and estimation is not needed).

be any coalition and let α_i, $i \in \{C_1, C_2, \text{IXP}\}$, be the proportion of traffic exchanged by all participants at C_1, C_2, and the IXP, respectively. Then, we obtain the following:

$$\alpha_i = \frac{q_i}{\sum q_i}, \quad i \in \{C_1, C_2, \text{IXP}\}, \tag{5.2}$$

and given aggregated external traffic exchanged by coalition A:

$$q(A) = \max(q_{in}(A), q_{out}(A)), \tag{5.3}$$

where $q_{in}(A)$ and $q_{out}(A)$ are respectively the 95th percentile of *in* and *out* aggregated external traffic exchanged by A, we assume that the traffic exchanged by A at NSPs and the IXP is $\alpha_i\, q(A),\ i \in \{C_1, C_2, \text{IXP}\}$.

Establishing an overprovisioning factor K_i for each provider, we conclude that, for dimensioning purposes, the demands are the following:

$$d_i(A) = K_i\, \alpha_i\, q(A), \quad i \in \{C_1, C_2, \text{IXP}\}. \tag{5.4}$$

Table 5.6 shows the prices we considered. As already explained, NSPs prices are subject to private negotiations and non-disclosure agreements. Thus, our precise information on the offers is limited to the current services contracted. The rest of the NSPs values are estimations, as indicated. In contrast, the IXP fees are publicly available on its website [28].

Assuming cost additivity in the case of capacity aggregations, the minimum cost to allocate the traffic demand for each $i \in \{C_1, C_2, \text{IXP}\}$ is obtained by the solution of the integer linear program (ILP):

$$\begin{aligned} c_i(A) = \min\ & \textstyle\sum a_{ij}\, n_{ij}, \\ \text{s.t.}\ & \textstyle\sum b_{ij}\, n_{ij} \geq d_i(A) \\ & n_{ij} \geq 0,\ n_{ij} \in \mathbb{Z} \end{aligned} \tag{5.5}$$

where n_{ij} is the number of links of type j, with cost a_{ij} for a bandwidth of b_{ij} Gbps (rows in Table 5.6), and $d_i(A)$ is the demand given by Equation (5.4).

5.3.5.2 Other costs

We model these other costs as a three-term function. The first term gathers the fixed costs; thus, we model it as a constant. The second relates to the costs associated with the exchanged traffic,

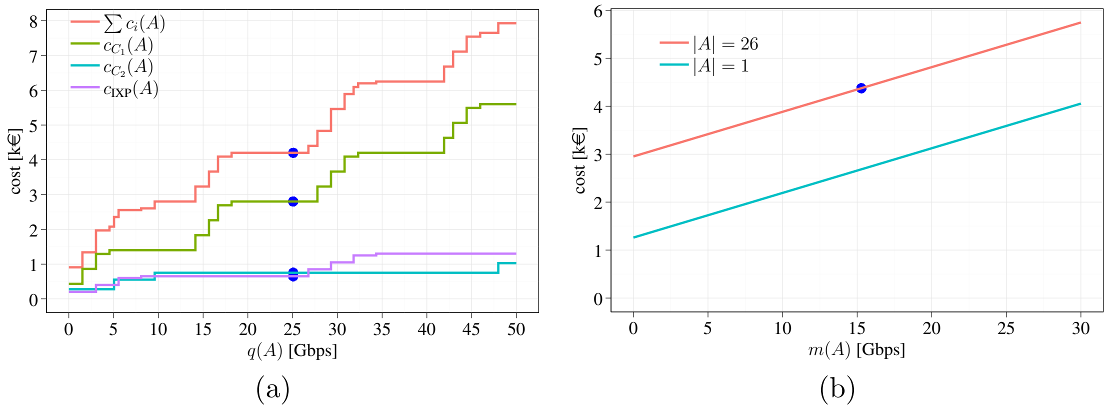

Figure 5.6: (a) NSPs and IXP costs (Eq. (5.5)), and (b) other costs (Eq. (5.6)). The dots show the costs for the grand coalition.

in this case, taking the addition of the means of inbound and outbound traffic, as shown in Equation (5.7). The third reflects the costs primarily influenced by the number of participants.

We estimate the other costs as follows:

$$c_h(A) = H_f + H_d\, m(A) + H_p\, |A|\,, \tag{5.6}$$

where $|A|$ is the number of participants in coalition A (i.e. the cardinality of A) and $m(A)$ is given by:

$$m(A) = m_{in}(A) + m_{out}(A), \tag{5.7}$$

where $m_{in}(A)$ and $m_{out}(A)$ are respectively the mean of *in* and *out* aggregated external traffic exchanged by A.

To assess the constants in Equation (5.6), we used the values in Table 5.2 and Table 5.3. We split the sum of the shared costs and the additional NSPs into three terms, and we added the RIPE-NCC fee to the constant, the C_2 excess to the traffic, and the cabling to the participant terms, respectively. This results in the values reported in Table 5.4.

5.3.5.3 Total cost of a coalition

Summarising, we estimate the overall monthly cost of the external traffic exchanged by any coalition $A \subseteq \{1, 2, \cdots P\}$ using the following equation:

$$c(A) = \sum_{i \in \{C_1, C_2, \text{IXP}\}} c_i(A) + c_h(A), \tag{5.8}$$

where $c_i(A)$ are the NSPs and IXP costs given by Equation (5.5), and $c_h(A)$ includes the other cost given by Equation (5.6).

Figure 5.6 shows the NSPs and IXP costs (a) and the other costs (b) using the model given by Equations (5.5) and (5.6), respectively. In Figure 5.6 (b), we show the resulting cost for a single participant, $|A| = 1$, and the cost for the total number of participants present in the current dataset, $|A| = 26$. The NSPs and IXP costs account for 4,200.00 €, the other costs for 4,325.00 € and the total for 8,575.00 €. The difference between the calculated total and the total in Table 5.2 (9,325.00 €) is because, for the calculation, we did not impose d_{C_2} to be equal to or greater than d_{C_1} as done in Guifi.net, as explained in Section 5.3.1. If $d_{C_2} = d_{C_1}$ were set to compute $c_{C_2}(A)$, Equation (5.8) would also give 9,325.00 €.

5.3.6 Cost-sharing

In this section, we formalise the cost-sharing mechanism used by Guifi.net, and we compare it with the Shapley value. Let P be the total number of participants, $P = 26$, and A_P the set of all participants. Using Equation (5.8), the total cost assigned to the set of all participants is as follows:

$$c_T = c(A_P). \tag{5.9}$$

5.3.6.1 Guifi.net's cost-sharing mechanism

As explained in Section 4.4.3, a portion of the costs are equally weighted among the participants, and the rest are allocated according to their resource consumption. We refer to these parts as the *fixed*, F, and *shared*, S, costs:

$$\begin{aligned} F &= \gamma\, c_T && \text{fixed cost} \\ S &= (1-\gamma)\, c_T && \text{shared cost,} \end{aligned} \tag{5.10}$$

where $0 \leq \gamma \leq 1$. The fixed cost, F, is equally divided among all participants. For simplicity, the shared cost, S, is proportionally divided according to each participant's usage. Thus, the cost g_p assigned to a participant p is given by the convex combination:

$$g_p = \frac{F}{P} + S\,\frac{u_p}{\sum u_p} = \frac{\gamma\, c_T}{P} + (1-\gamma)\, c_T\,\frac{u_p}{\sum u_p}, \quad p \in \{1, 2, \cdots P\}, \tag{5.11}$$

where u_p is the bandwidth usage of each participant, defined as the addition of the 95th percentiles of its inbound and outbound traffic:

$$u_p = q_p^{in} + q_p^{out}, \quad p \in \{1, 2, \cdots P\}. \tag{5.12}$$

In the rest of the section, *traffic* and *usage* of a participant will be used interchangeably to refer to u_p given by Equation (5.12). Note that the fixed cost in Equation (5.11), the first summand, is the same for all participants (i.e. it corresponds to the membership fee). The allocation in Equation (5.11) is *budget-balanced* (i.e. $\sum g_p = F + S = c_T$) and possesses the *anonymity property* (i.e. the labelling of the participants does not play a role in the assignment).

5.3.6.2 Shapley value

The Shapley value is a solution concept in cooperative game theory that fairly and uniquely solves the problem of the distribution of surplus (or joint-cost allocation) among players when considering the worth (or cost) of each coalition [138]. Today, the Shapley value is perhaps the most commonly used method to allocate the costs in cost-sharing games [120] because it is budget-balanced and guarantees equilibrium in any game, regardless of its parameters [66]. We compute the Shapley value (see Appendix 5.A) using Equation (5.8) as a characteristic function.

5.3.6.3 Optimal γ

Let s_p be the cost assigned to participant p by the Shapley value. We call γ^* the value of γ in Equation (5.11) that minimises the mean square error with Shapley values (i.e. $\min_\gamma \sum (g_p - s_p)^2$).

Computing $\partial \sum (g_p - s_p)^2 / \partial\gamma = 0$, it can be easily found that a unique critical point exists and has a positive second derivative; thus, it is a global minimum. The value is given by the following:

$$\gamma^* = \frac{\sum_{p=1}^{P} (s_p/c_T - \eta_p)\,(1/P - \eta_p)}{\sum_{p=1}^{P} (1/P - \eta_p)^2}, \tag{5.13}$$

where $\eta_p = u_p / \sum u_p$, $p \in \{1,\, 2, \cdots P\}$, $0 \le \eta_p \le 1$, $\sum \eta_p = 1$. Thus, η_p represents the relative system usage of participant p. Note that, for an arbitrary mapping between relative usage η_p and Shapley values s_p, γ^*, given by Equation (5.13), is not bounded (i.e. $\gamma^* \in (-\infty,\, \infty)$). However, it would not be reasonable to take γ in Equation (5.11) outside the interval $[0,\, 1]$. What this result shows is that having $\gamma^* \in [0,\, 1]$, Shapley values might be approximated well by Equation (5.11), taking $\gamma = \gamma^*$, while Equation (5.11) might not approximate Shapley values well when $\gamma^* \notin [0,\, 1]$. We see that the condition $\gamma^* \in [0,\, 1]$ holds for our dataset, and we believe that this happens in most practical cases. Furthermore, when $\gamma^* \in [0,\, 1]$, its value can be used as an indicator of how balanced the system is. If the system is very unbalanced, for example such that a single participant $\hat{p}$ consumes all resources (i.e. $\eta_{\hat{p}} \to 1$, $\eta_{p \ne \hat{p}} \to 0$, and thus, $s_{\hat{p}} \to c_T$, $s_{p \ne \hat{p}} \to 0$), then from Equation (5.13) we have the following:

$$\lim_{\substack{\eta_{\hat{p}} \to 1,\ \eta_{p \ne \hat{p}} \to 0 \\ s_{\hat{p}} \to c_T,\ s_{p \ne \hat{p}} \to 0}} \gamma^* \to 0. \tag{5.14}$$

Alternatively, if the system is balanced, such that $\eta_p \to 1/P\ \forall p$ (i.e. all participants consume the same and, thus, $s_p \to c_T/P\ \forall p$), then from Equation (5.13), we have the following:

$$\lim_{\substack{\eta_p \to 1/P \\ s_p \to c_T/P}} \gamma^* \to 1. \tag{5.15}$$

Therefore, we conclude that $\gamma^* \to 1$ for a system where participants equally consume the resources, while $\gamma^* \to 0$ for a system where most resources are consumed by a reduced number of participants. For our dataset, we obtain $\gamma^* = 0.43$. Thus, we can expect that Shapley values can be approximated well by Equation (5.11), taking $\gamma = \gamma^*$. We will confirm this with the numerical results explained in the following. Moreover, $\gamma^* = 0.43$ is far from 1, showing a rather unbalanced system, as we have seen in Section 5.3.4.1 (the four participants with the highest usage account for 77.12 % of the traffic).

Figure 5.7 (a) shows the cost assignments according to the two previous cost-sharing mechanisms, the Shapley value and Guifi.net, with several values of γ in the last case. All of the distributions are *individually rational* because, in any case, a participant pays more when not cooperating with anyone else (*standalone* curve). Figure 5.7 (b) shows the normalised values of Figure 5.7 (a) resulting from dividing the assigned costs by the means of the inbound and outbound traffic, giving the cost in €/Gbps. The €/Gbps is a metric commonly used by service providers to assess alternatives. The curves of this figure are not strictly monotonically decreasing due to the differences between the metric used in the cost-sharing calculations, u_p, and the metric used for the normalisation, $m(p)$. Figure 5.7 (c) shows the cost gain, defined as the standalone cost over the cost incurred inside Guifi.net (i.e. the cost depicted in Figure 5.7 (a)).

Interestingly, Figure 5.7 reveals that for $\gamma = 0.4$ a striking coincidence exists between costs computed using the Guifi.net method and the Shapley value. Indeed, recall that $\gamma^* = 0.43$. The fixed cost per participant resulting from Equation (5.11), $\gamma\, c_T/P$, is 142.37 € for γ^*. This is rather close to the membership fee of 154.00 € used in Guifi.net, which corresponds to $\gamma = 0.47$. In other words, without being aware of it, Guifi.net participants are contributing an assigned cost that is very close to the Shapley value.

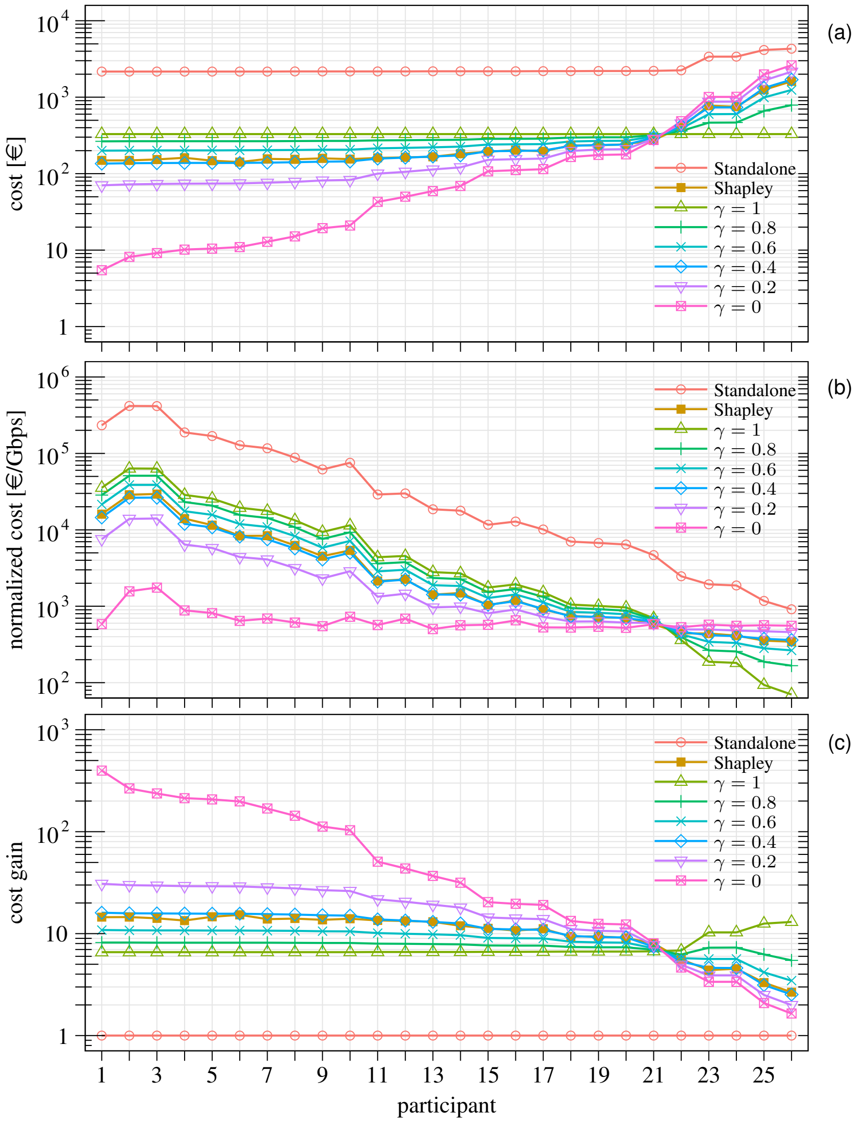

Figure 5.7: Cost sharing: (a) absolute value, (b) normalised to the traffic mean, and (c) cost gain.

5.3.6.4 Meaning of γ

Note that, from Equation (5.10), in one extreme, by setting $\gamma = 0$, we assign the whole cost to the shared part, thus proportionally dividing the cost according to each participant's traffic. At the other extreme, by setting $\gamma = 1$, we assign the whole cost to the fixed part, thus equally weighting the total cost among all participants. As shown in Figure 5.7 (a), the assignment line varies from a curve with the highest positive slope when $\gamma = 0$ to a flat line when $\gamma = 1$. Therefore, for the participants on the left (with low traffic) the lower the γ is, the lower the cost they pay. While the opposite holds for the participants on the right, with high traffic, the lower the γ is, the higher the cost they pay. The boundary between these regions is given by the point where the cost does not change with γ. Therefore, this point can be computed by $\partial g_p / \partial \gamma = 0$. Using Equation (5.11), we find that the boundary is given by the following mean usage:

$$\langle u \rangle = \frac{1}{P} \sum_{i=1}^{P} u_p. \tag{5.16}$$

This is a logical result because users with a lower usage than the mean, $u_p < \langle u \rangle$, prefer $\gamma = 0$; thus, every participant is paying for his or her usage. On the other hand, users with higher usage than the mean, $u_p > \langle u \rangle$, prefer $\gamma = 1$, thus dividing their cost among all participants. The optimal γ computed before using the Shapley value is a good compromise between these opposite interests.

5.3.7 Sensitivity to participants with high usage

The participants with the highest bandwidth consumption, those that contribute the most in absolute terms, might be tempted to leave Guifi.net and build their own coalition, or at least to threaten to form one to impose cost-sharing rules that are more favourable to their interests, for instance, a higher γ. To elucidate whether this reasoning is well-founded, in this section, we investigate the increase in costs that participants would incur upon the largest contributors leaving the current coalition.

Let S be the set of participants leaving Guifi.net and $\bar{S}$ be the remaining set, $\bar{S} \cup S = \{1, 2, \cdots P\}$. Recall that we assume the participants are ordered from the least (participant 1) to the most (participant 26) bandwidth usage (see Equation (5.12)). Figure 5.8 shows the Shapley value assigned to a selected group of participants, including the participants having the least and most usage, s_1 and s_{26}, respectively. The figure also shows the total cost assigned to the participants in S and $\bar{S}$, $c(S) = \sum_{p \in S} s_p$ and $c(\bar{S}) = \sum_{p \in \bar{S}} s_p$, respectively (see Equation(5.8)), and its sum $c(S) + c(\bar{S})$. The abscissa corresponds to the cardinality of the subset S, $|S|$. For instance, for $|S| = 0$, all participants are inside $\bar{S}$, and for $|S| = 1$, participant 26 has already left the Guifi.net coalition (i.e. $S = \{26\}$). For $|S| = 2$, $S = \{25, 26\}$, and so on. Note that for $|S| = 1$, s_{26} corresponds to the standalone cost of 26, already depicted in Figure 5.7 (a). The figure shows that between s_{15} and s_{10}, a threshold exists beyond which joining the new coalition is more beneficial than staying in Guifi.net. The figure also shows the local minimums in the staying curves (thin segments) and local maximums in the leaving curves (thick segments). These are because the NSPs and IXP cost components of the cost function are step functions. Hence, the unit price functions are not strictly decreasing, which is the condition for economies of scale to take place. This creates intervals with local optima that discourage traffic growth and, thus, cooperation. For instance, when participant 25 leaves, the costs incurred by most of the rest who stay decrease, and the same happens for participant 9. Nevertheless, from a general perspective, these local reductions of savings are, by far, compensated for by the region of savings that the greater order of magnitude of products entails (e.g. when moving from combinations of 1 Gbps links to a 10 Gbps setting).

Figure 5.9 shows the minimum and maximum increments in log scale of the Shapley value for both the participants staying in Guifi.net (top) and those leaving Guifi.net (bottom) with respect to the Shapley value before splitting into the staying and leaving sets. That is, let $r_p(k)$ be the relative cost increment of participant $p \in k$, $k \in \{S, \bar{S}\}$, and $s_p(k)$, $k \in \{S, \bar{S}, A_P\}$ be the Shapley value assigned to participant $p \in k$, where $A_P = \{1, 2, \cdots P\}$ is the set before splitting. Then, we obtain the following:

$$\max_{p \in k}(r_p(k)) = \max_{p \in k} \left(\frac{s_p(A_P) - s_p(k)}{s_p(A_P)} \right), \quad k \in \{S, \bar{S}\}, \tag{5.17}$$

and likewise for the minimum. The labels next to the points indicate which participants reach the max and min cost increments.

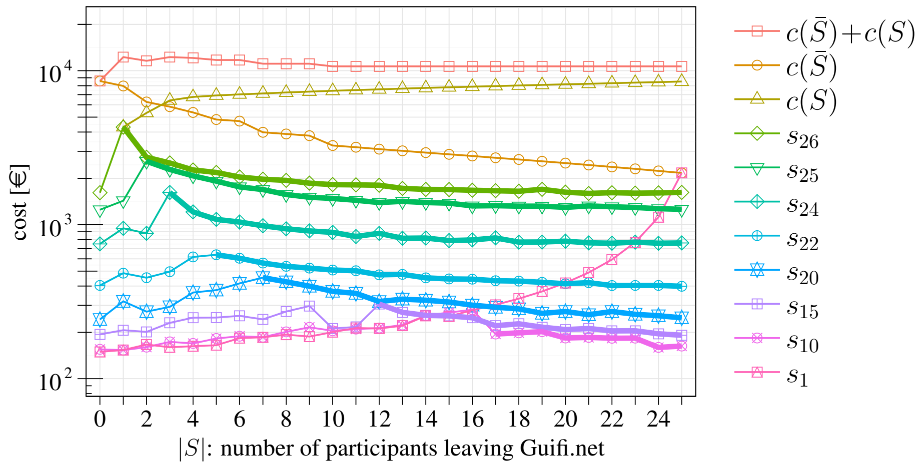

Figure 5.8: Shapley value of a selected group of participants (1 and 26 are the participants exchanging the least and most external traffic, respectively) upon a subset S of the highest-usage participants leaving Guifi.net, and $\bar{S}$ staying. Segments are thicker after the participant has left Guifi.net.

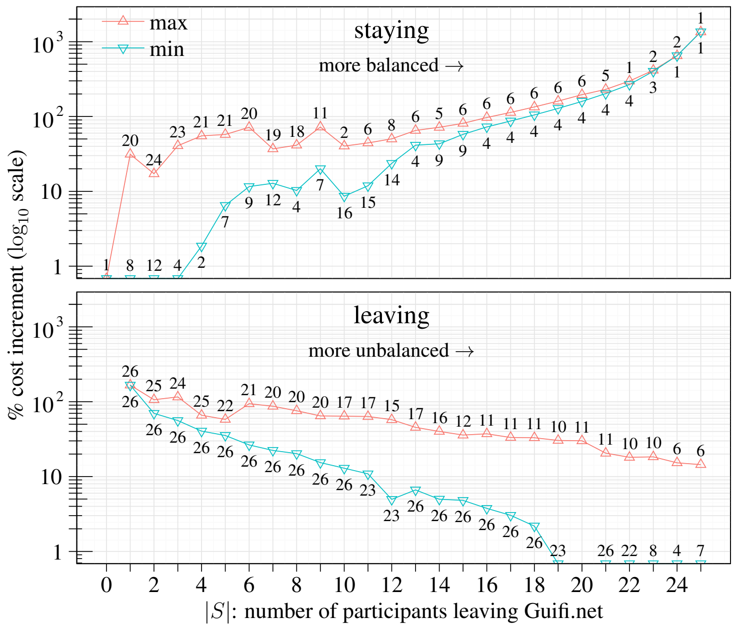

Figure 5.9: Maximum and minimum percentage cost increment over all participants in $\bar{S}$ (staying in Guifi.net) and S (leaving Guifi.net) corresponding to Figure 5.8 in log scale.

Figure 5.9 shows that the Shapley value increments are very different among the participants. For instance, when $S = \{26\}$ and $|S| = 1$, we find that $\max(r_p(\bar{S})) = 31.26\,\%$ (reached by participant 20), and $\min(r_p(\bar{S})) = -4.33\,\%$ (reached by participant 8). Therefore, participant 8 is slightly favoured by the departure of participant 26, while participant 20 has a significant increment in the assigned cost. When more participants with higher usage leave Guifi.net, the set of staying participants are more balanced, and the ratio between the maximum and minimum is lower (top of Figure 5.9). Recall that the ordinates are in log scale, and we observe that $\log(\max) - \log(\min) = \log(\max / \min)$ diminishes up to 0 at $|S| = 25$, when there is a single participant in $\bar{S}$. At this point, Figure 5.9 shows that the cost increment for the single participant

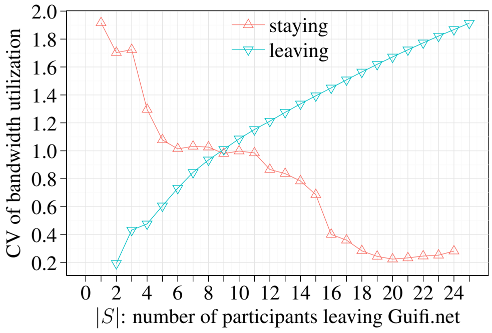

Figure 5.10: coefficient of variation (CV) of the participants' bandwidth usage, u_p, in each staying $\bar{S}$ and leaving S sets. The lower the CV is, the more *balanced* the sets are.

in $\bar{S}$ increases more than 1000 %. It becomes apparent that the cost would not be affordable for a single participant, nor even for a small group of participants with low usage.

The opposite occurs for the set of leaving participants (bottom of Figure 5.9). When more participants join the set, the max / min ratio is more unbalanced and higher. To assess how balanced these sets are, Figure 5.10 shows the CV of the participants' bandwidth usage, measured using Equation (5.12). Figure 5.10 confirms that the CV of the staying set tends to 0 (more balanced) as participants leave the set. Alternatively, the CV of the leaving set increases (more unbalanced) as new participants join. Thus, we conclude that, in general, the more unbalanced the set becomes when a new participant joins the set, the greater the ratio will be between the maximum and minimum cost increments that the participants of the perturbed set will have. We can guess that the same occurs when participants leave the set.

If we assume that the participants leave Guifi.net from the lowest usage (participant 1) to the highest usage (participant 26), we would obtain Figure 5.9 moving from right to left and with the staying and leaving sets being those at the bottom and top, respectively. For instance, if participant 1 leaves Guifi.net, Figure 5.9 at the bottom shows that participant 6, a participant with low usage, would have an assigned cost increment of 14.44 %. This is a remarkable increment, given that the participant leaving is the one with the least usage, and, thus, with a low assigned cost. Furthermore, participant 6 would have a cost increment of −1.15 % if participant 26 left instead of 1. We thus conclude that some participants are more sensitive to departures of low-usage participants rather than high-usage participants.

It is also interesting that, in set $\bar{S}$ (staying), the participants with a higher usage are those with higher cost increments, while the opposite occurs in set S (leaving). This is a logical result because, when a participant with high usage leaves Guifi.net, the other participants with high usage must afford the cost that their need for greater resources requires, which had been shared with the participant who left. The opposite occurs for the set S, where the leaving participant joins. Thus, we conclude that, when a participant with high usage joins the set, the participants in the perturbed set that will have the least assigned cost increment will be those of the same type (high usage). Alternatively, if a participant with high usage leaves the set, the participants of the same type will have the highest cost increment.

Yet again, because the unit price functions of some cost components are not strictly decreasing, on some occasions, the traffic reduction through the reduction of the number of participants is beneficial for some of those who stay, reaching up to 10 % in savings between s_9 and s_{10}.

Nonetheless, Figure 5.9 as a whole confirms that the dominant strategy is to be part of the grand coalition.

5.3.8 Approximation of the Shapley value using Guifi.net's cost sharing

In Section 5.3.6, we found that Guifi.net's cost sharing is close to the cost assignments obtained using the Shapley value. This is a significant result because the Shapley value is difficult to compute for numerous participants. In this section, we analyse how well the Shapley value is approximated using Guifi.net's cost-sharing mechanism given by Equation (5.11). We investigate the approximation for all sets S (participants leaving Guifi.net) and $\bar{S}$ (participants staying in Guifi.net) analysed before. Note that these sets form coalitions of participants with very different characteristics, as shown by the high variation of the usage CV in Figure 5.10 (ranging approximately from 0 to 2). Thus, our analysis will compare the approximation for a wide range of situations.

For each S and $\bar{S}$ sets of participants, we consider two cases: (i) when Guifi.net's cost sharing uses γ^* given by Equation (5.13), and (ii) when Guifi.net's cost sharing uses a fixed membership fee. We denote these cases by γ_k^* and $\hat{\gamma}_k$, $k \in \{S, \bar{S}\}$, respectively. Case (i) gives us the best approximation of the Shapley value (with the minimum mean square error) that can be obtained using Guifi.net's cost sharing. Case (ii) is more practical. Note that computing γ_k^* requires knowing the Shapley values of the participants in the set $k \in \{S, \bar{S}\}$. In practice, it is likely that Guifi.net's cost sharing is used, fixing a reasonable membership fee. The fee can be fixed with different criteria, for instance, such that participants with a low budget can join Guifi.net. In our analysis, we will consider the membership fee currently used in Guifi.net (i.e. 154 €).

Figure 5.11 shows the value of γ_k^*, $k \in \{S, \bar{S}\}$ given by Equation (5.13). The curves labelled with $\hat{\gamma}_k$ show the value of γ_k, $k \in \{S, \bar{S}\}$ corresponding to the fixed fee of 154 €, that is:

$$\hat{\gamma}_k = \frac{154\ |k|}{c(k)}, \quad k \in \{S, \bar{S}\}, \tag{5.18}$$

where $|k|$ and $c(k)$ are the number of participants and total cost (Equation (5.8)), respectively, of the sets $k \in \{S, \bar{S}\}$.

To assess the approximation, Figure 5.12 shows the maximum relative error (MRE) in percentage between Guifi.net's cost sharing and the Shapley value assigned to any participant using γ_k^* and $\hat{\gamma}_k$:

$$\mathrm{MRE}(\gamma) = \max_{\forall p} \left(\frac{|g_{p,k}(\gamma) - s_{p,k}|}{s_{p,k}} \right), \quad \gamma \in \{\gamma_k^*, \hat{\gamma}_k\},\ k \in \{S, \bar{S}\},\ p \in k, \tag{5.19}$$

where $g_{p,k}$ and $s_{p,k}$ are the Guifi.net's cost sharing (Equation (5.11)) and Shapley value, respectively, for each set $k \in \{S, \bar{S}\}$ and for each participant $p \in k$.

We observe the following:

- Figure 5.11 shows that, in most cases, we obtain $\gamma_k^* \in [0,\ 1]$, $k \in \{S, \bar{S}\}$. Thus, at least for the cost model derived in this section, Shapley values might be approximated using Guifi.net's cost sharing using γ^*.
- Figure 5.12 shows that, in all cases, the MRE corresponding to γ^*, $k \in \{S, \bar{S}\}$ is lower than 20 %. Thus, confirming that Shapley values are reasonably well approximated by

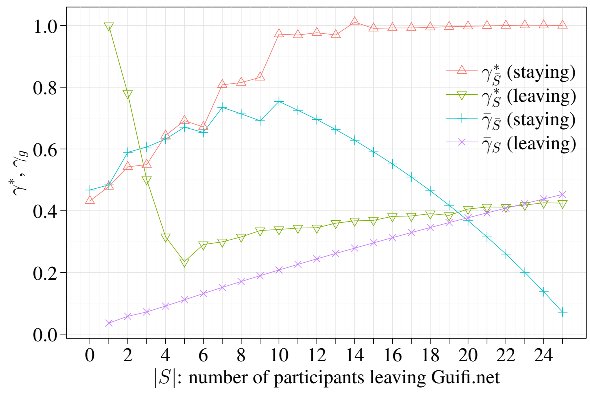

Figure 5.11: γ^*_k and $\hat{\gamma}_k$ for each set k: S (leaving Guifi.net) and $\bar{S}$ (staying in Guifi.net).

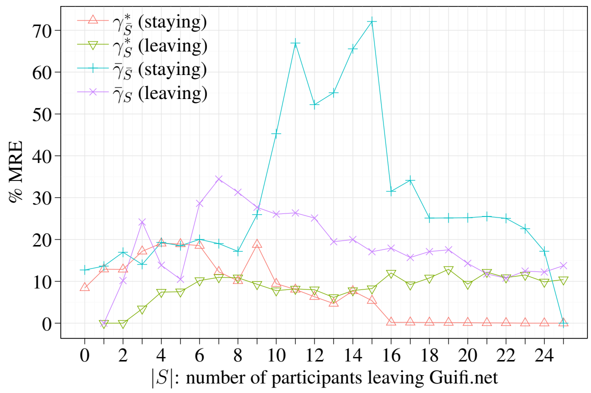

Figure 5.12: MRE between Guifi.net's cost sharing and the Shapley value.

Guifi.net's cost sharing using γ^*. Furthermore, because γ^* minimises the mean square error, the relative error is expected to be much lower for participants with higher costs. Indeed, we found that the participant with the highest assigned cost, participant 26, has a lower relative error than 4.14 % in all scenarios. This is important because participants with the highest cost assignments are those that bother the most about the fairness of the assigned cost.

- In Section 5.3.6.3, we derived that, if the system is balanced, $\gamma^* \to 1$. The *staying* subset becomes more balanced each time as participants with higher traffic leave (see Figure 5.10). Figure 5.11 shows that $\gamma^*_{\bar{S}} \to 1$, as expected.
- In Section 5.3.6.3, we found that, if the system is unbalanced, $\gamma^* \to 0$. The *leaving* subset rapidly becomes unbalanced as participants with lower traffic join the group (see Figure 5.10). Accordingly, Figure 5.11 shows that γ^*_S decreases and remains low (less than 0.5) as expected.
- Figure 5.12 shows that the MRE corresponding to $\hat{\gamma}_k$, $k \in \{S, \bar{S}\}$ is below 20 % in most cases. For instance, for $|S| = 0$ (when all participants are within Guifi.net), the maximum error is only 12.72 %. Figure 5.12 shows that the MRE corresponding to $\hat{\gamma}_{\bar{S}}$ increases beyond 50 % when a considerable number of participants with higher traffic leave Guifi.net, and the group still has more than 10 participants. This is motivated by the fact that when all participants have lower traffic usage, the *other cost* dominates the *shared cost* in Equation (5.11). Consequently, the Shapley value equally divides costs among all participants. That is, the membership fee should cover the overall cost, hence the higher MRE($\hat{\gamma}_{\bar{S}}$). In all other cases, even if γ^*_k and $\hat{\gamma}_k$, $k \in \{S, \bar{S}\}$ are significantly different, the MRE corresponding to $\hat{\gamma}_k$ is lower than 40 %. We conclude that, for a reasonable value of the membership fee, Guifi.net's cost sharing is not expected to be significantly different from the Shapley value (MRE less than 40 %).

5.3.9 Tuning Guifi.net's cost sharing

Although the Shapley value can be considered a sensible fair scheme from an economic point of view, it has some drawbacks when used directly as a cost assignment mechanism in Guifi.net or other similar scenarios. Possibly the most important drawback is that the Shapley value is difficult to compute because it needs to formulate the characteristic function and use numerical methods, such as Monte Carlo simulations. Thus, many participants would possibly not be able to compute or estimate the assigned cost and validate whether it agrees with the Shapley value.

On the contrary, the simple Guifi.net cost sharing is easy to understand and easy to estimate. Participants know that they are assigned a membership fee and a variable cost that is proportional to their bandwidth usage. Thus, participants with low usage can estimate that the assigned cost will be close to the membership fee. Possibly, these participants do not care if the cost they are assigned has a relative error of 20 % with the Shapley value, as long it is not far from the membership fee they knew beforehand. Furthermore, Guifi.net's cost sharing is easily computed using the average traffic, which is a measure available to all participants. Thus, they can easily validate the cost they are assigned.

As seen in Section 5.3.6, participants with higher usage in Guifi.net afford costs that are orders of magnitude higher than those of the participants with low bandwidth usage. Such participants are concerned about the cost they are assigned and the fairness of the amount of the membership fee. One convincing justification to them can be the Shapley value. That is, if the cost they are assigned is close to the Shapley value, it is a sound argument to convince them that the cost assignment is fair.

We have seen in Section 5.3.8 that, when using γ^* in Guifi.net's cost sharing, the MRE with the Shapley value is expected to be less than 20 %. Because γ^* minimises the mean square error, for participants with high assigned costs, the relative error with the Shapley value is even lower than 20 %. Indeed, we found that the participant with the highest assigned cost, participant 26, has a relative error that is lower than 4.14 % in all analysed scenarios in Section 5.3.8. Therefore, considering that traffic patterns are not much different in consecutive months, we propose the following modification to Guifi.net's cost-sharing approach. Every time the membership fee is to be updated, the following should be performed:

1. Compute γ^* using Equation (5.13) and the dataset of the previous month. We assume that we obtain $\gamma^* \in [0, 1]$.

2. Compute the membership fee M corresponding to γ^*:

$$M = \frac{\gamma^* \, c_T}{P}. \tag{5.20}$$

Thus, Guifi.net cost sharing will be used with the membership fee of M. Participants with high usage who are worried about the fairness of the cost assignment could compute the Shapley value and validate that it has a small deviation from the assigned cost.

5.3.10 Arguments against ceasing cooperation

Cooperation is an inherent part of Guifi.net history. It is only through collaboration and aggregation of demand that small players can access competitive solutions, such as the architecture presented in Section 5.3.1 and the associated services. All participants started from scratch; thus, they directly benefited from the joint efforts to overcome the telecommunications' sector entry barriers. The forms of cooperation have evolved over time from the initial informal agreements around small and rather isolated projects to the current well-structured and legally binding body of normative agreements to meet new external challenges and the changes in interests, expectations, and objectives of the participants. This transformation process, which involved long discussions, agreements, and concessions among the participants, has had to cope with internal tensions recurrently jeopardising the cooperation. The threat of ceasing cooperation by one or more members has frequently been one of the causes of this tension or has at least been used as a means of enforcing internal rule changes.

In this regard, our findings not only provide arguments in favour of staying within the Guifi.net coalition but also to focus the efforts towards integrating new participants and increasing the resource usage. As Figure 5.8 shows, leaving would entail the broadly accepted fact that considerable extra costs would result for the remaining participants and for those who leave, which is something much less well known or at least less publicly acknowledged by those promoting the schism. Figure 5.9 illustrates that the losses greatly exceed the meagre benefits of the few participants when others leave. Conversely, both figures together, read from right to left, underline the benefits of the increasing number of participants and amount of usage consumption. Lastly, to obtain an approximation of the order of magnitude of the losses due to the cease of cooperation, we must consider that the external traffic case we analyse in this section is just a minor fraction of the total activity volume in Guifi.net for these service providers.

5.4 Conclusions

This chapter has been structured in two main sections, Section 5.2, which is on the economic system of Guifi.net in general, and Section 5.3, which elaborates in detail a case study of cost-sharing.

As far as the economic system as whole, our main conclusion is that it seems sound and coherent with the fundamental principles of the project. The financial sustainability approach is backed with a remarkable practical level of investment recovery, specially taking into account that the most successful deployments are in areas that had been unattended by the traditional telecoms due their long-term ROI.

The success of the Guifi.net economic system is deeply rooted in the governance system developed and implemented by the community in general, and in one of its components in particular, the cost-compensation system and the clearing houses through which it is implemented. The implementation details of these two instruments are established in the template of the agreements that the professionals must sign with the Foundation to be able to develop any remunerated activity in the system. Therefore, what we presented in Section 5.2 is, essentially, the results of the application of these agreements.

The distinction between the professional activity in the CPR and the professional activity developed on top of the CPR, which is liberalised, has contributed in great manner to clarify which of the professional task are regulated –installation, maintenance and operation– and which are liberalised –service provisioning. This clarification has, in turn, contributed in a great manner to sanitise the system.

Setting mandatory the recuperation of all CAPEX and OPEX regardless the source of funding is also an innovative contribution. In addition to recapitalise the system, this rule has proven to be effective against dumping practices, which put the whole system at stake at some point in time.

The activation of this flourishing economic ecosystem by the incorporation of professional activity as an organic component of the system has contributed to drastically reduce the dependency on volunteering work and has enabled an unprecedented growth. However, the good ROIs achieved are the basis of some tensions that at this time exist between the professionals and the rest of the community. The question has strong legal background, and depending on how it is eventually solved it can have catastrophic consequences for the CPR. However, the interim results already achieved through the dialogue combined with the successful resolution of previous conflicts, and the long experience in conflict management already achieved, leaves room for optimism. The conflict is part of the Guifi.net history and has triggered major changes, which have made the system more resilient.

In Section 5.3, we analysed the cost-sharing mechanism that the Guifi.net community network has developed and put in practice to split the transit costs among their more than 20 beneficiaries for almost a decade. How costs are distributed among the participants is a key question in the management and viability of shared resources. Although all cost-sharing mechanisms are subjective and thus it is eventually up to the participants to accept one or another, some general criteria seem desirable, such as being budget-balanced and that, in any case, a participant pays more when not cooperating with anyone else.

We started our analysis introducing the general context and present the particularities of our case study, for which we elaborated a mathematical model including the characteristic cost function and cost-sharing mechanism. Then, we evaluated the model for a specific dataset, and we compared the results with the Shapley value, a reference cost-sharing mechanism in many areas. We followed with an investigation on the sensitivity of the system to reductions of the number of participants and demand. We concluded with some observations derived from our work for communities of practice to consider to face what seem to be recurrent periods of internal tension in which cooperation is endangered either because some participants cast doubt on the cost-sharing criteria or because they think that they would obtain a better payoff outside the coalition. The considered cost categories include network service providers, Internet exchange points, housing, electrical power, and human resources.

Our results show that the Guifi.net's cost-sharing mechanism of the external connectivity, which follows the Guifi.net approach, that is, it comprises an equal membership fee for each participant plus a proportional distribution of the remaining costs according to the resource consumption, yields a cost assignment similar to the Shapley value. Furthermore, we found that the simple sharing approach of Guifi.net can approximate the Shapley value in a wide range of cases. We believe that this is a significant contribution because the Shapley value for a large number of participants is difficult to compute.

Our analysis also shows that any alternative to the coalition of all participants entails significant total cost increases and detrimental widespread cost allocation. For instance, that the four highest-usage participants account for 77.12 % of the traffic. We estimate that, upon these participants leaving Guifi.net, the staying and leaving groups of participants would have increased overall external traffic costs by 28.11 % and 54.01 %, respectively.

The quality of the data that are made available to us has allowed us to reach an uncommon depth of analysis. To ease the validation of our results and to enable further investigation, we have made a great portion of this information publicly available.

This chapter concludes the block we have devoted to the Guifi.net CN study. Given the interest by the raised by the project in general, and by its governance tools in particular, as it is been agreed that they are the keys to success of the project, we hope that the work we have presented fulfil the expectations of those who were interest in understanding the particularities of this innovative, but complex, system for the participatory construction and management of network infrastructure as a CPR.

Appendix 5.A Shapley value

The Shapley value is a well-known concept in coalitional game theory. For the sake of completeness in this appendix, we provide a brief review of the Shapley value adapted to our problem, using the notation defined in previous sections. The selected literature about the Shapley value can be found in [129].

Our coalitional game consists of the pair (A_P, c), where

- $A_P = \{1, 2, \cdots P\}$ is the set of participants (the *grand coalition*), and
- $c : 2^P \to \mathbb{R}$ associates with each coalition $A \subseteq \{1, 2 \cdots P\}$, a real-valued cost, $c(A)$, given by Equation (5.8). We assume $c(\emptyset) = 0$.

The Shapley value assigns the cost to each participant:

$$s_p = \frac{1}{P} \sum_{A \subseteq A_P \setminus \{p\}} \frac{c(A \cup \{p\}) - c(A)}{\binom{P-1}{|A|}}, \quad p \in \{1, 2, \cdots P\}, \tag{5.21}$$

where the summation extends all subsets of A_P not containing participant p (with one of the subsets being the empty set), thus resulting in 2^P summands. Note that the idea behind Equation (5.21) is assigning the average marginal cost to each participant, that is, the average increment of the cost that each participant adds to every possible coalition where he or she is included.

The Shapley value is the unique assignment that satisfies the following desirable properties:

1. *Budget-balanced*: $\sum_{p=1}^{P} s_p = c(A_P)$.
2. *Symmetry*: If $\forall A \subset A_P : c(A \cup \{p_1\}) = c(A \cup \{p_2\})$, then $s_{p_1} = s_{p_2}$.
3. *Dummy player*: If $\forall A \subset A_P, p \notin A : c(A \cup \{p\}) - c(A) = c(\{p\})$, then $s_p = c(\{p\})$.
4. *Additivity*: If we combine two coalitional games $(A_P,\, c_1)$ and $(A_P,\, c_2)$, in $(A_P,\, c_1 + c_2)$, then $s_p(c_1 + c_2) = s_p(c_1) + s_p(c_2)$.

Due to the exponential growth of the summands, computing the Shapley value using Equation (5.21) is impracticable for large P. In our research, we used the R package [130] to compute Equation (5.21) up to $P = 10$. For larger values of P, we used a Monte Carlo simulation (see e.g. [103]). We provide our source code in the public repository [31]. The Shapley value is the unique assignment that satisfies the following desirable properties:

1. *Budged-balanced*: $\sum_{p=1}^{P} s_p = c(A_P)$.
2. *Symmetry*: if $\forall A \subset A_P : c(A \cup \{p_1\}) = c(A \cup \{p_2\})$, then $s_{p_1} = s_{p_2}$.
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4. *Additivity*: if we combine two coalitional games $(A_P,\, c_1)$ and $(A_P,\, c_2)$, in $(A_P,\, c_1 + c_2)$, then $s_p(c_1 + c_2) = s_p(c_1) + s_p(c_2)$.

Due to the exponential grow of summands, computing the Shapley value using (5.21) is unfeasible for large P. In our research we have used the R package [130] to compute (5.21) up to $P = 10$. For larger values of P we have used a Monte Carlo simulation (see e.g. [103]).

Chapter 6

Scalability in community networks

Preface

In this chapter analyses the scalability of CNs once many of these initiatives have shown the feasibility to build bottom-up network infrastructures around the world. Scalability in the design of CNs makes the difference between an infrastructure for limited membership clubs and a general-purpose production network for an entire population. Following the perceptive introduction of the topic and an analysis of the reasons for scaling up, the rest of the chapter is structured in two main parts. On the basis and comparison of our studies of Guifi.net and other CNs, in the first part we elaborate on the overall strategies from what we consider the four main dimensions of CNs: social, legal, economic, and technological dimensions, along with an analysis of cross-disciplinary factors. The second part presents a selection of patterns and anti-patterns that, as a whole, cover the vast majority of the components of the generalisation of the Guifi.net's internal organisation architecture.

6.1 Introduction

Once an initiative has proven its initial feasibility and delivered results (see Chapter 3), developed a solid governance in response at the challenges faced or anticipated (see Chapter 4), and developed a sustainable economic model that allows investment, deployment, maintenance, revenue streams and cost sharing (see Chapter 5), the next challenge is in terms of scale.

Scalability is a property related to the ability or sensitivity of a system to accommodate change in a relevant dimension. Scaling up relates to *an increasing number of elements or objects, to process growing volumes of work gracefully, and/or to be susceptible to enlargement* [23], but finding the right size and determining how the size in terms of orders of magnitude affects a system are challenges.

The aforementioned terms are widely used in the fields of computer science, telecommunications, and economics. In the field, the capability of physical systems and theoretical designs to handle a growing amount of work is commonly analysed in terms of resource consumption (time, CPU, RAM, and storage). The potential to be enlarged falls into two broad categories: horizontal scaling, which refers to the addition of nodes, and vertical scaling, which refers to the enhancement of existing nodes [161]. In economics, the term is usually applied to companies or business models to denote their capacity *to maintain or even increase its level of performance or efficiency even as it is tested by larger and larger operational demands* [89].

In this chapter, we elaborate on the scalability of CNs understood as the potential of these initiatives to deliver connectivity to their current members and to extend it to larger populations.

Particularly, we look at scalability in the design of CNs, arguing that, despite starting out tiny, pioneers should be aware of and plan for the size and characteristics of the potential group of participants and beneficiaries. That makes the difference between clubs (see Section 2.4) –organisations restricted to a few– from institutions for the common good –extensible network commons able to accommodate, serve, and benefit all members of a given community or area. [1] We base our analysis on our personal experience in Guifi.net combined with our knowledge of other CNs with the sole ambition to share our thoughts and vision.

The reader must be aware that a comprehensive analysis of the factors that may influence the scalability of any of the initiatives that can be regarded as a CN and how they should be faced is out of scope. Solid scientific evidence on these aspects is needed for the consolidation of CN as a worldwide alternative for its target population because, today, despite the existence of models and many promising practical experiences, CNs as a whole are not yet mature enough to deliver such an ambitious objective at the scale of demand. We hope the research community will tackle this challenge further, as our contribution aims at contributing positively, setting the basis for such an all-important debate on CN scalability.

The rest of the chapter is structured as follows. In Section 6.2 we discuss the reasons CNs should scale and the general strategies to achieve it. In Section 6.3 we analyse the reasons and strategies to tackle scalability more in-depth. In Sections 6.3.1 to 6.3.4 we do it from the perspective of what we consider to be the four main dimensions of CNs: social, legal, economic, and technological[2] dimensions. In Section 6.3.5 we make a cross-cutting analysis to address the relevant aspects that do not fit well in the previous thematic approach or that needed further discussion from another point of view. The arguments are illustrated with experiences and lessons learned by Guifi.net and other CNs and each of them concludes with a footnote with a proposed set of activities to be completed by the reader. We conclude our analysis and the section in section 6.3.6 with a review of the main actions that global external organisations can take to boost the uptake and development of CNs. In Section 6.4 we present a set of most common and relevant organisational patterns that apply to any CN or even artificial material commons, and present it in an structured way. These emerge from specific experience in Guifi.net or close CNs and, after generalisation, can be applied in re-engineering CN practices to promote the benefits of patterns or prevent the drawbacks of anti-patterns. Finally, we present our conclusions in Section 6.5.

6.2 Reasons for scaling up

There are four main reasons for scaling up. The first is the willingness to share a satisfactory experience with new people. Indeed, the keenness to share is one of incentives most commonly invoked by many contributors for participation [O1]. By getting involved in a CN, the participants not only have the opportunity to help their peers but also help extend the Internet, which has fostered sharing and collaboration in an unprecedented manner. In addition, the larger the CN, the more opportunities to share one's experience and to learn from others. In the specific case of Guifi.net, sharing knowledge and resources and helping neighbours were the fundamental conditions set by the mayor of the village where the CN was born (Gurb, Catalonia) to give

[1] *In the past, networking infrastructures were considered a club good (excludable and virtually non-rival as a commercial service) provided by for-profit ISPs to those fortunate to be in coverage areas and willing to pay the service fee. CNs are a social response to the wide recognition of connectivity as a basic human right, and therefore the network infrastructure connecting people becomes non-excludable.*[O8]

[2] In fact, from the technological perspective, CN are not so different from any other network deployment. Even though, technological aspects too often mistakenly attract the attention of the debate.

access to the council's DSL, the only existing Internet access in the village at that time. These conditions aligned with the spirit of the promoters of the project.

The second reason relates to reaching economic sustainability. To persist over time, any project must grow at least to the point where the contribution of beneficiaries meets the resources required to maintain the activity, the so-called break-even point in economics. In the case of the CNs, the costs to be covered include at least the hardware (routers, antennas, cables, etc.), but from a given time, manpower costs should also start being included, as the projects that are purely based on voluntary work do not scale well and tend to decay.

To attract enough users to reach the break-even point, CNs must offer value, that is, competitive services that maximise the satisfaction of the user needs in comparison to competitors. In turn, competitive services can only be offered after a minimum outlay, meaning that only projects over a certain budget are viable in the long term. In addition, scaling up also helps reach the critical mass to counteract the demotivating effect that the stabilisation of the infrastructure and the access to good quality Internet access may have over those initial members who were looking for technical challenges.

The third reason is that growth strengthens self-protection. The larger the community, the larger the community knowledge is and the higher the chances to provide mutual support are. Moreover, the stronger the dependencies on a given resource, the more difficult is to be obstructed by potential adversaries. Social pressure is a recourse to warn against situations of injustice, like unfair and discriminatory treatment by public bodies or private companies. For instance, Guifi.net has used its presence in the territory and its social support to denounce malpractice cases by public administrations and by the incumbents.[3] As a result, many public administrations had to backtrack on policies that were manifestly abusive and discriminatory, like levying a tax only on new operators after the established operators deployed their networks and the incumbents had to review their initial positions.

Finally, yet importantly, larger scales increase efficiency and are conducive to economies of scale. Some cost savings, such as in procurement, are quite predictable. Others, though, are not so obvious beforehand. As an example, wholesale Internet access is generally significantly cheaper and of much better quality than domestic connections; thus, a CN makes a qualitative leap when it is able to switch from retail connections to wholesale and, at the same time, it reduces costs. Similarly, quantity discounts are common among hardware providers. In addition, less obvious savings appear with the increase of the activity within the CN ecosystem. For instance, in Guifi.net, we have observed that, as economic activity increases, the professionals tend to specialise, fostering their expertise and improving their productivity. The repetition of tasks leads to optimised procedures and good practices that can be collected, documented, and some even automated. In turn, these optimisations enable further growth.

Furthermore, the spirit of sharing that characterises CNs amplifies the ordinary positive effects of growth, as any progress (in software, methodology, etc.) is immediately available to all practitioners –also from other CNs– and the adoption rates are usually very high. Sometimes, the spirit of sharing is so deeply rooted that practitioners are not even aware of the benefits that come along with it. In Guifi.net, for instance, the contributors are so used to automatically getting the configuration parameters of their devices through the website that is highly likely

[3] For instance, the first connection between Guifi.net's fibre deployment and the public fibre network of the Catalan Government was only achieved after pressuring the authorities with roadblocks in Sunday afternoons to show the visitors that despite the two infrastructures were side-by-side the Catalan Government was rejecting to connect them.

that many of them are not even able to estimate the resources needed to do so manually, which is probably no longer possible given the size of the network.

However, growth has some drawbacks as well. As the community becomes larger, information exchange and personal interaction across the community may become costlier and require additional coordination to avoid overload. A larger community may increasingly need to stipulate and formalise procedures to reduce the burden of otherwise unstructured interactions across a larger set of participants without increasing complexity. Larger constituencies may benefit from distributing functions and responsibilities and more clearly defining the organisational structures. Thus, the challenge is how to accommodate growth with coordination mechanisms that keep the community equally or more effective in delivering benefits to its participants without disempowering them by centralising decision making or overloading them.

6.3 Multidimensional approach

There are many approaches and factors to be considered when it comes to quantifying the size of a network. Our viewpoint is from the socio-economic value of the infrastructure; thus, the most representative indicator is the number of beneficiaries. The maximisation of this indicator with respect to the size of its constituency, that is, the potential beneficiaries, should be the target of any non-speculative infrastructure[4] of any kind. Importantly, the strategies leading to this type of maximisation must always be subordinated to the principle of social fairness, which includes respect for the environment, fair wages and working conditions, inclusion and non-discrimination of minorities and the vulnerable, etc.

To maximise the number of beneficiaries, the ultimate goal of any action, direct or indirect, must be either the expansion of the network (acquisition of new beneficiaries) or the improvement of the services delivered (loyalty of beneficiaries). These actions must be prioritised by the principle of opportunity and repayment maximisation, again, carefully combined with social fairness goals. Direct actions include the deployment of new nodes (horizontal scaling), enhancement of the existing infrastructure through technology upgrades or migration (vertical scaling), and the improvement of services offered to the participants. Indirect actions include improvements in the governance system (licensing, agreements, procedures, etc.), development of software tools, dissemination activities, stakeholder engagement, and influencing public policies and regulations, among others. As discussed in the following section, the realisation of CNs generally leads to disruptive innovation. As such, it can create relevant resistance on the part of well-established interests, which see any innovation that they cannot control as a threat. Countering the strong influence of these interests demands cleverness and perseverance. In this respect, the basic literature on strategies and tactics offers appropriate tools. For instance, in Guifi.net, the frequently used tactics of distributed action, rapid action, and exploitation of apparently minor opportunities to provoke significant changes are very reminiscent of the lessons from Sun Tzu [162].

In the following sections, we deepen the analysis on the factors influencing scalability. We structure our study around the four main areas that, in our opinion, every CN should consider, followed by a section analysing the cross-disciplinary requirements. We elaborate on external and internal threats and on internal mistakes and make recommendations based on our experience and research on Guifi.net and other CNs.

[4]Speculation has its own logic which is out of the scope of this chapter, but certainly does not have social good as its ultimate goal.

6.3.1 Social considerations

The social objectives are the main shaping factors of any project. Computer networks, aiming at an experimental network for hackers,[5] have very different implications at all levels than aiming at a general-purpose production network for an entire population. In the same manner, the implications of aiming at a network for dozens of users are not the same as aiming at one for every one of the hundreds, thousands, or millions nearby. The social objectives do not need to be necessarily prescribed since the beginning and might evolve over time,[6] but an early tentative definition[7] facilitates initial progress because many of the critical decisions needed to move forward depend on them.

Moreover, explicit definitions and clear positioning on fundamental relevant topics (e.g. support of the right of participation in the decision-making process) are needed to ensure that there is common ground among the participants on these topics for an effective progress. Nevertheless, it is important to note that the requirement of consensus must be strictly restricted to the truly relevant matters to avoid unnecessary and undesirable exclusion.[8] One of the first decisions to be explicitly made with a determinant influence on the nature and potential of our project is the choice of the socio-economic model for the infrastructure: the network.

To this end, we propose to learn about the predominant ones considering their (real) social objectives[9] and understand their (unwanted) implications[10] and to raise a number of questions, such as whether we envision the network to be self-sufficient by allowing economic activity and, if so, under what conditions (e.g. do we allow profit making? Do we allow competition?). Our social objectives do not match those underlying the traditional network models. Thus, finding a suitable socio-economic model requires us to be innovative. For instance, it is clearly incompatible to pursue a user-centric network and to choose a model prone to speculation. The topic to address in this decision-making chain relying on social objectives is to select the governance model.

We again propose to review the existing solutions and address some questions, such as who may participate in the CN governance, how decisions should be taken, what the usual practices emerging at the local level are in similar initiatives, etc. As in the previous case, given the divergence between social objectives, most likely we will have to be innovative because, arguably, the top-down traditional governance practices will not satisfy our needs.[11] Such divergence in aims and fundamental approaches leads to the emergence of disruptive models and practices.

In Guifi.net, for instance, the social objective is stated as "a fair Internet for everyone."[12] At first sight, it may resemble the motto of any of the existing large telecom companies, but

[5]It is not our intention to establish a classification schema for CNs, but for us such restrictive initiative does not meet the minimum requirements to be labelled as CNs.

[6]See the discussion on the iterative development process in Section 6.3.5.

[7]We can start being conservative and then become more ambitious.

[8]The example of open content is illustrative. A sympathy for open materials and services can be presumed among most of the participants. Nonetheless, in a participatory project the rule on openness must and can only be imposed on the content and services that are strictly necessary to run the project but not on others contributed by the members.

[9]For instance, maximization of the dividend to shareholders.

[10]For instance, that the network resources and customers are mere speculative assets.

[11]Strategies of organizational maturity: debate (learning), construction (testing, implementation): scaffolding and consolidation, replication (in new areas, communities). Related to Ostrom's principles for sustainability (every time, short term) and adaptability (to changes, medium or long term) [112].

[12]"*Una Internet justa per a tothom*" in Catalan.

the terms fair and for everyone have implications that few of them would ever fully implement. Regarding fair, one could argue that the concept may hold different meanings for different people, but certainly it is quite apart from the real underlying principle of the business models of the current dominant telecom operators, which is the profit maximisation of the investors.[13] In any case, the other Guifi.net motto "neutral, open and free network"[14] makes the implications of the term clear on the properties of the network to be implemented. The use of *for everyone* leaves no room for interpretation: it means exactly for everyone regardless of one's individual capability to afford it or not.

From the socio-economic model viewpoint, in Guifi.net, the infrastructure is conceived as an open CPR, and it is basically governed following Elinor Ostrom's (1990) principles. The Guifi.net community has followed a long process to establish its theoretical basis. The concept of CPR and Ostrom's principles had to be adapted to suit the specificities of an artificial resource (the network) because the previous experiences –and the academic studies– were restricted to natural resources.[15] In conjunction with the governance system, the stakeholder groups and their rights and duties must be defined. Special care should be dedicated to the definition of the non-transferable roles of each stakeholder to ensure that there are no intrinsic incompatibilities or uncovered tasks.

The solution should strike a clear distinction between for-profit and not-for-profit contributors, as there are tasks that cannot be transferred from one to another. For instance, we argue that core governance activities must be under the responsibility of not-for-profit participants (to avoid conflicts of interest), while delivery of services to customers should be done by for-profit actors (to prevent market distortion).

Lastly, it is clear that, to create value, any network infrastructure must be connected to the Internet. Even more, it is not a matter for the active participants to decide whether the users may have access to the Internet or not. Their duty is to ensure proper Internet connectivity and let the users decide for themselves.

6.3.2 Legal considerations

The telecommunications sector is a highly regulated area, and CNs cannot afford disrespecting established rules, as the lack of compliance to the legal framework would only jeopardise their development. Although CNs are local initiatives and thus develop their activity under diverse legislative and regulatory frameworks, some practical guidance is applicable to nearly all contexts, regardless of the specific domestic legislation. The first is to acquire knowledge on the legal system as a whole: how the legal system is structured where the CN will be developed, what the fundamental components are, such as the authorities that can regulate and bodies that can legislate, and how they relate to each other. The internalisation of this knowledge is crucial given the existing strong economic interests of the telecommunications sector and the influence that their lobbies usually enjoy.

The telecommunications sector is very dynamic with a global trend towards liberalisation. As a result, the legislation is constantly evolving, making compliance even more complex. This changing scenario is harnessed by a wide range of lobbies aiming at shaping the new rules towards

[13]This explains overbuilding (deploying excessive capacity) while there are underserved areas at the same time, the business concentration, etc.

[14]"*Xarxa oberta, lliure i neutral*" in Catalan.

[15]These adaptations the most important contribution of Guifi.net at the theoretical level; at practical level, it is the size achieved.

their interests (influencing policy) and influencing the public perception of these rules when they are not satisfied with the existing provisions (manipulation, FUD[16]). Importantly, CNs organisers willing to lobby for legislation and regulation facilitating CNs should consider that legislative and regulatory competences are often distributed between several public administrations, and this situation increases the difficulty even more for the general population to participate in public affairs, while favouring the activities of those interests enjoying well-funded lobbying organisations. In addition, CN organisers should be prepared for the frustrating reality that critical decisions may be left undecided or in the hands of less than expeditious bureaucratic processes.

Under these circumstances, CNs have no other choice but to be smart and creative. A good knowledge on legal matters will facilitate a clear understanding of the limits posed by our legislative frameworks, that is, what is allowed and what is not. It is important to reiterate that the public understanding on these matters is typically confused and may even reveal contradictions between what it is generally assumed to be legally possible and what the law really says. Furthermore, in several occasions, we have realised that just a fraction of the true potential of the legislative framework is put into practice. The rest remains unexplored and unrealized.[17]

This generalised lack of knowledge and the unexplored possibilities of existing legislation bring us to the first line of action, which is to make creative proposals, working hand in hand with public servants whenever possible, and pursuing win-win situations through proactive actions. This must always be the first choice for CN members because positive attitudes are undoubtedly much more effective than any confrontation.

These win-win tactics, which should not be restricted to legal matters but should be extended to the other areas, have been very satisfactory for Guifi.net. As an example, the Guifi.net

[16]FUD: Fear, uncertainty, and doubt. A clear example that illustrates the bad practices by public authorities and the private sector is the case of the Torelló council against Guifi.net. The first key point is that it should have been Guifi.net against the Torelló council because it was Guifi.net who complained about an abusive tax for ducts usage, but the Torelló council took advantage of its longer experience to open a case first at the regulator with a question that was not the substance of the matter. Instead of asking about the prices, they asked about the right to levy taxes on public infrastructure usage. This right was something that Guifi.net never discussed and it was not until the allegations made by Guifi.net that the prices were considered as well, which was the question really disputed. To this, the council alleged that there had been an error in the calculation of a parameter and proposed a newer one which resulted in a fair amount. Unfortunately, the regulators resolution (available at `https://www.cnmc.es/sites/default/files/1538376_7.pdf` only in Spanish) is written in a way that makes the reader think that it says that the council is right because it answers the initial question: yes, councils have the right to levy taxes on public infrastructure usage, which, again, is something that Guifi.net never discussed and it is just later in the text body that addresses the tax quantities issue, and just stating that thought the process of the dispute resolution a technical error for its calculation was fixed.

Despite it is a clear case lost by the council (they had to change the prices) it is being presented by the council as well as by the competitors as a case lost by Guifi.net because they still claim that Guifi.net wanted to use the public ducts without paying.

[17]For instance, one of the keys to success of the XAFOGAR (see Section 3.6.2) project has been a new finance scheme for the municipalities. This perfectly legal instrument ensures the capacity of the municipalities to make sure that the public money is allocated to build commons network infrastructure, that is, for what it is intended for, and it is not captured by traditional telecoms that build private infrastructure. In summary, the innovation is to allocate the money to an NGO instead to a private company directly through a public contracting process because these processes are completely dominated by the big telecoms. Nevertheless, the public procurement law direct allocation to NGOs. Through this novel procedure the Guifi.net foundation, which is only allowed to deploy network in commons, receives certain amounts of money from the municipalities under the commitment to deliver connectivity to the municipal buildings. This money represents just a fraction of the total project budget, but it is helpful to start and at the same time proves commitment of the local authorities to third-party participants such as beneficiaries or investors.

foundation, in collaboration with some small city councils, developed an ordinance to make the coexistence of the public, propriety, and commons usage of fibre ducts compatible.[18] Nevertheless, it is important to be on guard against malicious collaborations, and CN members should always consider that public administrations and regulators may be constrained by special interests.[19] In this respect, we have observed delaying tactics aimed at harming the project, for instance, by giving time to the competitors to deploy first.

The second line of action is to lodge complaints using all the resources available (ordinary courts, higher courts, national regulatory agency, etc.), thus exploiting reactive actions. These legal actions must be used very selectively because they might be costly in both time overruns and money. Nonetheless, they are worth doing because they can have a strong effect on the success of the case. They establish legal precedents and demonstrate maturity, strength, and capacity for action on the side of CNs.

The third line of action, influencing policy-making processes, is also very demanding but must not be left unattended because, to a large extent, the success or failure of our project depends on the laws to be passed. A single modification can kill an initiative or can drastically boost it. For instance, in the regulation of access to the backhaul, the introduction of a discriminatory fee on a resource, such as one based on distance, directly makes remote rural projects unfeasible, while a fixed price taxation with low prices fosters the rise of connections not only in rural areas but also in urban areas, as they become denser.

The number of policymaking bodies and the diversity of their competences demands distributed and coordinated action among the CNs. To be efficient, the international and regional activities must be led by international specialised organisations (like La quadrature du net[20] in Europe, APC,[21] and ISOC globally) to better cope with the requirements of this field, which is full of subtle details unknown to the layman. Furthermore, CN members must be ready to provide support and become involved in specific actions when needed. Conversely, national and local policy influence must be conducted by the affected CNs, possibly being endorsed by international organisations.

The power of apparently small successes should not be underestimated. Even small victories should not be kept unpublicised but should rather presented to other legislators and regulators for their consideration. For instance, the 2G spectrum-licensing scheme for indigenous communities developed by the Mexican government together with Rhizomatica[22] is currently being adopted by other Latin American states[23] with the help of the respective CNs.

Civil disobedience or disrespecting rules is something that we can only understand for very specific cases, where rules or their application are patently illegitimate or unjust and should

[18] Available at http://people.ac.upc.edu/leandro/docs/ordinancePEIT-rev14-en.pdf (outdated version – latest version, in Catalan, available at https://fundacio.guifi.net/web/content/2322). Unfortunately the ordinance could not have been passed by any municipality despite many of them are interested in doing so due to the (deliberate) lack of a clear response of the upper public authorities. In this case the administrations involved are the Ministry of Industry and the regulator. They always respond at the limit of the legal period of time allotted, with irrelevant observations or further requests, etc. but never entering into the substantive debate. This is terribly harmful because in the meanwhile the traditional telecoms are deploying in the same areas, in most of which there is market for just one deployment.

[19] For an analysis of the regulatory capture phenomenon, see e.g. [27].

[20] https://www.laquadrature.net/

[21] www.apc.org

[22] https://www.rhizomatica.org/

[23] At least in the case of Colnodo, with the government and Telecom regulator in Colombia.

never be considered a means to consolidate an illicit situation. Nonetheless, it is indispensable to distinguish between truly illicit actions and those that are deliberately presented as such by some stakeholders but, in reality, are perfectly legal. A clear example is the position of the Spanish incumbent against the usage of the telephone poles by Guifi.net to deploy fibre cable. As long as the technology used by Guifi.net was limited to WiFi, the position of the incumbent towards the initiative was mainly that of disregard, probably with the objective to make the CN look irrelevant. However, its position completely changed when Guifi.net started deploying fibre cable in 2009.[24] Since then, the incumbent has been hostile and the denial of Guifi.net's rights to use the existing telephone poles has been one of the most-used weapons by the incumbent.

On the one hand, this combative attitude clearly demonstrates that established telecommunications operators feel threatened by the emergence of CNs. On the other hand, the fact that operators, who certainly do not lack legal advice and funds, have never initiated a lawsuit in court shows that they are very aware that the utilisation of the poles by Guifi.net is completely legal.[25] The certainty set by a judgement would be fateful for the operators' interests; thus, the tactics of coercion and misinformation seem more profitable, as established operators usually enjoy relevance and influence. The Guifi.net example demonstrates that, when dominant operators applied these tactics, only the most motivated supporters stayed with Guifi.net, while the rest were frightened.

On another front, the conception of the network as a CPR has proven to be a very powerful legal shield against speculation. The network is a crowdsourced CPR from which the contributors can withdraw and have the right to be compensated for their contributions, but those who stay have the right to retain the infrastructure. So, as long as a participant is staying, the infrastructure remains in commons. In Guifi.net, the whole system is secured through the Foundation, which has the ineluctable mission[26] to protect the network commons.

6.3.3 Economic considerations

The development of an economic system with revenue streams and economic exchanges is fundamental to achieve sustainability and thus to expand the CN at a later stage. Even in resource-limited environments where external funds are needed to initiate the project or to contribute and maintain it over time, the development of a local economy is the most effective way to ensure the healthy survival of the network and its successful evolution, that is, to expand in the quality of services and the number of users served.

Any strict and self-imposed limitation of the scope of the project in terms of the area or the type of population to be served must be avoided. A project restricted to unprofitable regions or certain excluded segments of the population will rarely be self-sustainable, and it will most probably depend on external help; thus, its self-determination will never be achieved[27] [15, 16]. Limitations can be induced by third-party agents (external threat) but are also sometimes

[24]Obstructive strategies such as letters, minor litigation, etc. to create doubt, lengthen processes to delay and discourage deployments, while avoiding any clear public decision that would clarify competition.

[25]Reinforced by the adoption of the The Broadband Cost Reduction Directive (Directive 2014/61/EU) of the European Parliament and of the Council on 15 May 2014.

[26]The Catalan legislation establishes that a Foundation cannot change its mission and in case of dissolution of a foundation its assets are kept under guard by the Catalan Government until they can be reallocated to another entity that respects the conditions under which the assets were donated to the initial organisation.

[27]Self-determination in combination with the disruption capacity is the most frightening for the well-established business.

self-imposed (internal mistake) due to misconceptions.[28] Some of the external attempts to limit the scope of CNs are also due to more misconceptions,[29] but others may be intentionally instigated by adversary lobbies. Restrictions due to misconceptions can be prevented by raising awareness, for instance, by raising the question regarding why we should limit the potential of something positive. On the contrary, intentional attempts to limit scope must be countered by other means, such as judicial disputes, policy advocacy, etc. It is also important to note that access to profitable segments are not only needed to ensure sustainability but also to be able to implement redistributive policies because it will be the users of these segments that will generate the surpluses to sustain these policies.

In addition, to have access to profitable markets and to enable economic activity and thus investment, trust is needed. Initial investment by pioneers has several positive effects on building trust and increasing predictability. First, they allow covering the initial costs of the initial installations. These initial installations, in turn, allow the start of delivering services, which make repaying the investment possible, and they can be used as working examples in the dissemination activities aimed at expanding the network. Another positive effect of the increased trust resulting from the initial investments is that they are considered proof of commitment by new investors, thus facilitating new funding rounds.[30] It must be noticed that, currently in Guifi.net, the term investor usually refers to anyone putting money in the network, regardless of whether he or she does it to obtain connectivity (final users) or as an economic benefit either directly through an interest (money lender) or indirectly through creating business opportunities (service providers).

Transparency is a key component to create trust. In Guifi.net, transparency about what is done and predictability about what can be done are achieved through clear interdependent rules of (i) governance, (ii) recognition of investments, (iii) inventory of network assets, (iv) costs sharing, (v) monitoring of network resources consumed, and (vi) dissemination of good social, economic, technical, and legal practices.[31] Predictability is related to accountability (auditable statements for transparency that include investment, consumption, expected return of investment, depreciation, and margin) and the ability to plan and forecast social and economic impact and growth based on whatever goals and metrics are critical. For instance, cost accounting allows determining an estimate of the unit cost to expand the network to a new location or maintain a unit of network infrastructure, which determines the investment required and the critical mass for feasibility as a CN expands. Predictability and planning relate to risk mitigation, which becomes more critical as CNs grow.

Furthermore, organisational resilience is a concern, particularly for a commons infrastructure. In a cost-oriented ecosystem, reserve funds in the form of monetary deposits from participants are a key instrument to face and mitigate financial risks. Risk mitigation plans and the corresponding reserve funds must include the response to the technological evolution and hardware obsolescence. As a reference, the depreciation period of electronic components (WiFi, Ethernet, and optical

[28] Fortunately, the term wireless is not used any more to refer to CNs as it clearly was an unfortunate self-limitation towards a specific technology, which –paradoxically– also implied the violation of the network neutrality.

[29] There are still too many well-intentioned international organisations that circumscribe CNs to unprofitable spheres.

[30] The full-cycle of a funding round was described in Guifi.net in 2007: (i) dissemination, (ii) techno-economic proposal, (iii) crowdfunding, (iv) execution, and (v) re-start the cycle (`https://guifi.net/node/7934` available only in Catalan and Spanish)

[31] See [P2] for a diagram and further explanations regarding these elements.

fibre) should be no longer that four years, and the cabling (copper and optical fibre) from 10 to 15 years.[32]

In Guifi.net, the conception of the network as CPR has enabled a flourishing non-speculative economic system based on services in which over 30 Internet service providers (ISPs) are offering their services on equal terms to tens of thousands of customers and coexist with many other stakeholders, such as volunteers, public institutions, etc. From the economic perspective, the CPR is a crowdfunded infrastructure because it is paid by its users.

6.3.4 Technological considerations

Technological matters must be addressed in accordance to social objectives. From this perspective, technological decisions must also be driven by the opportunity criterion to optimise the extension of the network and the quality of services offered. Furthermore, these decisions must be taken in line with the economic capability and legal possibilities.

Therefore, it is important to elucidate technology challenges from a neutral perspective. A given solution might be the right choice at a specific time but inappropriate at another time. For instance, fibre-optic technology has unrivalled performance characteristics. Nonetheless, it is so demanding in terms of CAPEX and deployment time that it is the suitable technology for starting CNs only in very special occasions. In most cases, WiFi is the right option to initiate a CN due to its good value for the money and the legal and administrative facilities, as there are radio-frequency unlicensed bands in most states. Nevertheless, a WiFi-only network cannot grow infinitely due to the OPEX costs and capacity constraints of these technologies. Thus, in the long term, the adoption of fibre is cost effective even for most of the small WiFi deployments and is necessary and indispensable for a network that is growing.

The potential congestion of a resource (routers, links, etc.) is not a threat to combat with restrictions but an opportunity to improve the network. For instance, in Guifi.net, the rule is to double capacity when the usage exceeds 50 % of the capacity. The additional capacity enables better services for the current users, attracts new users, and makes the infrastructure more resilient because the spare capacity can be used to mitigate the effects of planned or unplanned outages in other segments of the network.[33] The challenge is to turn the demand for these assets into resources to enhance them. To this end, we need procedures to know who is using them and in which proportion and how to contact the users, gather the contributions, and track their usage, etc.

Technologists must provide effective tools –mostly software– to develop and implement not only the aforementioned procedures but also many others that are crucial for the healthy development of CNs, like those mentioned in the section of this chapter dedicated to economic matters. Most likely, the fulfilment of the social objectives will entail the publication of the source code (free software) and the data (open data), obviously in compliance with the law.

From the network architecture perspective, it must be understood that all components (last mile, backhaul, backbone, and interconnection) play a critical role in delivering connectivity to the

[32] These are pretty conservative estimations, especially for copper and optical fiber (electronics and cabling). The conservative estimations enable sound financial housekeeping and hardware reallocation policies. Cheaper deployment costs may increase maintenance costs (e.g. shallower or less protected fiber deployments accelerate deployment but increase the risk of cuts).

[33] Alternative paths allow to keep the network operational despite planned or unplanned outages. Monitoring, routing and load balancing mechanisms can automatically reconfigure the network to mask any effect.

users. Thus, they must be maintained in good condition and must be harmoniously engineered. Initial Internet gateways might be built by pooling consumer-grade Internet connections, but the sooner to access the wholesale market the better, not only for the reasons of economy of scale already discussed but also because, from the technological and management viewpoints, it implies major upgrades. Emergency and technology upgrade interventions must be scheduled to maximise the benefit of users served, but in the long run, the benefits must be extended to all users.

Community networks must exchange traffic with third parties in IXPs whenever possible, as peering (swap)[34] is better aligned with CNs principles[35] and network neutrality in general than transit (paid). From the management perspective, the community must ensure control over all critical resources (software and hardware), as loss of control of any critical resource might be misused to favour particular interests (internal attack) and jeopardise the collective interests of the CN community. For instance, in Guifi.net, we have observed that technical control over access routers from a given professional (see Section 4.2 and Section 5.2) has been used to harm the interests of competitors. In terms of content, CNs must promote the development and hosting of local content accessible locally and from the Internet. This way, not only does the content remain under the control of the community but it also increases the symmetry of traffic, which results in reduced interconnection costs.

6.3.5 Cross-disciplinary considerations

Community networks are likely to start out tiny, but their contributors must develop the strategic planning according to the target size of participants and beneficiaries. The strategic planning must have a holistic vision, the strategy to develop it, and the priorities and action plan to implement it (the so-called VMOSA).[36] Given that the composition of the initial group of *pioneers* has a determining effect on the initial choices, the character of the CN, and how it is perceived by the surrounding environment, special care must be taken to include representatives from different perspectives with different skills to reach a balance in terms of multiple dimensions that can represent a large community (e.g. gender, cultural, economic, and geographic dimensions). While some members may be more active than others, the involvement of all of them will help make the organisation more representative of the target community and therefore more suitable to serve their needs as it scales up.

Moreover, CNs develop their activity in such a demanding environment that, to be able to succeed, they need to take a holistic view, adopting a multidisciplinary approach without preconceived ideas beyond the driving principles that define the essence of the initiative.[37] That is, once the driving principles[38] are accepted, a rational attitude is the most effective to address

[34] The interconnection fees in IXP usually depend on the symmetry of the traffic exchanged (cheaper or even free with a balanced mix of content to provide and readers, while more expensive for only readers: also called eyeball networks)

[35] Technically speaking, internally Guifi.net is a fully distributed IX because its license makes compulsory to peer with the rest of participants.

[36] VMOSA: Vision (what aim), Mission (what and why), Objectives (what to accomplish by when), Strategies (how), and Action Plans (what change will happen). See `https://ctb.ku.edu/en/developing-strategic-plan-and-organizational-structure`

[37] In Guifi.net, for instance, decisions are taken by voting and not by consensus because in the past, the consensus process had been used to block the decision-making process because the blocked situation benefited the blockers.

[38] In this document we have discussed the driving principles as part of the social axis, but given their importance (they are the basis of the project) and their nature (they are indisputable – either one accepts them or not) they could have been analysed in a specific section.

the emerging challenges. Furthermore, from the risk management perspective, a multidisciplinary approach is optimal, as all areas or viewpoints previously discussed are equally important since any major failure in any of them would seriously undermine the whole project. Even more importantly, it would be difficult to find tasks or decisions to be made that would fit exclusively in one of the fields. For instance, the maturity level of a technological solution determines the amount of people able to actively contribute to implement it and thus the degree of dependency of skilled contributors, which is a social issue.

Decisions must be taken giving the highest priority to the less restricting options while trying to foresee the future consequences. Nonetheless, given that not all the consequences can be predicted beforehand and that decisions must be made to move forward, a compromise between design and planning tasks and actions on the ground must be found. Moreover, on the ground activities provide valuable knowledge –difficult to achieve otherwise– that helps to make better choices in the subsequent decision-making rounds.

An iterative and incremental approach with short iteration cycles enables finding a good balance between the need for design and planning and the need for action in a harmonious manner. It also allows us to rectify issues when needed without much loss of effort and to quickly integrate learning lessons from experience. The decisions of the subsequent iterations must be based on the objective assessment of the results of the previous ones (quality metrics). Thus, a continuous monitoring system is needed, and with such a system in place, quality assurance and quality assessment can be implemented. In addition, such formality and rigour also increases trust, which, as already commented, is essential to attract new investors and beneficiaries. Another reason in favour of short iteration cycles is that it allows the gradual introduction of changes in isolation, which is necessary to be able to well understand their effects. Lastly, changes must have specific and assessable objectives.

6.3.6 External support

The case of Guifi.net shows that a single CN can scale at least up to more than 100,000 beneficiaries with the latest networking technology[39] in a self-sustained manner. So far, we have analysed what practitioners can do to enlarge and strengthen their CNs. To conclude, we briefly discuss what are, in our opinion, the main external actions that can be implemented to support the development of CNs and ensure that they can develop all their potential to expand the Internet worldwide. External support is crucial to accelerate the development of CNs and make the efforts of their contributors more productive because, although many CNs are working to improve their procedures and methodologies, their margins are too narrow –if any at all– to make any significant progress at a world scale.

In our opinion, the most important thing is that these organisations also fully comprehend that CNs can be large-scale fully competitive networks and thus do not confine themselves to marginalised corner cases. From the legal perspective, the legislators and regulators must ensure at least the equality of treatment with the rest of the ISPs. Ideally, they should give preference to CNs given their openness and unequivocal social value and the wide range of positive externalities they trigger [15], but in any case, they should combat malpractice by commercial providers, such as predatory overbuilding or misinformation about their deployments.

[39] Other indicators for the health of the Guifi.net project: doubling inter-networking capacity (transit and peering) every 18 months, +30 microISPs, +20.000 customers for professional services, etc.

In economic terms, external funds should be allocated to develop a comprehensive platform (methodologies, databases, and software as well as training and seed funds) with global reach for supporting and assessing the creation and growth of CNs with regard to network design, monitoring, and management, project management, conflict resolution, etc. The development should follow an approach able to deliver operational products as fast as possible to make them available to existing CNs and to use them in all the deployments funded by international organisations, such as ISOC, Institute of Electrical and Electronics Engineers (IEEE), development agencies, etc.

Ideally, the development of the aforementioned platform could be led by an international organisation[40] commissioned to keep track of all CN initiatives around the world and to provide them technical assistance and assessment, while offering financial support. This international organisation could be funded with national universal access funds because their objectives are totally aligned and because the effect would certainly be more visible than any of the actions funded –and frequently failed– so far. Furthermore, universal access funds could also fund the deployment projects promoted by this organisation.

Lastly, international organisations must work to ensure that CNs have appropriate access to wholesale and backbone networks and to local IXPs, as these resources are critical for the healthy development of CNs. Nonetheless, they must also ensure that their actions do not (unintentionally) contribute to perpetuating the dominant position of the owners of these resources, as it could happen, for instance, if the access is achieved through a co-funding model or directly subsidising the connections. The right way to do so is to ensure that the owners of the infrastructure charge fair, reasonable, and non-discriminatory prices for their services.

6.4 Organisational patterns and anti-patterns

The idea of defining *organisational patterns* for CNs originates from the idea of a *design pattern*, the re-usable form of a solution to a *design problem* [2]. Patterns can be expressed in a *pattern language*, a method of describing good design or organisation practices or patterns of useful organisation within a field of expertise. Organisational patterns [132] and pattern languages can help people think about, design, develop, manage and use information and communication systems that more fully meet human needs. Conversely, anti-patterns are common responses to recurring problems that are usually ineffective and risks being highly counterproductive. We integrate this concept, which is well known and frequently used in software design, to supplement the effectiveness of the organisational patterns method.

Below, we present a selection of patterns and anti-patterns that, as a whole, cover the vast majority of the components of the generalisation of the Guifi.net's internal organisation architecture, which we take as a reference. Figure 6.1 shows this generalisation and how each of the patterns and anti-patterns relates to it.

6.4.1 Crowdsourcing/sponsorships (Pattern)

Problem Solving an identified bottleneck in a network infrastructure that affects one group of participants.

[40] It could be newly founded or operate as a section of an existing one.

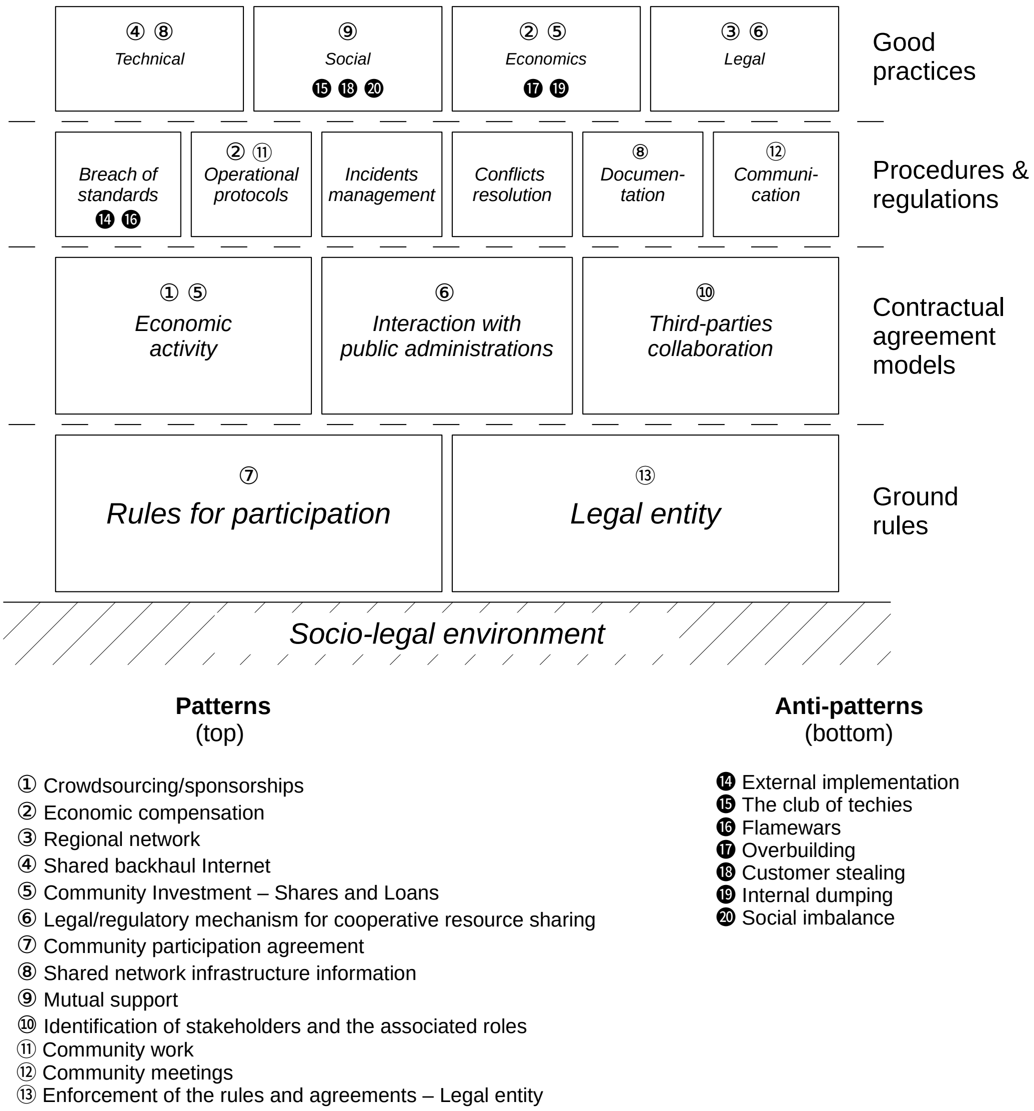


Figure 6.1: The mapping of patterns and anti-patterns to a generalisation of Guifi.net's internal organisation.

Context Community networks as they grow in an unplanned manner face bottlenecks that may be easily solved but depend on collective solutions that require contributions from several parties, particularly for solutions that benefit multiple participants (e.g. a village, region).

Discussion Before crowdfunding became popular, many CNs implemented crowdsourcing efforts to expand networks. This is particularly relevant for backbone nodes, that are more complex and expensive to deploy, requiring more economic contributions but also expertise from different people. These network segments can bring benefits to a wider range of people that may be interested in contributing to the funding and deployment of improved nodes and links.

Solution Once the bottleneck is identified and a solution agreed, a campaign is launched to collect contributions of economic, human and hardware resources with a soft or hard deadline. Once the objective is met, the contributions are collected and the solution implemented, and celebrated.

Figure 6.2: Web summary of one of the oldest calls for crowdfunding in Guifi.net for supernodes to cover key nodes in a village of the Osona county.

Example Guifi.net *apadrinaments* in Catalan (sponsorships) in date, status, priority, contact, description, items, payment instructions (January, 2006). See Figure 6.2.

References [P2].

6.4.2 Economic compensation (Pattern)

Problem Cost sharing, coordination of contribution and consumption, to achieve overall sustainability.

Context In remote or less populated areas, the demand and its growth may not be enough for small communities and ISPs to have access to long distance links, and therefore be competitive with larger operators.

Discussion Long distance links, particularly optical, have a high cost and may not be economically competitive for small or slowly growing demands. Pooling and compensation by sharing costs and expenditures across many participants may allow to bootstrap and promote the investment and consumption of network infrastructure among a larger number of participants. However transparency and auditability is required in the declaration and stipulation of costs, investments, consumption, and an authority to settle the required compensations oriented to cost, not to profit, considering return of investment, and quickly resolve conflicts.

The overall aim is to ensure the sustainability of the commons infrastructure, as all critical costs, investments and consumptions are declared, auditable and balanced.

Solution Declaration of investments and consumptions with periodic settlement (compensation tables).

Example The Guifi.net foundation compensation tables.

References [P3].

6.4.3 Regional network (Pattern)

Problem Regional backbone network connectivity across several islands of CN connectivity, avoiding higher costs of open Internet transit.

Context Remote, rural, under-serviced regions can benefit from larger and more resilient connectivity when islands of connectivity are interconnected. This is a critical attribute for long-term sustainability.

Discussion The concept of the IXP, an Ethernet fabric central to the structure of the global Internet, is largely absent from the development of community-driven collaborative network infrastructure. The reasons for this are two-fold. IXPs exist in central, typically urban, environments where strong network infrastructure ensures high levels of connectivity. Between rural and remote regions, where networks are separated by distance and terrain, no such infrastructure exists. A distributed IXPs architecture designed for the community network environment can help to scale up, and benefit from economies of scale and economies of larger population (the Metcalfe effect). This regional network can be used to bring the benefits of good interconnection across several separate densely connected areas. The interconnection can reduce the network diameter, increase the average performance and the reliability of the overall network. For the case of Guifi.net shown in Figure 6.3, it has brought huge improvements in performance, reliability, latency, as before the optical interconnection traffic had to go through many wireless links to get to distant nodes. Aside pure regional traffic, a typical use of a regional network backbone is sharing a backhaul Internet access, which is the next pattern. That regional interconnection can be obtained in different ways, ranging from wired or wireless long distance community links, or using public fibres in roads, or renting a leased optical link from a telecom provider or an open-access network provider.

Solution Sharing the costs of backhaul connectivity in a regional network to remote and underserved locations. This is an organisational vehicle that combines networks to generate economies of scale and a supporting network infrastructure. For example, a remote port into RemIX [O5] could be housed in a small cabinet atop a hill, or in space that is donated by a property owner for this purpose. Equipment is therefore restricted to the small and power-efficient. RemIX has four main components, consisting of a switching fabric, member autonomous systems (ASes), exchange transit and auxiliary services.

Example the Remix (HUBS) regional network, PoPIX in Guifi.net.

References [O5, P2].

6.4.4 Shared backhaul Internet (Pattern)

Problem Internet backhaul connectivity for a group of several islands of CN connectivity.

Context Remote, rural, under-serviced regions, can share the cost of good Internet connectivity across a regional network interconnecting small communities. This is a necessary attribute for long-term sustainability.

Discussion RemIX by the HUBS organisation and the Guifi.net foundation use the regional interconnection to share the cost of Internet access. In both cases several small CNs can share the cost and benefit from the economies of scale in contracting Internet carriers to reach the global Internet. For instance, in the case of Guifi.net, this arrangement allows to share among many Guifi.net participants 22 Gbps across four optical connections with at least three separate Internet carriers. This pattern depends on the previous two patterns: economic compensation, and regional network.

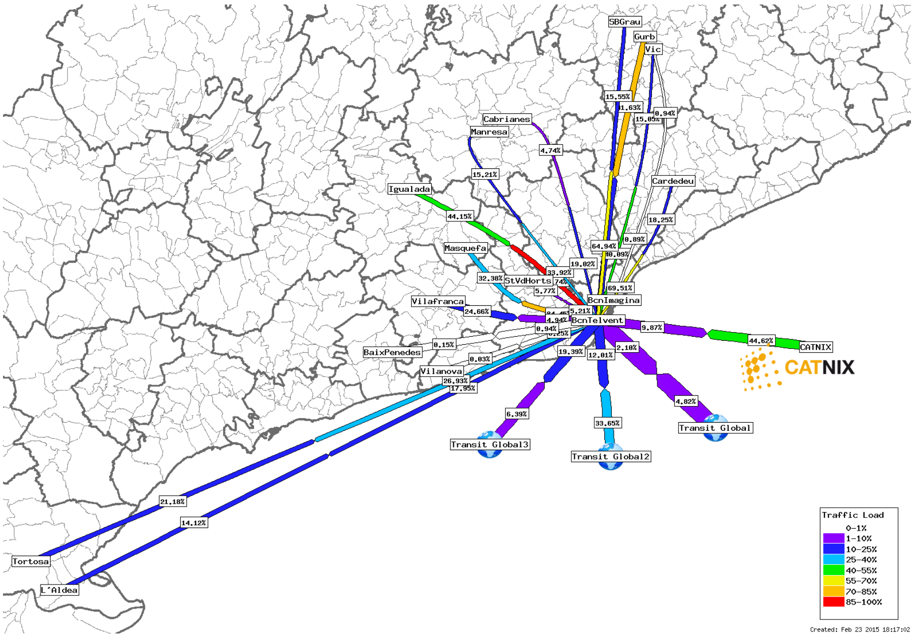


Figure 6.3: The Guifi.net PoPIX regional backbone, interconnecting several islands of connectivity.

Solution Sharing the costs of Internet access, relying on a regional network that allows to efficiently share the cost and the benefits of good Internet connectivity and benefit from economies of scale in Internet carriers, both in terms of higher speed at lower cost, and the possibility to have several separate connections that increase the reliability of the Internet connectivity.

Example Remix reference implementation in HUBS in Figure 6.4, Guifi.net carrier house cost sharing.

References [O5, 38, P3].

6.4.5 Community Investment – Shares and Loans (Pattern)

Problem Investment in a CN infrastructure.

Context Planning, initial deployment, expansion of networking infrastructure.

Discussion Funding sufficiently a network infrastructure allows its deployment to advance quickly and provide connectivity asap. A quick deployment not only benefits citizens but also leaves less room for overcapacity provisioning by competitors, typically incumbents that play strategies to deter competitors or reduce the coverage or feasibility of alternative operators when they emerge. Furthermore, a local networking infrastructure is a good way for citizens to invest in a resource that can provide good financial returns (interest) and contribute to add value to their houses and the region. Investments can also have good tax returns. At least for the case of B4RN in the United Kingdom and Guifi.net in Spain, investment in infrastructures or organisations (such as foundations) of public interest, has important tax incentives, with deductions of up to 30 % of the investment in B4RN. In the case of donations to the Guifi.net commons network under Law 49/2002 (rev.2015) for

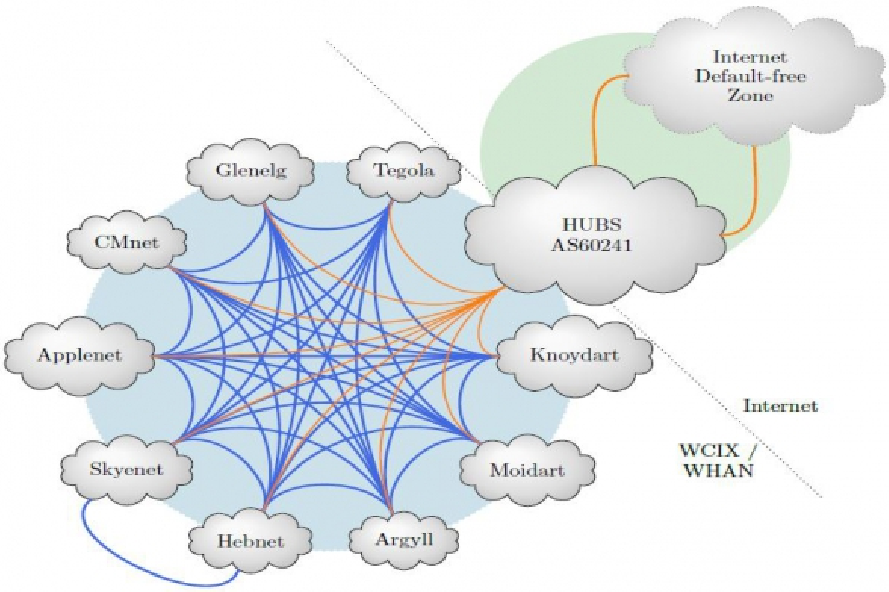


Figure 6.4: The Remix HUBS implementation

patronage, with the limit of 10 % of the total incomes every year, individuals can recover up to 35-75% and organisations can recover up to 40 % of their investment in CAPEX.

Solution Community shares, as a contribution/investment by citizens to fund the deployment of a network infrastructure. Returns in quicker access to connectivity, financial (interest) return, and tax return.

Community loans, subscribed by communities (collectively) from a common fund to be invested in the deployment of a network infrastructure in exchange of a return.

Example Broadband for the Rural North Limited was registered as a Community Benefit Society. It was formed to raise funds from the sale of shares to own and operate the network. However, much of the labour to dig trenches was supplied by local volunteers, who were rewarded with the chance to get a connection for their families or businesses, and some work is also rewarded in shares. Farmers and other landowners allowed free access for duct and the fibre within to cross their land.

Because B4RN is not-for-profit they only extend the network into communities where they are wanted. Each new area that invites B4RN in needs to raise the investment to cover the work and materials required for their area's installation.

Shares Every community's core investment is made up of shares, the value of which can be ring-fenced for supporting the build-out in their area. The shares are an investment, not only do they support the project in that community, but they have tax advantages and will pay a good return.

In a nutshell (See Figure 6.5 and Figure 6.6 and a sample share request form[41]):

- Minimum shareholding £100 / maximum £100,000.
- All shareholders are members of B4RN. One member one vote.
- Shares must be held for a minimum of 3 years.

[41] http://www.b4ys.org.uk/how-do-i-get-it/invest-shares/

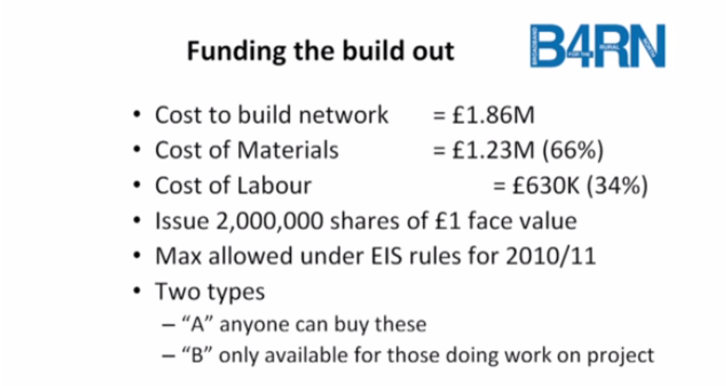


Figure 6.5: The B4RN summary of community shares.

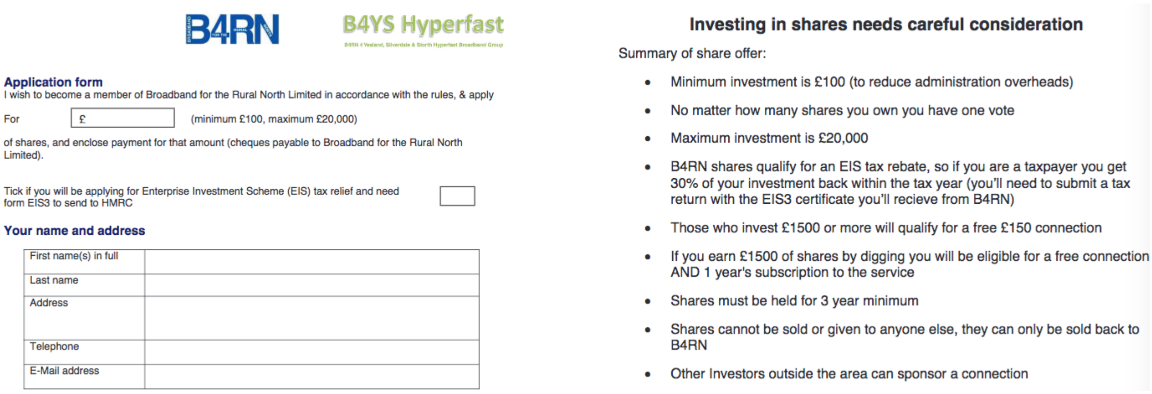
- Individual investors can claim 30 % tax relief (HMRC Enterprise Investment Scheme).
- After year 3, interest of 5 % can be paid out or reinvested.
- Some shareholders choose to invest £1,500 and claim free connection worth £150.
- Shares can only ever be sold back to B4RN at £1 each.

Loans B4RN also currently accept a limited number of 5 year loans from the community, paying 4 % interest. The minimum shareholding will be £100 and anyone purchasing this will become a member of B4RN and entitled to vote at meetings and become involved in the strategy of the society. The B4RN Investment Policy Statement rules investors may hold a maximum of £100,000 worth of shares in the B4RN. As a community benefit society a member is entitled to one vote irrespective of the number of shares they own. All shares are "withdrawable shares" and can only be sold back to B4RN. They have no potential for capital gains and will only be redeemed at face value. For the first three years the investment cannot be withdrawn nor will any interest be paid. From year 4 and onward annual interest will be paid at a rate which will be determined by the board after taking into account the financial position of the society and Financial Conduct Authority rules. At present our target rate is 5 % which will be paid in the form of additional shares credited to the investor's account. From year 4 onward investors may apply to withdraw their investment. We intend to put aside an amount each year to fund these withdrawals. However the amount available will be subject to the company's trading position and will be at the discretion of the board so there is no guarantee that it will be sufficient to meet all demands.

The shares issue is designed to be compatible with the tax office Enterprise Initiative Scheme which gives a 30 % tax relief against the value of the shares purchased.

References B4RN Resources for investors[42] and videos explaining the project and investment plans[43].

[42] https://b4rn.org.uk/resources/
[43] https://b4rn.org.uk/b4rn-launch-video-courtesy-of-lunar-creative-video/



B4RN B4YS Hyperfast

Application form
I wish to become a member of Broadband for the Rural North Limited in accordance with the rules, & apply

For £ (minimum £100, maximum £20,000)

of shares, and enclose payment for that amount (cheques payable to Broadband for the Rural North Limited).

Tick if you will be applying for Enterprise Investment Scheme (EIS) tax relief and need form EIS3 to send to HMRC

Your name and address

First name(s) in full	
Last name	
Address	
Telephone	
E-Mail address	

Investing in shares needs careful consideration

Summary of share offer:

- Minimum investment is £100 (to reduce administration overheads)
- No matter how many shares you own you have one vote
- Maximum investment is £20,000
- B4RN shares qualify for an EIS tax rebate, so if you are a taxpayer you get 30% of your investment back within the tax year (you'll need to submit a tax return with the EIS3 certificate you'll recieve from B4RN)
- Those who invest £1500 or more will qualify for a free £150 connection
- If you earn £1500 of shares by digging you will be eligible for a free connection AND 1 year's subscription to the service
- Shares must be held for 3 year minimum
- Shares cannot be sold or given to anyone else, they can only be sold back to B4RN
- Other Investors outside the area can sponsor a connection

Figure 6.6: Extract from a B4RN community share request form.

6.4.6 Legal/regulatory mechanism for cooperative resource sharing (Pattern)

Problem A reliable way to access and share critical resources for communication under a cooperative scheme, which includes cost sharing and infrastructure sharing schemes.

Context Community networks need ways to establish communication links. That implies right of pass to access to public space (like streets, roads, pipes, poles, towers, water channels, other cables) for the deployment of cables, or the right to use electromagnetic spectrum for wireless communication (unlicensed spectrum such as WiFi frequencies, or licensed spectrum such as Global system for mobile (GSM) or TV frequencies). That access can be used for long distance links (backhaul) or access to end-users (also know as "the last" or "first mile").

Discussion Rights to setup communication links, either as passing through public space with cable, or using wireless spectrum is a critical resource for communications. Governments can privatise the public space (either underground, or over ground used for different types of infrastructures) or the electromagnetic spectrum, in exchange of huge amounts of money in licensing fees. However once privatised, it can be exploited to provide cost effective services covering most of the population (in terms of geographic coverage and price), or only a few (for different reasons) but at the same preventing others to try. The Universal declaration of human rights (UDHR) declares the right to information and communication, to implement that right citizens should have a way to access public space to communicate digitally as well as it can be done over other means. That implies defining ways to ensure access to public spectrum and public space. Different regulations and works look at that, but there are different solutions in different contexts, but all look at different degrees and forms of sharing, as ITU described in its report [87], and global organisations for a free and open network have promoted [7].

According to [141] Mexico in 2015, *the Mexican communications regulator, Instituto Federal de Telecomunicaciones (IFETEL), published its new frequency plan (IFETEL 2015). IFETEL has set aside mobile spectrum in the 800MHz band to serve social good. The criteria for using this spectrum is that the population of communities being served must be less than 2,500 or the community must be designated as an indigenous region or priority zone.* Rhizomatica is a not-for-profit organization that has been providing GSM services to indigenous communities around Oaxaca since 2012. Until 2015, it operated under a special dispensation from IFETEL, but the allocation of spectrum to this purpose is now official and any organization may apply for access to this spectrum under the conditions specified. This access gap is identified by studies from ITU in [90] and there is ongoing work with ITU to promote that type of regulation for spectrum sharing with underserved communities. The specific instrument is Recommendation D.19 (approved in March 2010) [91], that provides guidance on a number of issues concerning ICTs in rural and remote areas considering *that provision of ICT services and applications by small entrepreneurs in rural and remote areas have the potential of creating employment. These ventures can be supported by financial institutions and receive support from various government schemes* and *that the accumulation of experiences world-wide on community access institutions (telekiosks, multipurpose community telecentres, multi-media centres), points to the need for pro-active and supportive government policies to simulate demand of the services available.* Examples of support instruments are *These facilities, where necessary, should also be supported by Universal Service Funds as an essential component of rural communications.*

According to the model of universal deployment for access networks to next-generation telecommunication services (ANNGTS) by the Guifi.net foundation [59]: *Since the authorities already manage spaces and public domains in order to host various services and, to the extent possible, plan for these infrastructures to support the deployment of ANNGTS not only in a private manner but also on a shared basis, providing any type of service in any mode of operation or business model is not mutually exclusive. It is an opportunity to improve efficiency and diversity and consequently develop the existing regulatory framework at the municipal level in a consistent and orderly manner.*

Consequences of not adopting it:

Perpetuation of old practices and conflicting interpretations of the law *It is important to note that, prior to the regulatory changes, the framework was very different; therefore, procedures that are appropriate for a state monopoly for the use of the infrastructures that are currently capable of supporting ANNGTS were set. For example, in the previous situation, when a public operator occupied an infrastructure, it occupied the domain in its entirety. Currently operators are private. In those cases where sharing is technically feasible, if they have a chance, they could aim for occupations to be interpreted according to the existing practices to hinder the presence of new competitors. New entrants would then be forced to attend an exception proceeding, such as having to appeal through the regulator, so that they are forced to share or to present a conflict, when this obviously proves much less effective from the perspective of compliance of the law than having a well-established form of sharing from an applicable rule. All this results in a slowdown and discourages new deployments.*

Increased costs and the digital divide *The necessary infrastructures to effectively provide these new generation services have a significant cost. If not shared effectively, this entails several dangers: that the availability of the infrastructure will result in a lack of real diversity in supply, that the deployment will become uneven or slow following strict speculative or economic efficiency-based criteria, that some operators will try to hinder the entry of others, over-investment, or that the performance of the administration will affect certain business models, excluding or hindering new ones.*

All these dangers can ultimately materialise, cause discrimination when it comes to access, and unnecessarily increase the cost of services.

This practice is linked with the different initiatives around the world to promote sharing, that can be defined in terms of facilitating sharing the cost of building infrastructures (e.g. including fibre when building roads), but that typically do not define the details of the sharing, either at cost (cooperatively) or at market prices (competitively), or the obligations to use the resources effectively, prevention of obstacles, etc. Different studies worldwide support this [14, 7, 141].

Solution Regulation and policy measures that promote infrastructure sharing, both for construction and usage, both for wired and wireless scenarios. Given the social role of CN, and the strength of the competitors, particularly in underserved or "market-failure" areas, additional support is needed, such as default mechanisms to allow communities to operate under clear terms that do not create uncertainty, that facilitate deployment, both for the "first mile" deployments and for regional connectivity. This is related to the patterns of regional network and the anti-pattern of overbuilding.

Example Community GSM Spectrum Allocation for communities in the Mexican regulation, the Universal Deployment model promoted by the Guifi.net foundation for high-speed network infrastructures, the APC Infrastructure sharing recommendations, the ITU sharing recommendations, the European cost savings directive.

References [14, 141, 7, 59, 87], Recommendation D.19 [91].

6.4.7 Community participation agreement (Pattern)

Problem Definition of clear rules for participation that are create a well defined boundaries and unambiguous framework for collaboration.

Context Community Networks can involve many diverse participants. In a crowdsourced infrastructure, the principles must ensure i) the openness of access to the infrastructure (usage), and ii) the openness of participation (construction, operation, governance) in the development of the infrastructure and its community [O8].

Discussion Different CN have defined their own community licenses. This formal or informal document is the basis for community participation. Without it conflicts can arise and destroy the community without remedy given that the boundaries of participation are not defined. This is related to the flamewars anti-pattern.

Solution A document, typically know as participation license or community license, that defines an agreement between the participants in a CN. It defines the permissions, and therefore clearly defines the boundaries of participation. Typical clauses promote neutrality (no discrimination) and transitivity (share links alike, to allow expanding the network from any existing node).

Example the Picopeering agreement, and the FONN.

References [54, 68].

6.4.8 Shared network infrastructure information (Pattern)

Problem Having a common repository of information that represents a network infrastructure.

Context A structured repository of that represents the state of a network infrastructure provides transparency, an unambiguous common status information, and facilitates all community network related processes to build and operate the network infrastructure.

Discussion Community Networks typically have a database that describe the relevant resources (e.g. routers, links, locations, address assignments, configuration, status) must be kept up to date to reflect the addition of nodes, their removal and changes to their configuration. It is desirable that the process requires minimal manual intervention and, if possible, that changes are reflected rapidly.

Solution A centralized database with an exhaustive representation of the network infrastructure.

Example LibreMap, NetJSON, Freifunk map, Guifi.net, QMPSU Map, Wind database.[44]

References [32, 9].

6.4.9 Mutual support (Pattern)

Problem Finding and combining complementary capacities to achieve a goal.

Context Community networks are open for participation by any interested citizen, however interventions (such adding new nodes, creating new links) may require a set of concrete competences to be successful.

Discussion Since CN are open for participation, and tasks may be complex, there must be a way to find out participants willing to contribute the necessary and complementary competences to perform certain tasks.

Solution This is typically achieved through stipulated mechanisms to discover, attract or encourage the contribution of complementary capacities to make sure a goal can be achieved.

Example Calls for participation, sometimes linked to the crowdsourcing pattern. Incentive mechanisms to promote and recognise voluntary contributions, as planned in Ninux.

References [5].

6.4.10 Identification of stakeholders and the associated roles (Pattern)

Problem Diversity of ways and incentives to participate in CN and contribute to sustainability of the commons infrastructure and the benefits to each and all the participants.

Context As CNs grow, the divergence in motivations, expectations, needs, incentives and interests become more diverse. In this context, if the roles are not well established, conflict must be expected to increase.

Discussion The clear differentiation of interests, thus the stakeholder groups, and the delimitation of the associated roles is a necessary step towards the implementation of an effective governance system aimed at making possible the coexistence of such diversity.

Solution In the Guifi.net community, as shown in Figure 4.1, we have identified up to 17 stakeholders groups, which we have grouped in three sets based on the primary motivations

[44] LibreMap: `http://libremap.org/`, NetJSON: `http://netjson.org/`, Freifunk map: `https://www.freifunk-karte.de/`, Guifi.net map: `https://guifi.net/maps`, QMPSU Map: `http://dsg.ac.upc.edu/qmpsu/`, Wind database: `https://wind.awmn.net/`

for participation, that is to say, *altruistic*, which make not-for-profit contributions, the *in return*, which expect some return either economic or as a service from their participation, and the *public interest*, which are responsible for the social welfare. We believe that the three main sets is applicable to any CN which aims at scaling, and that the rest of the classification can be used as a guideline for the other communities.

Example The stakeholder groups of each set in Guifi.net are: *altruistic* (*DIY*, *volunteers*, *donors*), *In return* (*CPR professionals –installer, operators, maintainers–*, *service providers*, *end-customers*, *lenders*, *for-fee reduction*, and *social interest –coops and associations–*), and *public interest* (*governance bodies*, *system operators*, *public administrations*).

References [O8].

6.4.11 Community work (Pattern)

Problem Doing something collectively that cannot be achieved by a single participant.

Context While many aspects of a CN can be done in isolation (the DIY attitude), there are key tasks for a community that require complementary profiles to succeed.

Discussion Several key tasks in a community may require diverse contributions from several participants. This may involve sharing and combining diverse knowledge (such as setting an optical or wireless long-distance link, or developing an open-source firmware or a central node database).

Solution Setting up a team from a set of volunteers in a (mailing) list, defining a near-term goal, assigning responsibilities and commitments, with a date to deliver, and ensuring that at the end there is a reward, like a group celebration such as a group lunch or party such as in.

Example Many deployments in Guifi.net or Ninux end with a group lunch to celebrate the collaboration and the collective achievement, and recognise the contributions.

6.4.12 Community meetings (Pattern)

Problem Coordination requires a sense of being part of a team, and sharing opportunities for easy spontaneous, opportunistic, informal and formal communication.

Context Communities need to build a sense of group, which implies trust, shared values, since that creates opportunities for informal interaction, that can result in more focused activities such as knowledge sharing, coordination, community building, etc.

Discussion Although discussions in the communities are primarily carried in mailing lists or other social media, periodic (weekly, by-weekly, monthly) face-to-face meetings facilitate many types of informal and formal interactions, interactive discussions, and decision making typically with a consensus-based method.

Solution Periodic meetings create an opportunity for interaction, sharing information, exchanging devices and materials, building social bonds, decision making, conflict resolution, and having positive feedback (fun). These meetings can be unstructured (in the spirit of "what is discussed/decided is what it had to be") or structured, with an agenda, moderator, minutes, decision making policy. These meetings can be done remotely with conferencing tools, or in a given place. Each way has its own limitations and strengths.

Example The weekly meetings in several of local groups in CNs like ninux and Guifi.net.

References [100].

6.4.13 Enforcement of the rules and agreements – Legal entity (Pattern)

Problem A mechanism is needed to ensure the fulfilment of the rules and agreements.

Context Several CNs have developed internal regulation to coordinate the collective action and to protect the shared resources. However, the regulation alone does not suffice to protect the community against possible breach of rules, because an active actor is needed to this end, including going to court, where necessary.

Discussion Although occasionally the required actions to ensure respect of rules can be taken by specific individuals, a legal entity established to this end is more appropriate in the long term, as it reduces dependencies on specific individuals, who might become unavailable or change their minds. Furthermore, rule enforcement through collegiate body reduced the risk of biased decisions, and doing so through a legal entity increases the sense of legal certainty.

Solution Different CNs have developed different solutions, from informal decision-making bodies to formal legal bodies, but in any case it is recommended to get legal aid to clearly understand the benefits and risks of each option because the applicable legislation vary a lot geographically, and the protection measures change in a great extent depending on decision made. For instance, in the case of the establishment of a legal entity, many legal frameworks allow to change the mission of the legal associations (usually with a simple majority in the general assembly) while changes in the mission of foundations are significantly more limited.

Example The Guifi.net community established a Foundation in 2008 with the mission to protect the community's network assets and ease the governance of the community. Redes por la Diversidad, Equidad y Sustentabilidad A.C. is a civil association in Mexico that helps indigenous communities to set up community GSM infrastructure and help the communities to come up with the convenient organisational structure to protect the resulting infrastructure. Similar solutions exist in the free software community (e.g. the Free Software Foundation).

References [P2].

6.4.14 External implementation (Anti-pattern)

Problem Addressing needs in a community through the deployment of an external implementation.

Context Typically in calls from a community, emergencies, campaigns, with an international component.

Discussion This a typical discussion in the are of information and communications technology for development (ICT4D) with a distinction between emergencies relief and cooperation for development. The urgency to bring a solution prevails over the process required to understand the need, the environmental conditions, empower the local community, work with them or just support them to find a local solution. In simple terms, the durability of an infrastructure is proportional to the amount of time in the preparation and the level of local involvement, sense of ownership and entitlement.

(Anti-)Solution Juast after a call, bring a pile of devices and experts that deploy an operational network and leave them connected but ignorant of the operation and troubleshooting of the network, or the financial aspects of it. Did I mention the locals? No, because they don't speak English.

Improvements Training, preparation with target communities and follow-up in key areas: technology operation and maintenance; planning, business models and economic sustainability training and advice; digital literacy.

Example Wireless deployments in emergencies that are left in place but the locals ignore all details except its usage. After any minor problem the network becomes useless and the infrastructure is abandoned due to lack of local knowledge.

References [126], local ownership [128], active entitlement [127].

6.4.15 The club of techies (Anti-patttern)

Problem CNs are by techies for techies (only).

Context Many CNs are bootstrapped by a group of tech savvy people that enjoy testing connectivity solutions. It starts because that group has the skills to start the network.

Discussion The infrastructure may grow quickly among other similar technologists, but it may be unable to go beyond that group given the technology and complexity barrier. Normal citizens may find it not accessible not due to the economic cost, but due to its complexity and the lack of training or the need to invest too much time to benefit from it. The core techie group may not appreciate "externals" that do not share their passion and language, or that want to connect without being able to contribute technically.

(Anti-)Solution CN for those that really understand the technology, share a nerd language, and can invest a lot of time in it.

Improvements Development of training material and activities, pairing techies with "normal" citizens, twinning, developing tools to simplify the deployment, usage and maintenance of the network.

Diversification of the activities including and highlighting non-technical contributions to the network.

Organize courses for externals led by techies. They have a lot of experience and information to share, and with guidance from non-techies, they can help the non tech savvy to be introduced in the movement. Plus, if these courses are done with the help of some external association it can be a way of enlarging the audience of the community.

Example Unfortunately any CN is part of the problem. All suffer from different degrees of club behavior. A positive example of this anti-pattern is the Battlemesh[45].

6.4.16 Flame wars (Anti-pattern)

Problem Different participants get into emotional discussions as a result of a real or apparent conflict.

Context Communities need to take collective decisions that affect differently the membership. This involves very diverse people, with different values, objectives. Sometimes discussions lead to an amplified conflict.

Discussion Interaction in network-based communication tools, particularly text-based, can create situations where a conflict cannot be solved by argumentation, but amplified. Flame wars might involve many people and generate hostility. In the Usenet community it was common to say that some discussions became unproductive, generating "more heat than light" (Hamlet).

(Anti-)Solution Sending more messages to clarify and continue the discussion, hoping to guide it to a solution.

Improvements A conflict-resolution system that can stop the discussion (even blocking the mailing list or other communication mean, and follow a structured process to close the discussion).

Example The conflict-resolution system is a systematic and clear procedure for resolution of conflicts with a scale of graduated sanctions. It consists of three stages –conciliation, mediation, and arbitration– all of them driven by a lawyer chosen from a set of volunteers. The cost of the procedures is charged to the responsible party or to both parties in case of a tie. This system was developed based on experience and has defined in a precise manner to help in addressing these conflicts in a quick and standard way, with help from lawyers, and scalable for a growing community. It was developed at a time when the flame wars between a few participants threatened the entire project. The Guifi.net foundation had to take a leading role in its development and implementation.

References [P2].

6.4.17 Overbuilding (Anti-pattern)

Problem External network providers, such as incumbents or providers deployment proprietary network infrastructures, may use competitive tactics to prevent a commons to develop.

Context In many countries we have seen that dominant telecom providers may be doing quick overbuilding actions to prevent any other provider to expand in a region by making strategic investments to block alternatives.

Discussion For instance, when a CN decides or starts to deploy in an area, a dominant telecom provider might decide to quickly deploy and start serving in a few key locations to make any

[45] Image from the excellent Wireless Battle Mesh (Battlemesh: `http://battlemesh.org/`) event, a great techie forum, Maribor 2015

other investment not economically feasible. They don't intend to really address the needs of the community, but just prevent or block others to do it with the minimal investment and coverage that makes alternative deployments unfeasible. The proverbial dog in the manger, which neither eats nor allows others to do so.

(Anti-)Solution Communities plan full deployments (covering all households, including the more and the less financially feasible), and use community shares or loans to perform the deployment as quickly as possible to reduce the temporal window where overbuilding can produce a effect. Once 100 % of homes are covered by the CN, overbuilding becomes futile.

Improvements Deterrent effects in deployments: planning deployments covering 100 % of a given area, no publicity before the deployment is done, initial commitment of citizens like with community shares, which contribute to disincentive reactive deployments by incumbents or privative operators.

Example Most of the times a community announces a plan to deploy a community or municipal network in an underserved area, the incumbent quickly deploys the minimal infrastructure to make the local deployment unfeasible. There are examples all over the world of this behaviour, not very productive since the overbuilding is not an alternative but just a deterrent: it does not try to satisfy the needs of all the underserved population or locations, but just connect the minimum to prevent the viability of alternatives. The B4RN model of 100 % coverage and community shares has succeeded in many areas in preventing overbuilding, since when the news are out, everyone in the community is connected or committed through investment, and overbuilding there will be a clear waste: no one will choose to leave the local community for a slower and more expensive service.

6.4.18 Customer stealing (Anti-pattern)

Problem Participants, particularly professionals, act strategically to steal customers from other professionals, typically in the same area, instead of looking to new customers.

Context It is easier to steal a customer from another professional rather than expanding to new customers or new regions. Stealing customers may appear to work in the short term, but brings instability to the community and since it creates uncertainty to the professionals and the value of their services, it affects negatively the sustainability of the commons and the community in general.

Discussion The expansion of the user base and the area covered is the best strategy in the medium and long term for the sustainability of the commons and its professional participants. In fact, the faster, wider and better the network infrastructure commons is, the more business opportunities for professionals. The real competition is with external operators and service providers that have proprietary/privative infrastructures, particularly incumbents given its economies of scale and influence. The population that has bad, expensive or no service are a great opportunity for the expansion of the commons to new people and new areas.

(Anti-)Solution Competition to steal customers from other local professionals involved in the commons. Connected to the next "internal dumping" anti-pattern.

Improvements Focus on creating new markets: new customers, new areas, new services.

Example Several cases among professionals in Guifi.net of competition, differentiation, and specialisation to benefit from complementary offers from other providers.

6.4.19 Internal dumping – Downward spiral of prices below cost (Anti-pattern)

Problem Participants forget that beyond the initial cost of purchase and installation of a network device and link, there is a need to contribute to the development and maintenance of the network infrastructure. Participants do not want to pay any fee to maintain the network infrastructure beyond its own node and link. Professionals and service providers using a CN infrastructure compete in price and features compromising the sustainability of the infrastructure.

Context Humans have bounded rationality, and may not have a clear distinction between the commons and their own interests or beliefs; or between its own link and the whole network. A volunteer or professional participant (individual or SME) can be confused by the openness of a commons infrastructure, and assume things are free and magically sustainable. Participants forget that beyond the initial cost of purchase and installation of a network device and link, there is a need to contribute to the development and maintenance of the network infrastructure.

Discussion Freedom to join the network does not preclude contributing to the cost of the commons (not free of charge). There is sometimes the assumption that community initiatives may be "magically" free, just as opposition to expensive private resources and services. Open access (freedom) to a commons does not mean it is free of any cost. The two main sources of confusion are that the commons infrastructure is free of cost once deployed (for maintenance or usage particularly), and that lowering prices is the best strategy (related to the previous "work stealing" pattern). Ignoring these costs may appear as a good way to get more customers (for a professional participant) or more participants (for a volunteer), but it is unsustainable for all: for the newcomers that do not get what they expected, for the intermediary that is in a conflict and at loss, and for the commons infrastructure that is subject to an unsustainable usage. The lack of nurturing of the commons leads to a scenario of "tragedy of the commons".

(Anti-)Solution **Trivialisation** the network is just a sum of nodes contributed by participants, not more, and it would magically work for anyone and forever with no maintenance costs.

Omission a participant does not plan for recurrent contributions to maintenance, it just reacts to crisis (congestion, repairs).

Internal dumping Professional operators using the commons may reduce the prices for services below the cost (not collecting contributions to maintain the infrastructure commons) or deliver more features than competitors (below their internal costs).

Cannibalisation Professional operators using the commons focus their efforts in competing against each other instead of putting the efforts in acquiring new customers from outside of the ecosystem.

Improvements For activists: create not-for-profit user association that collects periodic contributions to maintenance cost.For professional service providers: separate the fixed per-client contribution to the infrastructure costs from the added value services costs provided by the service provider.

Example Guifi.net in Barcelona and in the county of Bages have created user associations (EXO, Guifibages) that collect network maintenance fees to ensure the sustainability of the infrastructure.

The Guifi.net foundation model of service invoices for professionals using the commons infrastructure, that details in two separate subsections the service fees, and the required contribution to the commons. See Figure 5.2.

6.4.20 Social imbalance (Anti-pattern)

Problem Participants in an open group may not be balanced across all dimensions. Typically there's a strong gender imbalance to men, a interest imbalance to technically focused people. How to compensate these imbalances with an inclusive spirit?

Context Communities tend to be more welcoming to people that match the profiles of the majority. Many CNs have a strong imbalance in terms of gender and interests.

Discussion A decision making protocol is needed when the community enlarges. Communities start with local, small-scale groups and auto-coordinate. Then when the community enlarges, people will still want to use the informal way of decision taking they used in the past, while it is not usable anymore.

(Anti-)Solution Not doing anything because "*the community is open to anyone*".

Improvements The choice of reference models, examples, speakers to external audiences, specific support to new members from existing members with a close profile, help to address these imbalances. People representing a community become role models, and deliberately or not, embed their own values and language in their interactions. Therefore, they create proximity and facilitate understanding with potential members with similar profiles.

Example The gender and techie imbalance in probably all CNs.

6.5 Conclusions

The sustainability of a project, that is, the capacity to persist over time, requires a minimum critical mass of beneficiaries to raise the required resources to repay the initial investment and continue the operations, thus reaching the so-called break-even point. Once reached, CNs may consider expanding their activity beyond that, that is, to scale up. Based on the results of our comparative research between several European CNs and from the rest of the world, we claim that they must do so not only because it helps realise their fundamental values of social justice but also because they become more resilient. By becoming larger, CNs enable dynamic local economies which, in turn, reduces the dependency on volunteers and increases their freedom, who then can focus their efforts on more specific tasks that cannot be professionalised, like those related to the governance of the project. Growth also brings savings through economies of scale and strengthened self-protection against external and internal attacks and against internal mistakes, as there more people involved and thus overseeing the project.

At internal level, our experience recommends that, to achieve a healthy and sustainable development, these communities must adopt an inclusive multidisciplinary approach to cover the needs of the social, legal, economic, and technical dimensions in a balanced manner, that is to say, without leaving any of them excessively unattended. In line with the most relevant works on the study of collective action, we also sustain that adaptation to local conditions is as critical as having a multidisciplinary view, hence, successful solutions from a given community of practice must not necessary deliver similar results if they are directly implemented in another. However, our results show that general guidelines as well as specific illustrative examples can be extracted from successful experiences.

Successful cases show the potential of these communities to become a truly driving force for the expansion of the Internet by developing tools to make the existing initiatives more effective and to incubate new ones. However, specially in developing regions, it is hard for CNs to develop. In this regard, there are positive experiences of external organisations contributing to the strengthening of existing CNs and to the establishment of new ones. On this basis, we believe that this external support should increase and have a special priority in the development of sustainable and replicable (and scalable where possible) solutions. To this end, we propose the creation of an international organisation to be funded with funds already oriented towards universal access, such as the universal service funds in several countries. Such organisation could lead the development of standardised methodologies, databases, and software, in addition to provide technical assistance and coordinate funding and financial support to CNs.

From our research and formalisation of the experience in Guifi.net and other CN, we have identified a set of the most common and relevant organisational patterns and anti-patterns in CNs that are presented in an structured way. In that form, these patterns are more generic and, while working with diverse local communities in Guifi.net or other CNs interested, can apply some of the organisational patterns or mitigate certain anti-patters, always adapted to the characteristics of each.

In the specific context of this dissertation, the comparative work among CNs we conducted enabled us to identify key aspects that have enabled Guifi.net to reach its current size and complexity as well as the coming obstacles (see Section 5.2.6). Based on all the knowledge we gathered, our main conclusion regarding the capacity to scale of Guifi.net is that it does not have any major known impediment beyond its current scale. Thus, although we dare not to establish any quantitative limit, our conjecture is that the model can scale, at least, several orders of magnitude from its current size, specially taking into account its replicability, federation and nesting potentials.

Chapter 7

Applicability to cloud computing

Preface

In this chapter investigate on the exportability of the model to other types of infrastructure by analysing the case of cloud computing infrastructure. Inspired by the Guifi.net case and its governance and economic systems, we explore the feasibility and sustainability of community clouds as participatory commons. We propose organising the IaaS and PaaS cloud service layers as CPR for enabling a sustainable cloud service provision. On this basis, we outlined a governance framework for community clouds, and we developed Cloudy, a cloud software stack that comprises a set of tools and components to build and operate community cloud services. In a mix of action research and experimentally-driven methodologies, Cloudy was designed to the needs of the Guifi.net community network in the first place, but we believe it can be adopted by other communities with minor changes. We validated the feasibility of our concept of community clouds in a deployment in Guifi.net of some 60 devices running Cloudy for over two years. To gain insight into the capacity of end-user services to generate enough value and utility to sustain the whole cloud ecosystem, we developed a file storage application and tested it with a group of 10 Guifi.net users. The experimental results and the experience from the action research confirm the feasibility and potential sustainability of the community cloud as a participatory commons. Based on this particular result, the lessons learnt during our experiments with Cloudy, and our previous studies on CNs, leads us to believe that the other infrastructure can also be organised as participatory CPR.

7.1 Introduction

The generic term CCs refers to cloud systems designed to address the needs of a community [110]. The CCs have the potential to solve unattended needs of CN members and improve the efficiency of some existing services (mostly latency, performance, cost, and availability of services such as web, video, and data content) through the benefits of the cloud paradigm. These come mainly from the flexibility and savings that elasticity, pooling, and on-demand self-service bring in terms of performance, cost, and availability from the use of multiple alternative nearby servers in the same community or access network. The technical knowledge of the participants and their openness to research and innovation are other positive factors in this regard. The CCs deployed locally can bring benefits to communities and can address unattended needs, such as latency-critical applications; critical local sensing and control services that cannot rely on non-existent, fragile, or expensive Internet connectivity; local storage services with customised access control policies for content; applications for emergency and disaster scenarios; and privacy and data-security sensitive uses, where remote services may not be trusted or they gather, expose, or exploit sensitive data.

The CCs describe a model that can be organised in diverse ways, such as a competitive free market, a firm, a hierarchy, or a cooperative model. In this chapter, we explore CCs as *participatory commons*: open user-driven (self-provided) clouds formed by community-managed computing resources, where the IaaS and PaaS cloud components are organised as CPR, on top of which the users deploy SaaS to consume resources and platform services or provide application services for free or for a fee. We claim that the Guifi.net offers a suitable model for this type of CCs to emerge. According to our view and findings, the local management of CCs creates more opportunities for access to the cloud infrastructure adapted to the local socio-economic conditions, in terms of both production and consumption of resources and services. Thus, they have the potential to involve further participants and leverage new spaces of relationships, bringing new opportunities to entrepreneurship and innovation for more people. In the context of CNs, the capability of CCs to generate local value translates into incentives to strengthen the existing networks and to bootstrap new ones, especially in developing countries.

The two key interrelated concepts and related research questions are:

1. *Feasibility*, as the possibility of being easily or conveniently done, which is related reaching technology and demand readiness. This leads to the first question: *Which social and technological artefacts and what factors are required to bootstrap CCs organised as open commons?*

2. If feasible, then we look at *sustainability*, as the ability to be maintained at a certain rate or level, which is related to organisational, governance, and economic aspects. This leads to the second question: *Which artefacts and factors are important to sustaining CCs, and how do these affect the value of CCs for their participants?*

We argue that this kind of cloud can emerge through a suitable cloud software stack (the artefact we have identified as the cornerstone of the initial phase) and an enabling networking infrastructure in place (not necessarily a CN). They can grow and become sustainable when the appropriate governance tools are in place and when they can generate value for the community. This value comes from the usefulness and economic utility of the specific services the CC provides to their participants. With these conditions, feasibility translates into sustainability.

To prove our claims and answer our research questions in detail we:

a) Analysed a success case of digital infrastructure managed as an open commons, inspired in the Guifi.net experience,

b) Proposed a framework for the structure of a CC,

c) Designed a CC software stack and implemented it in a Linux-based environment,

d) Co-designed and promoted our cloud software stack in a community and assessed its initial uptake to confirm feasibility of this kind of cloud,

e) Made a techno-economic analysis of the viability of a cloud storage service in this environment as a proof of concept of the sustainability of CC services.

In terms of research methodology, for this study in particular, we supplemented the participatory action research with a significant amounts of iterative experimentally-driven research [62].

We worked closely with the Guifi.net community and specifically with a subgroup of volunteers to elaborate together our proposals, conduct our experiments, and discuss our results and implications. After an initial analysis, research, co-design, and prototyping during part of 2013 and 2014, we worked with the Guifi.net community in two main iterations of the research over a period of two more years starting in June 2015, integrated in a community of practice with around 60 participants. After the intensive iterative development phase, the Cloudy system is still maintained and extended with new features jointly developed by the community of users and the research group.

The interactions with the community took place in two mailing lists for discussion and mutual support and in focus groups in several weekly community meetings. The group discussions were around the planning, co-design, transformation, and result phases of the action research, with a focus on the cloud deployment and the use of the software system, services, and applications. We used a combination of larger meetings to collect diverse opinions, and small group meetings for analysis and decision making. These interactions were useful to better understand the needs and preferences, to obtain feedback about new features and changes as the software evolved, and to refine the community cloud model and its governance instruments.

The rest of this chapter is organised as follows. In Section 7.2, we propose a framework for managing CCs as open commons. In Section 7.3, we discuss the design and implementation of our CC software stack, and in Section 7.4, we evaluate the feasibility of its deployment. Section 7.5 explores the economic sustainability of a production storage service as a case for professional activity in the CC. Section 7.6 discusses and further elaborates the results as they relate to the main research objectives. Finally, in Section 7.7, we conclude outlining our findings and future work.

7.2 Framework for community clouds as open commons

As with CN resources, cloud resources can be developed as open CPRs, and for that we have build on the analysis in the previous section. In the case of a CC, the core resource is nurtured by the diverse contributions of networking, computing, storage, and service elements that the participants deploy to expand or improve the CPR, and the fringe unit is the services they obtain. An architectural comparison of clouds to networks in the context of CPRs, detailed in [156],[1] leads to the following main differences:

Diversity of building elements For a CC, the building elements are more diverse than in the underlying network. In addition to the physical level where host devices (servers) provide computing and storage capacity and the network provides connectivity, the cloud software stack components (IaaS, PaaS, and SaaS) are also building elements that provide diverse additional services (e.g., resource allocation and user authentication). This higher complexity has a direct effect on the CPR model, architecture, and implementation, as described in the following sections.

Inter-dependency among resources At the network level, the CPR is a primary infrastructure, that is, it has no inherent dependencies on other infrastructures. This is not the case for the cloud, which inherently depends on network connectivity for the interaction among building elements and users. In addition, there are inter-dependencies among physical resources with services and across different services (e.g., a PaaS depending on

[1]The comparison of models, conceptual and system architectures, and identification of requirements was part of Clommunity (EC FP7-317879).

IaaS). Moreover, some resources or services are more critical or demanded than others. Thus, the consequences of the deployment of an infrastructure with such dependencies must be studied not only from the viewpoint of usage/demand/traffic of a specific class of resources but also from a holistic approach. This will allow us to answer questions concerning the following: the complexity of interaction and balance across classes of cloud resources, resource bundles required in services, congestion management and fairness across services, and the influence of related infrastructures, such as the underlying network, the power grid, the environment, or the socio-economic aspects of the community of users and organisations. The answers to these questions have a direct effect on the design of the CC software architecture and particularly in the mechanisms for service allocation and discovery used to select service instances, described in Section 7.3.

Boundaries of the CPR The rule applied for the network infrastructure level, *the Guifi.net community takes care of the infrastructure as a CPR, the content is left up to the users* (considering content to be pure usage and therefore external to the CPR), can also be applied to a cloud. However, the criteria to determine what must be considered external (as content) and what is considered infrastructure are flexible at the design level (see Figure 7.1 of Section 7.2.1) and might not be so obvious at the implementation level. In hybrid clouds, where in-house (private) infrastructure is complemented with external (public) infrastructure, that boundary is clear; external owned vs external rented and therefore metered. In our context, the main distinction depends on the nature of the exchanges that can be done cooperatively (to cover the costs declared) in a CPR, or competitively (at profit, with market prices ignoring the costs) in a commercial market, and even for free for some amount of exceeding resources. The different nature of the exchanges has a direct effect on the application of the CPR model to the governance of the different cloud layers, described in Section 7.2.1.

As for any other open CPR, the implementation and sustainability of a cloud requires effective rules and tools for the governance, maintenance, expansion, etc. In the following sections, we discuss our proposals to meet these challenges according to the same structure as in Chapter 4 and in Chapter 5, and compare to the network infrastructure case, paying special attention to the differences just outlined.

7.2.1 Community clouds as open common-pool resources

The fundamental principles of Guifi.net also apply to a CC. It must be fully inclusive, that is, it must ensure the openness of access (usage) to the infrastructure, and the openness of participation (construction, operation, and governance) in the development of such an infrastructure and its community. The application of these fundamental principles results in a CC resource and service infrastructure that is a *socially produced collective good* governed as a *CPR*. Likewise, the high-level design requirements (e.g., standardisation of resource management, interoperability of individually contributed resources, and ease of participation) are equally valid.

With a set of essential IaaS and optional PaaS cloud services given as a CPR, enhanced and aggregated SaaS services can be built upon them and be offered on a cost-sharing or for-profit model. Similar to how the network CPR reduces the entry barrier (through transparency, network neutrality, and cost sharing, resulting in reduced CAPEX and OPEX costs) and enables the market niche of proximity services, a cloud infrastructure held as a CPR appears to contribute

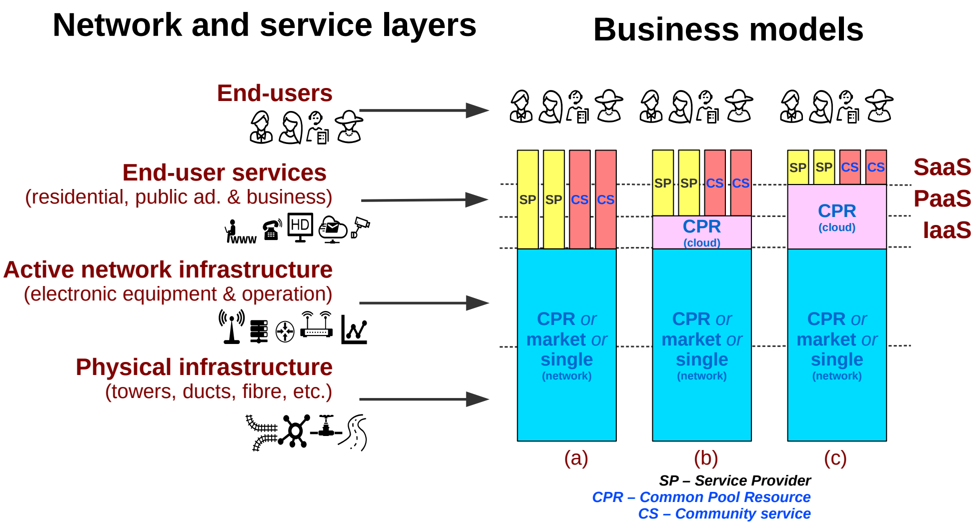


Figure 7.1: Alternatives in the layering of community cloud service provision over any kind of network service.

to making cloud computing even more accessible for entrepreneurs or SMEs as described next in general, and specifically in the comparison with commercial cloud providers in Section 7.5.4.

7.2.2 Scenarios for community clouds

Figure 7.1 illustrates different scenarios for CCs. In CNs like Guifi.net, although the network infrastructure is a CPR, the network can be provided according to different models by single or multiple commercial providers in a market [49]. Over the network layer, for the cloud service layers (i.e., IaaS, PaaS, and SaaS), different combinations of service provider solutions and community solutions are possible to satisfy the users' needs.

The scenario on the left of Figure 7.1 (a) corresponds to the *vertical integration* approach, the most widespread implementation, with no cloud CPR. In this scenario, a dedicated hardware deployment and software stack must be developed and maintained without the possibility of benefiting from any cooperative resource federation among different providers. Examples of that are the well-known commercial cloud providers, or private clouds, the combinations (hybrid) without horizontal integration at the IaaS or PaaS layers.

Scenario (b), the *infrastructure commons*, addresses a novel cloud scenario where the resources for the IaaS, such as virtualised or bare-metal computing, storage, or networking resources in community locations like cabinets, warehouses, or mini data centres, are provided by the participants and pooled cooperatively. One of the benefits for such a case is inherited from the characteristics of the cloud resources on which the IaaS is built. For instance, a geographically distributed heterogeneous IaaS enables new types of services that cannot be provided by centralised data centres. The proximity to its users translates into lower latency, lower network partition sensitivity, and higher trust, among others. Examples with various levels of cooperation are the ExoGENI or EGI, mentioned in the related work, and the Brighton Digital Exchange,[2] a cooperatively-owned and run data centre, where member businesses can peer and co-locate equipment and provide services to Brighton businesses and the world.

[2]BDX: http://bdx.coop/

In scenario (c), the *platform commons*, commercial or community organisations provide end-user services through cooperative community-based IaaS and PaaS. In this case, the community-owned PaaS can provide valuable platform services of local interest, with tighter integration with the local environment. This setup, built on community-managed platforms can, for example, deliver activity logs that enable higher levels of transparency and auditability of cloud applications. A practical application is in the IoT domain, where a publish-subscribe platform service can be audited in terms of data input and output, thus providing more local control about personal data flows (such as running cloud applications in community or home locations, firewalled from the open Internet, and monitoring or auditing data transfers for trust and privacy reasons). An example of a platform commons is ELIXIR, mentioned in the related work. The experimental Guifi.net CC is another case detailed in Section 7.3.

7.2.3 Stakeholders

Our experience over two years working with the Guifi.net community and its community cloud deployment confirms a similar stakeholder structure of the Guifi.net network commons. The coexistence of volunteers and for-profit participants, already happening at the network level, has started to expand to all cloud layers, with initiatives, experiments, or offers at all cloud levels, but not to a significant scale yet. In a comparable way, the presence of a minimum number of customers (and the corresponding service providers) is crucial to ensure the required income to sustain the system. The participation of public administrations is also desirable but is not there yet. Nevertheless, the *proactive* motivations (*we participate because we want to, either to self-satisfy our cloud needs or to contribute to the initiative*) must be explicitly promoted because, at the cloud level, public administrations have much less legal obligations to intervene than at the network infrastructure level. Ideas such as the digital exchanges mentioned above, create opportunities and incentives for local partnerships among all stakeholders in creating local data centres to host computing and service infrastructure and to promote local public and private services, socio-economic development, and digital inclusion.

One topic in the discussion between the research team and members of the community involved in the pilot was about the inter-dependency between the different cloud components that can lead to a separation between volunteer and professional initiatives given the quality of service expectations, unless the software can provide effective quality control (e.g., isolation, prioritisation, interference, and congestion control), and a socio-economic mechanism exists to quantify and compensate the contribution and consumption of resources and services among all participants. However, this is still under research, regarding examining virtualisation [47], incentives [4], activity logs, and payments ledgers using blockchains or digital currencies [5].

During the pilot, the central role of software development was clear to all. The CCs require an international community of open-source software developers (voluntary or professional but not necessarily local) that develop and maintain a set of core tools, APIs, and compatible applications that can be shared by many CCs. The software, far from trivial, requires not only initial developments but also adaptation of cloud software intended for other scenarios (e.g., data centre), integration, and maintenance.

Finally, working with the community of users, the need for a reference authority was clear, similar to Guifi.net foundation in the case of the network, as proposed by the Guifi.net community. This role was assumed experimentally by the Guifi.net foundation. This allows us to bypass the overheads of creating a new organisation, but in the future, if the project consolidates into a stable CC, a dedicated organisation is imperative to preserve the independence of the two ecosystems.[3]

7.2.4 Participation framework

As a result of the pilot, and the discussion with the Guifi.net community, we propose a separation of the body of normative structure into layers with a general mandatory licence and a set of complementary dedicated agreements. The details of the structure can vary for other CC, but the principles will be equivalent.

Licence A cloud computing licence, which harmonises the contribution and usage of the cloud resources, eases the take-up process of the CC model in a similar way as the network licence has had on the network infrastructure. The discussions about cloud computing licence were started, but the licence has not been established yet. Similar to the network license (FONN) process [68], the steps to draft the cloud computing licence go through deliberation with the community and evolve as the commons develops and transforms. The discussion with the community, with a rights-based approach [65], has resulted in the following proposals. The licence must consider aspects like the relationships between users and service providers and between the cloud layer and network layer. We propose that the licence must cover at least the following aspects:

- ***Neutrality*** The requirement of public access without discrimination, that is, providing the same treatment (service) unless there is some compelling reason.
- ***Fair use*** Rules of conduct and means of control to avoid abuse of the resources in commons.
- ***Transparency and accountability*** As discussed, access to information and accountability is essential in any CPR and is an enabler for participation in the operation and governance of the commons.
- ***Privacy*** In an architecture where sensitive data are distributed across the network, privacy respect and protection must start from the licence. This implies precautions to handle private data, which may be collected deliberately or not, with proportional care, according to data protection laws.

Collaboration agreements As with the network infrastructure, the level of commitment of the operators with the commons is expressed through a supplementary agreement detailing the specific implications of the licence, considering service-level objectives (SLOs). The set of collaboration agreements for the cloud contributes to enhancing confidence among operators offering cloud services, comparable to our experience with the network infrastructure commons.

7.2.5 Socio-economic tools

As in other communities, the governance involves all actors to drive a CC infrastructure through challenges and changes to keep it operational and balanced, which is key to resilient and adaptive CPRs. From the discussion with the Guifi.net community, the following tools were proposed as necessary, although they must be adapted to local conditions:

[3] Guifi.net foundation has actively participated in the whole conceptualisation process as well as the development of the software stack and in the implementation of the experiments.

Conflict-resolution system In the case of Guifi.net, the already existing system for the resolution of conflicts can be applied 'as is' to CC related issues.

Sanctioning system The general structure as well as the administrative provisions of the Guifi.net sanctioning system is a good starting point. The technical provisions must be tailored to the specific requirements of CC.

Economic compensation system It must clarify the terms of participation to promote investment and reduce the number of disputes. The already existing network compensation system (see Section 4.4, Section 5.3, and [P3]) can be adapted to fit the cloud requirements and can be used to balance expenditure at the cloud layer. In addition, the effect that the usage of the cloud services can have on the network infrastructure and its consequences on the economic compensation system of the network must be investigated to determine whether the current calculation system, which is based on the total amount of network traffic at the points of presence of the infrastructure, suffices or needs to be adjusted. This system must balance the exchanges of disparate resources (IaaS, PaaS, and SaaS) between the different participants (volunteers, coops, and for-profit enterprises).

7.2.6 Communication and coordination tools

As with the network infrastructure, the diversity in the requirements for the coordination of the collaboration can only be covered through the combination of several tools. The discussion with the Guifi.net community raised the need for the following tools:

Software tools for cloud management and provisioning The Guifi.net website success shows that efficient and easy-to-use solutions for participant needs are key for the project uptake and harmonisation of the participation. As for the CC, most of the needs can be grouped per cloud layer as follows: for IaaS, contribution and request for computing and storage capacity; for PaaS, deployment and discovery of services, user authentication, and access policy management; and for SaaS, an initial set of appealing applications.

Communication tools From the experience during the pilot, tools (mailing lists, web fora, etc.) and strategies (face-to-face meetings, presentations, etc.) were indispensable. In an equivalent way, the provisioning and management of the infrastructure and services can benefit from specific solutions and separate communication channels.

7.2.7 Initial key enablers

Our experience shows that the start-up phase of any community initiative is critical, including our action and experimentally driven research. From the initial discussion with the group of volunteers to prepare the launch of the pilot and from the ongoing discussions and experience with the Guifi.net community during the pilot, these are our collective findings on the key conditions (feasibility factors) that must be met to ensure a successful bootstrap of a CC:

Demand As a result of an increasing global awareness on data privacy, security concerns, etc., there is a growing demand worldwide for user-driven (self-provided) cloud services. We confirmed during the pilot that this demand also exists within that community. We collected requirements and suggestions from the participants, which determined the priorities in the implementation of the service offering.

Early adopters The start-up phase is critical for any cooperative project. Among the Guifi.net members, there is a respectable number of technology enthusiasts interested in experimenting with innovations. Moreover, the authors have been involved in Guifi.net for more than a decade, which facilitates the introduction of the product. The involvement of a few key active and recognised adopters in the start-up phase accelerated the involvement of the rest of the community in the pilot.

Third-party technology availability The two main requirements are network connectivity and computing and storage capacity. Affordable off-the-shelf devices powerful enough to run our cloud software stack have been available in the market for more than half a decade. Thus, a CC can be bootstrapped anywhere with local or Internet connectivity. In terms of software, the existence of many open-source base components (e.g., GNU/Linux, services, and applications) were enablers for the start-up phase.

Cloud licence In view of the positive effects of the Guifi.net network lincense (e.g., CPR protection, encouragement of investment, and dispute avoidance) and given that the introduction of major changes becomes more difficult in larger communities, the precise definition and approval of the cloud computing licence is the main next step to ensure the sustainability of a larger community beyond the pilot.

7.3 Cloudy: a community cloud software stack

As part of our participatory action research, we have worked with the Guifi.net community to understand the needs, and design, develop, test, and evaluate the solution over at least two cycles. Several iterations were made with many formal and informal meetings with groups of community members across all phases of the research, with key plenary meetings in two of the annual Guifi.net conventions.

We envisioned the CC in the scenario (c) of Figure 7.1 (infrastructure and platform commons), realised through the combination of two main types of devices on top of the Guifi.net network commons. The first consists of low-power consumption mini-computers contributed by the end users and installed in their homes and offices. The second are more powerful dedicated servers located in more centralised points, like local data centres, warehouses, or street cabinets, usually contributed as a result of a coordinated action of end users or by organisations, such as companies, universities, cooperatives, or public administrations.

Regarding software development and re-utilisation, we prioritised the open-software solutions for our own convenience (licences, access to the code source, and ethics) but also because this model is the best aligned with our target audience (e.g., activists, SMEs, and educational institutions). We have also prioritised the utilisation of existing solutions over our own developments, restricting the last to the minimum strictly necessary. In accordance to this open spirit, we made all the code and related documentation publicly available.

In the remainder of this section, we describe how the cloud software stack presented in Section 7.2 has been implemented as an operational Linux distribution that we named Cloudy[4] that runs a combination of IaaS, PaaS, and SaaS on end-user oriented cloud nodes (user devices), presented in Section 7.3.1, and includes the Community-Lab[5] software that can run multiple

[4]Cloudy was started as part of the Clommunity research project (EC FP7-317879).
[5]https://community-lab.net/

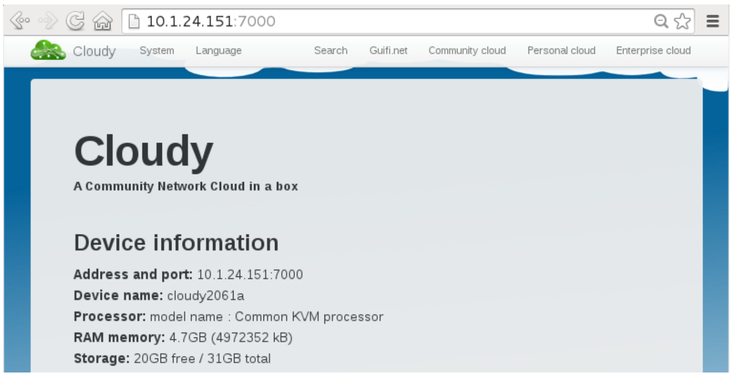


Figure 7.2: Main menu bar of the Cloudy's web user interface.

service IaaS instances on server nodes (resource devices), presented in Section 7.3.2. Sections 7.3.3 to 7.3.5 discuss the specific aspects related to IaaS, PaaS, and SaaS, respectively.

7.3.1 Cloudy software for user devices

Cloudy[6] is a Debian GNU/Linux-based software distribution aimed at participants of a CC that we have developed as part of our research.[7] Conceived as an open-software platform to bootstrap and manage decentralised CCs and services in them, it includes a set of cloud services and applications that are managed through a common web front-end interface. As an open platform, it integrates a set of pre-installed applications, which the user can activate through the web interface, and allows users to install additional services (see Section 7.3.5). As a cloud software stack, it offers IaaS and PaaS services (see Sections 7.3.3 and 7.3.4). These include common services needed by every participant to join and participate in the CC as well as most common network services used in Guifi.net. In addition, users can extend Cloudy with their own services. This flexibility allows the service offerings (for free or for a fee) to grow and adapt to specific needs of the community. The source code as well as the binaries are freely available in public repositories.[8]

Given the wide range of essential and optional software and services (IaaS, PaaS, and SaaS) for a decentralised CC, Cloudy can have a similar role in terms of standardisation and unification at the cloud infrastructure and service level as the Guifi.net website has had at the network infrastructure level. Two mailing lists have been set up, one for the standard users[9] and another for coordination of the development.[10]

7.3.2 Community-Lab software for resource devices

Resource devices are network-attached low-power computers (desktop, mini, or rack) deployed in several locations in the Guifi.net CN. The resource devices provide computing and storage resources in the form of virtual machines implemented as Linux containers with access control,

[6] Documentation for users: http://cloudy.community/ and for developers: http://en.wiki.guifi.net/wiki/What_is_Cloudy/.

[7] In the Clommunity and netCommons (EC H2020-688768) projects.

[8] The source code is available as a GitHub project https://github.com/Clommunity/ or http://dev.cloudy.community. The binaries are available as ISO images and as Linux containers http://cloudy.community/download/.

[9] https://llistes.guifi.net/sympa/info/cloudy-users.

[10] https://llistes.guifi.net/sympa/info/cloudy-dev.

some degree of resource isolation, and management capabilities to grant a trusted remote user full access to the processing, storage, and network resources allocated to a given container. The software[11] for resource devices is based on the OpenWRT GNU/Linux distribution[12] extended with a remote control (representational state transfer (REST) API) resource manager service that can manage the life-cycle of multiple containers running concurrently in the same host. We call each of these containers a *sliver*, and the set of slivers on diverse resource devices belonging to the same service is called a *slice*.

A collection of resource devices delegates its resources to a (single) resource controller service, as seen in Figure 7.3. The resource controller[13] is a software package and a service that provides a web interface as well as a REST API to a resource registry. It allows users to create and manage slices in all associated resource devices as well as register and offer new resource devices, among other tasks. The resource controller allows service owners to select and request several computing resources from a collection of associated resource devices. The resource devices periodically poll the controller and launch the jobs requested, thereby downloading an operating system template and launching a container where a service can be installed: a sliver of a given slice.

7.3.3 Community cloud infrastructure

The infrastructure layer (IaaS, scenarios (b) and (c) in Figure 7.1) includes the infrastructural resources of the Guifi.net CC. These are i) user-oriented cloud devices, acting as local interfaces or proxies between users and the cloud, so that participants can interact with these devices and the rest of the cloud through a web user interface, ii) dedicated computing and storage devices, devoted to running service instances and storing pieces of data, iii) the underlying network infrastructure, and iv) the locations where these devices are housed. All these resources can be sliced (virtualised) to be shared and provide isolation across multiple users (containers for computing and storage, VLAN or SDN for networking, and rack space in shared locations).

Cloud user devices Home devices running Cloudy as described in Section 7.3.1. The hardware used is either desktop PCs (e.g., Dell Optiplex 7010SF), mini PCs with Atom CPUs (e.g., Jetway, Minix NEO Z64, Jetway JBC372F36W-2600-B), or single-board computers (e.g., Beaglebone Black, Intel Galileo, or Raspberry Pi).[14]

Cloud resource devices Pure server devices run the Community-Lab resource manager, as described in Section 7.3.2. The hardware corresponds to network-attached low-power computing devices (desktop, mini, or rack computers) deployed in diverse community locations. In the peak of the deployment, during the CONFINE project (2011-2015), there were 80 resource devices. All these devices are managed through a single resource controller where a set of containers (a slice) can be deployed on several resource devices in multiple locations.

[11] The software was developed in the CONFINE (EC FP7-288535) research project, as the Community-Lab.net testbed, with a set of research devices in multiple locations of several CNs. Initially intended to run research experiments, it is integrated in the Cloudy software stack to run experimental services distributed across several resource devices.

[12]

[13] Also known as CONFINE controller or Community-Lab controller: https://wiki.confine-project.eu/soft:server

[14] More details on the hardware installation procedures with performance and typical workloads in http://cloudy.community/es/hardware/.

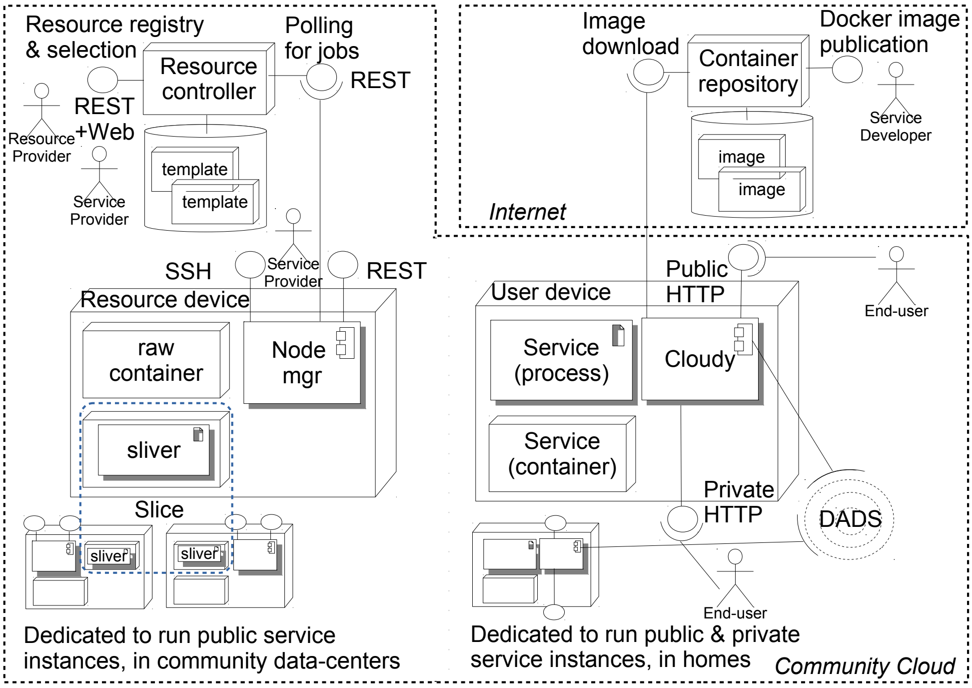


Figure 7.3: Structure and components of a community cloud deployment.

Underlying network infrastructure All server devices are connected to the Guifi.net network, most of them in the Barcelona mesh network. The rest are spread across other rural or urban areas. We also have a few servers in the campus network and connected to other ISPs. A tinc overlay can be used to create a distributed overlay network with tunnelling and encryption across multiple ISPs, even bridging over NATs. Therefore, the model, software, and deployment can run on any IP network, including the open Internet.

Locations The devices are typically deployed at homes together and connected to the network router as well as in-service rooms, offices, or our research laboratory. Without restrictive environmental requirements, the devices just need power and network (wired or wireless), without any I/O connected device, as management is done remotely over the web or ssh interface. Most other Guifi.net locations for routers qualify (e.g., homes, service rooms in buildings, street cabinets, warehouses, and public data centres). Only the resource controller server is a rack server hosted in the university data centre.

7.3.4 Community cloud platform

The Cloudy platform layer (PaaS) offers services oriented to develop and support CC applications in a decentralised setting. The current platform includes three essential generic services, and three specific Guifi.net services are also part of the platform. The generic services are:

Distributed announcement and discovery of services (DADS) This is responsible for automatically discovering the services available in the network and to present them in a meaningful manner. This is a critical service in a decentralised community context because the services are made available in an uncoordinated fashion. Moreover, DADS is based on Serf, a tool for cluster membership, failure detection, and orchestration that is decentralised, fault-tolerant, and highly available [73], which uses a gossip protocol based on SWIM.[15] The Cloudy web interface presents the discovered services grouped by category (see Section 7.3.1) and allows sorting the services according to several metrics including locality (based on latency) and availability.

User authentication service This service provides user authentication through a recognised independent third party that manages a registry of users. The concept results from the evolution of the solution to the authentication needs of the Guifi.net federated proxy system. Currently, it is implemented using the LDAP protocol in a redundant master-slave architecture hosted and operated by Guifi.net foundation.

Service activation and deployment Pre-configured applications or generic application containers can be started as Docker containers. These applications can be private or public (shared) in the CC (not in the open Internet).

The three main Guifi.net specific services that have been integrated in the Cloudy platform layer are:

DNS service To participate in the Guifi.net DNS system for the resolution of internal addresses (RFC1918). It is based on BIND.

Network monitoring To contribute data to the network monitoring system. It is implemented using SNMP feeding RRDtool ring buffers.

Web proxy To be part of the hundreds of Internet gateways contributed by volunteers that allow other Guifi.net members to have free best-effort Internet access. Any validated user can access any of the federated web proxies. The service is based on the Squid proxy software.

7.3.5 Community cloud application services

To identify the most demanded SaaS components, we did a survey of the application-oriented services offered in several European CNs, including Guifi.net. Given that our work was primarily intended for this CN, we complemented our work with interviews with Guifi.net participants in several face-to-face workshops. Our analysis [156] showed, on one hand, that remote file storage (backup, replication, and remote access) and video streaming of community events were almost common factors in all the cases, and on the other hand, that a solution to the diversity of other applications was mandatory to ensure the success of our development. The second finding motivated the *activation and deployment* service presented in Section 7.3.4. In response to our first, the following third-party applications have been integrated (pre-installed) in the current Cloudy software stack:

Syncthing A decentralised cloud storage system with cryptographic features for privacy, which gives full control to the users over where their data are replicated and shared with a group.

Tahoe-LAFS A fault-tolerant encrypted decentralised cloud storage system, which distributes user data across multiple servers in replicated data chunks. Even if some of the servers fail or are taken over, the entire file store continues to function correctly while preserving the users' privacy and security.

[15] SWIM: Scalable Weakly-consistent Infection-style Process Group Membership Protocol.

WebDAV server A set of extensions to the HTTP protocol, which allows users to collaboratively edit and manage files on remote web servers. Implemented with the Apache Web server DAV module.

PeerStreamer A peer-to-peer media streaming framework with a streaming engine for the efficient distribution of media streams, a source application for the creation of channels, and a player application to visualise the streams.

To ensure a satisfactory user experience, each application was carefully tested and some were tweaked (e.g., PeerStreamer) before becoming part of the pre-installed applications of the Cloudy software stack [137]. Assessments were done for Tahoe-LAFS [136], PeerStreamer [134], and the search service [133]. The evaluations included the deployment of the applications under realistic conditions on several nodes in the CN, considering the relevant metrics affecting the user experience in each case (e.g., read times in the case of Tahoe-LAFS, video chunk losses in the case of PeerStreamer, and service discovery effectiveness in the case of the search service).

7.4 Feasibility analysis of community clouds

The feasibility of our concepts and developments were tested in Guifi.net. For this purpose, we bootstrapped a CC inside this CN. The first Cloudy instances were deployed in March 2015 and are still active (September 2017). The main objectives were:

a) Confirm the feasibility of the deployment (hardware and software) with a group of volunteers, and evaluate its performance and overhead in a realistic environment, starting from the first release of the software. Section 7.4.1 summarises the features of our experimental deployment, and Section 7.4.2 presents quantitative results.

b) Work with a group of volunteers from Guifi.net to co-design, fine-tune, and evaluate the benefits and limitations of the software system. Section 7.4.3 presents the main qualitative results from that experience.

c) Discuss and develop the governance model with the participants and their experience as participants in the Guifi.net CC. The results were the basis for Section 7.2.

d) Discuss and assess the interest, feasibility, and sustainability of specific community services of interest. Section 7.5 describes our analysis and experience for the case of file storage.

The main findings of the feasibility analysis of the software system, which provide an answer to our first research question, are presented in Section 7.4.4.

7.4.1 Experimental deployment

To test the software system under realistic conditions of number, distribution and heterogeneity of users, devices, locations, and connectivity, we prepared an experimental deployment in the Guifi.net network. In June 2015, as part of our research in the Clommunity project, we made a call in the Guifi.net mailing lists for volunteers to host MINIX NEO Z64 Android TV devices (150 € each) with Cloudy installed to be connected to active network nodes. The initial plans were to donate 25 units, the number funded by the project. Nevertheless, given the positive response, we finally donated 28 in the first call, and we made an additional call in July in which we donated another 16. In the second call, half of the costs were sponsored by Guifi.net foundation and the other half by the end users. Beyond the sponsored devices, we know that, until the end of the year, around 15 additional devices were contributed by community members, making a total of 59 user devices involved. In addition, during that period, we maintained around five cloud community instances of our Community-Lab cluster online. There is a public Cloudy instance available online[16] for demonstration purposes.

7.4.2 Quantitative evaluation

With the aim to assess the ability of the Cloudy-based CC to operate in the experimental deployment, we performed experiments to qualify its operation. We evaluated the performance and availability of several services and applications, reported in [137]. However, the performance results reflect the performance and variability of the underlying Guifi.net network across Cloudy devices and the network influence on each specific application, but does not help to judge Cloudy itself. The most representative metric we found about the value of Cloudy comes from the number of nodes and service instances reachable from a typical Cloudy node. As the discovery service presents to users the list of discovered service instances for a given service, in order of growing latency, the number of accessible nodes and services represents the level of choice that a Cloudy instance offers to its users. Beyond that, the choice and usage belongs to each CC service instance, and the resulting performance will depend on the specific devices and networks used.

Figure 7.4 shows the number of Serf network nodes and the accessible services seen by one of the Cloudy nodes in a typical week during the pilot study (end of November 2015). The figure is representative of what was observed over the duration of the pilot. The variations over time are due to the changes in the network conditions (load and network partitions) and the number of cloud nodes and services made available by the participants. The 'Serf' (top) line corresponds to the number of nodes of the Serf network seen by that Serf node. It is interesting to note that, despite all nodes having DADS activated by default, the 'DADS' line is usually below the 'Serf' line. This is due either to a manual deactivation of the DADS, which is very unlikely because there is no objective reason for that, or probably due to a timeout in the discovery of the DADS service. This parameter, set to 5 seconds by default, determines the maximum time allowed for responses to the search service queries. Thus, the most plausible explanation for the differences is that some of the nodes of the Serf network are too far away in terms of latency to be able to respond to a search query on time. The rest of services presented in Figure 7.4 are self-explanatory, except for the 'OpenVZ', the initial solution for computing virtualisation, which was later replaced by Docker. Current values can be seen at any time at publicly available Cloudy instances.

We know that at least two of the sponsored devices were not properly installed. Thereby, the rate between the total number of Cloudy instances deployed during the second half of 2015 that we are aware of (62), and the average number of online cloud nodes at the end of that year (50) was around 80 %.

7.4.3 Qualitative evaluation

Our main source to get qualitative feedback was informal interaction with the community, which we already started during the design process, and it involved at least 64 members. These interactions took place in two plenary meetings with a year of difference, several smaller meetings

[16] http://demo.cloudy.community User: *guest*, Password: *guest*

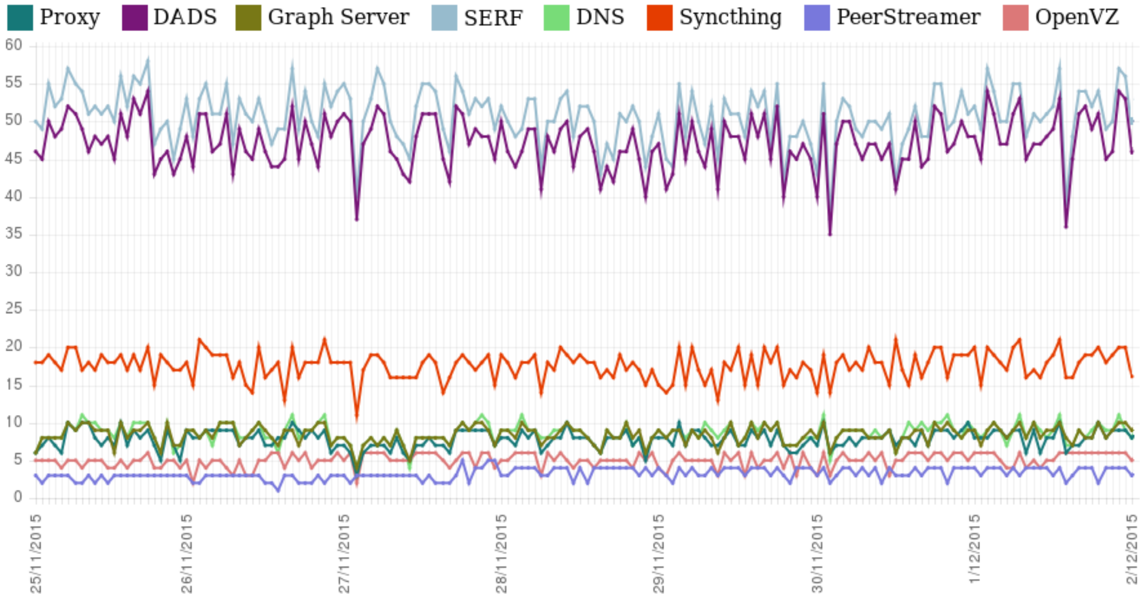


Figure 7.4: Number of Cloudy instances and services in the community cloud during a typical week (sampling period: 1 hour).

in different locations (Guifi-labs), short and small weekly follow-up meetings between a few members of the community and the research team, and the continuous interaction in two mailing lists. According the discussions with the users, Cloudy was considered a useful instrument that effectively addressed some of the practitioners' needs and has a lot of potential. The most frequent motivations for adopting Cloudy are the easiness to install and activate services, particularly the Guifi.net specific services that are otherwise difficult to set up (see Section 7.3.4), and the flexibility to decouple services from servers. The users have acknowledged the ease of installation of the distribution as a key aspect for a successful uptake, and the search service as a satisfactory alternative to the current publishing services system (a static web page). The unification of management tasks through a meaningful website has also been well received. The main drawbacks were the need to go through an installation process, the limited set of applications, and the difficulty to expand the system with new features or customise the software.

7.4.4 Findings and implications

The positive qualitative feedback matches the quantitative results. The high rate of online nodes (around 50 on average) and the estimated successful adoption rate (around 80 %) are well aligned with the positive comments received. This is also supported by the number of nodes contributed by the community members during the first half year: 15 fully paid by them plus another 16 partially paid (50 % contribution).

The experience with the design of a CC, implemented through the Cloudy software stack as a key element, combined with the co-design and adoption of the CC governance model and the quantitative and qualitative evaluation of adoption by the Guifi.net community validates the feasibility of CC as open commons. Feasibility is not only achieved at the level of 'system prototype demonstration in operational environment' (TRL 7) but, as being adopted by the Guifi.net community, it can be considered 'actual system proven in operational environment' (TRL 9). The identification of key social and technological artefacts and factors that result in showing feasibility at certain levels is the answer to our first research question, further discussed in Section 7.6.

The difficulties found are mainly intrinsic to any experimental software system with a small developer community and were helpful to drive the development towards including more applications, particularly an extension that allows running third-party services, such as Docker containers, to increase the range of applications available. The fact that the system has a web interface was considered another limitation. In fact, while the majority found the system very useful to offer specific Guifi.net services, a few users expressed decreasing interest given the software was less polished than other free commercial offerings. Regardless, these negative results were expected from such a pilot with limited resources, and this was not our ambition in the research.

The range and quality of the applications have an effect on the interest and value of a CC. The next section provides a detailed analysis of the technical feasibility and the economic sustainability of an application of wide interest among the participants in the pilot.

7.5 Sustainability analysis through SaaS: the case of file storage

The analysis of long-enduring CPR depends on two key factors: (i) the design of a comprehensive governance system, which implies the existence of convenient tools to implement it [113] and adapt to change [116], and (ii) the overall goal to ensure the preservation and maintenance. As far as CCs is concerned, we have already discussed the first in Sections 7.2 to 7.4, and in this one, we explore the second.

A system can reach economic sustainability after its total cost is below or equal to its total revenue. In our scenario, the total revenue is the sum of donations, in kind contributions, direct contributions (active participation), and sales. As discussed in Chapters 3 to 5, the emergence of professional activity, which is mostly based on sales, permits overcoming the limitations of the dependency on amateur contributions and increases the growth rate. Therefore, it is essential to elucidate whether such professional activity can emerge on CCs, that is, whether CCs can offer business opportunities. We focused our research efforts on the SaaS layer because we believe that there are few chances to find business opportunities either in the IaaS or PaaS, at least in the initial stages. We were interested in a service to meet the break-even point (the point at which cost or expenses and revenue are equal) as quickly as possible. Thus, we were interested in a service with a good balance between the potential to attract users and the costs to put it in place and operate it.

We eventually analysed a low-cost file backup and synchronisation service (FBSS), a service we developed over Syncthing, which was already part of the Cloudy distribution. The rest of the section is structured as follows. First, in Section 7.5.1, we explore the software design, and then, in Section 7.5.2, we review the technical implementation assessment of a pilot deployment with real end users. In Section 7.5.3, we analyse the economic viability and sustainability of the file storage service, which is compared to the existing cloud commercial offers in Section 7.5.4. Finally, we present our findings and their implications in Section 7.5.5.

7.5.1 Application design

The FBSS we developed is called SwebFS. SwebFS is essentially a web interface for Syncthing,[17] an open-source software that enables file synchronisation between devices that already was part of Cloudy (see Section 7.3.5). Syncthing provides users with control over where the data are stored and how often they are updated. It addresses several features relevant to end users: communication is encrypted, nodes are authenticated, the user can choose where the data are stored, and data can be shared with a group if desired. The Backup Syncthing (BST)[18] is a web application that manages the provision of remote, private Syncthing instances for end users through Docker containers. SwebFS, BST, and Syncthing are part of Cloudy, and combined they implement the FBSS.

There are other FBSS-like cloud services offered by large commercial providers,[19] like Dropbox, Google Drive, SpiderOak, Box, SugarSync. Most of them offer a *freemium* service, with a limited amount of free storage space available to engage customers into one of the paid subscription plans offering more space. These services are based on closed-source proprietary solutions (e.g., the Dropbox client) with data lock-in in the hands of a foreign private company. Privacy handling of these services is a concern if the data of the users are hosted in countries with different data protection laws or the users do not trust the provider.

As an alternative, a few open-source software solutions,[20] provide file synchronisation between devices. To our knowledge, Syncthing is the only open-source application that provides easy multi-device file synchronisation without the need for a central server.

7.5.2 Technical implementation assessment

Even though typical storage services are intended to be decentralised, we prepared a simple single-server experiment to evaluate the technical feasibility of the service. This is an experimental SwebFS server for the FBSS. The hardware of this server exceeds the needs of the service (8 CPU cores, 8 Gb RAM, and 1 TB HDD), but the experimental results are not significantly affected by the hardware choice. Comparable results were obtained with smaller servers of equivalent CPU architecture in preliminary experiments. The server is connected at 100 Mbps to the Guifi.net backbone. We had 10 users involved as participants in the experiment, running a Syncthing instance each, and 10 instances on the server.

The experiment consisted of monitoring the resources used to provide the FBSS to these 10 participating users during a period of two weeks. To do so, the users were required to sign up to the SwebFS server, install Syncthing on at least one of their devices (desktop computer, laptop, mobile device, etc.), link them, and share at least one file repository between them. The users were asked to copy at least 1 GB of data of any kind to the shared repository across their devices and the SwebFS server during the first week and to use this service to synchronise and backup their files as they would with any other commercial service they might be using. No specific protection measures were taken for this experiment to ensure privacy and security. Thus, users were recommended not to use files with personal information.

[17]Syncthing: http://www.syncthing.net.

[18]BST: https://github.com/Clommunity/bst-mux.

[19]Dropbox: http://www.dropbox.com. Google Drive: http://drive.google.com, SpiderOak: http://spideroak.com, Box: http://www.box.com, and SugarSync: http://www.sugarsync.com

[20]rsync: https://rsync.samba.org/ OwnCloud: http://owncloud.org/, Seafile: http://seafile.com, SparkleShare: http://sparkleshare.org/, Duplicati: https://www.duplicati.com/

Hardware requirements			Costs			
Resource	**Per user**	**Per unit**	**Item**	**Base**	**Per unit**	**Per year**
RAM	27.6 MB (Active sync)	37 users (1 GB)	**Server**	3,000 €	Depreciation over 4 years	750 €
CPU	0.1 (Active sync)	10 users (1 core)	**Operation**	1 hour/month	23 €/hour	276 €
Storage	50 GB (Average)	20 users (1 TB)	**Hard disk**	0.1 €/GB	Depreciation over 4 years	0.025 €/GB
Energy	–	135 W server 30 % avg. load	**Energy**	355 kWh/year	0.14 €/KWh	50 €

Table 7.1: Estimated costs of resources.

The following metrics (per user) were measured as a reference to estimate values in larger scenarios: *CPU usage*, *RAM consumption* and *network traffic* with a group of 10 users (1 server and 10 client devices). The results were very encouraging: only 0.1 (10 %) CPU usage during active periods and negligible daily CPU usage averages, 27.6 MB RAM usage per user during active periods, and 12.5 MB on idle periods, less than 0.25 kbps data traffic on idle periods, and negligible control data traffic overhead during synchronisation periods, given the amount of data exchanged and the number of nodes involved. We use these numbers in the following economic analysis assuming resource usage scales linearly with the number of users or files, due to infrequent activity periods and file changes, and independent users. A super-linear growth in resource usage would require a redesign of the file storage service, with a lower ratio of users per server, or a redesign of the algorithms to have a sub-linear growth.

7.5.3 Findings and implications

We use the previous experimental technical assessment to extrapolate to many more users for an economic assessment regarding hardware, setup, operation, and service pricing. The summary of costs per resource appear in Table 7.1 and the costs per number of users appear in Table 7.2.

Hardware requirements Although a storage service can have multiple servers, here we focus on a single service instance. Extrapolating from the experimental results, any server instance of the service with similar hardware specifications to the one used in the experiment, per each GB of RAM, can provide service to 82 concurrent idle users or to 37 concurrent active users.[21] In terms of CPU, one core can serve 10 concurrent active users[22] or virtually any number of idle users. The concurrent all-active scenario considered above, however, is very unlikely to occur, as files typically do not change often. Thus, active periods are quite infrequent and short-lived. In addition, we expect that most of the users to be disconnected most of the time, with periodic or sporadic connections to synchronise, which is a short active period between the long idle periods. Although usage patterns may vary significantly according to scenarios, we can assume a 100x ratio of disconnected over connected users at any time. In fact, memory, processing, or network congestion due to many concurrent active sessions would only lead to longer synchronisation time, which is unnoticeable in most cases. Consequently, the service resources can probably be oversubscribed with much higher order of magnitude without affecting the quality of the service.

[21] $((1024Mb)/(12.5Mb/user))$ and $((1024Mb)/(27.6Mb/user))$, respectively.
[22] $((1cores)/(0.1core/user))$

Therefore, our 10 GB RAM and eight-core server can probably effectively handle thousands of users. In terms of data storage usage, we have considered an average of 50 GB per user (assuming an uneven distribution, with many users storing less, and a few storing much more), that is, 1 TB for every 20 users. However, in a group file-sharing scenario, or with de-duplication mechanisms, the average user usage estimation can be safely reduced.

Costs The yearly operation cost of a server, with similar specifications to the one used in the experiments in a data centre facility, excluding the hardware storage for the service, plus the personnel costs for maintaining it online is estimated as 1,076 €/year[23] (last column of Table 7.1), for which 70 % corresponds to equipment depreciation, 25 % is server operation, and 5 % is electrical power.[24] Although values can vary significantly in different contexts, it is interesting to note the dominance of the hardware purchase costs. The server consolidation approach can help mitigate the hardware costs notably.

We estimated the cost of the hardware for storage for the service (HDD) at 0.025 €/GB/year.[25] For 1,000 users (see Table 7.2), this represents 1,250 € of yearly pure hardware storage cost that, including the operation cost, nearly duplicates reaching 2,500 €.

The network usage can generate substantial amounts of traffic but only internal to the CN. According to the compensation system (see Section 4.4), that would result in a compensation fee for the network maintenance and improvement, proportional to the share of network traffic for each user. In this section, we assume that this contribution is already included in whatever network service fee the participants pay (e.g., 12 € per month in the Guifi.net community in Barcelona). Traffic to and from the Internet to exchange data with a traditional Internet-based cloud provider would be more expensive, particularly in peak hours. This is an important cost saving in a CN compared to a remote cloud provider.

Service pricing Considering a constant yearly operation cost of 1,075 € for the server and a variable cost according to the required amount of storage capacity, as the number of users increases, the total storage costs grow, but the cost per GB decreases towards the pure cost of the raw storage (HDD), as the effect of operation cost becomes less significant. Table 7.2 summarises the minimum service pricing according to the number of subscribed users, assuming 50 GB per user, all part of the CN.

7.5.4 Comparison to commercial cloud providers

The comparison of the results of Section 7.5.3 with estimates for minimum prices of commercial storage services[26] of large cloud providers (last column of Table 7.2), shows that, beyond 65 users, the cost of our service matches the standard *hot* storage service costs of the main cloud providers (Amazon S3, Microsoft Azure, or Google Cloud Storage). However, these costs do not include data transfers or replication. Depending on the read/write traffic patterns of the storage usage, these costs could easy multiply, making data transfer more relevant than pure

[23] $750 + 276 + 50$

[24] Reference values in our experiment. Yearly server costs: 3,000 € CAPEX over four years depreciation, 30 % load of a 135 W server at 0.14 €/KWh = 50 € electricity, 12 hours of maintenance at 23 €/hour.

[25] Yearly storage costs: assuming 100 € purchase cost per TB of low-cost HDDs with redundancy, depreciated over four years.

[26] We consider three classes of storage service: *hot* means high performance, such as in SSD; *cold* means low performance, with infrequent and slow read access, such as Amazon Glacier; and *warm*, with medium performance and cost.

Total # users	**Storage** [TB]	**Storage** [€/year]	**Storage** [€/GB/year]	**Service** [€/year]	**Service** [€/GB/month]	**Market prices** (comparison)
50	2.5	62.5	0.45	1,125	0.038	N/A
65	3.25	81.25	0.36	1,170	0.030	0.030 (hot)
100	5	125	0.24	1,200	0.02	0.024 (warm)
180	9	225	0.14	1,260	0.012	0.012 (cool)
1,000	50	1,250	0.05	2,500	0.004	N/A
5,000	250	6,250	0.029	7,250	0.002	0.002 (HDD)

Table 7.2: Estimated costs per user (monthly and yearly, in €) of the FBSS for different number of subscribed users. However, market prices that are heavily influenced by network transfers are not included (e.g., price can x4 for 10 % transferred, x10 for 100 %).

Offers for a server (no storage or traffic)	**Monthly cost**
Amazon (Central Europe zone, September 2017)	
'Disaster recovery and backup' (per server)	233
Single EC2 4 cores (m3.xlarge)	179
Single EC2 4 cores (c4.xlarge, m4.xlarge)	138
Smallest dedicated host (c3)	1,528
Community cloud (Small 4 core Intel NUC server, 33 W, 400 €)	
Depreciation over 3 years + energy (0.14 €/KWh)	12 + 4

Table 7.3: Price (monthly, in €) comparison for a server between a commercial offer and a community cloud.

storage in the contribution to overall cost.[27] The references for the *warm* and *cool* storage costs are matched with 100 users and 180 users, respectively. Increasing the number of users, the server part becomes less relevant. As a reference, the pure cost of hardware storage only (HDD) corresponds to 0.002 €/GB/month (or 25 €/GB/year).

Table 7.3 compares the prices of a commercial server offer (Amazon, September 2017) with the cost of a small home server. A CC with these small servers running Cloudy could benefit from the difference in the cost of a server (16 € vs. 138 € or 1528 €). However, there are obvious huge differences between both models: one at home inside a CN managed by volunteers or professionals from the local community not relying on an Internet connection, the other in a remote data centre over the Internet professionally managed at huge scale. We need to account for the maintenance and operation costs of the infrastructure and the software, and the required level of replication for comparable reliability. However, the table shows that, after certain costs are included, the economies of sharing in a CC infrastructure leave an economic margin for local initiatives to provide useful local services given the small cost of sharing a set of computing, storage, and communication resources on stand-by for a pool of running services.

7.5.5 Findings and implications

The technical measurements provided data to estimate costs and prices for a commercial initiative in our CC. The viability of the commercial service depends on the number of users. With 65 users, the FBSS matches the minimum current prices of commercial cloud providers operating

[27]The pricing of commercial services depends on a detailed profile of resource consumption. For instance, there are web applications to estimate costs for Microsoft Azure `https://azure.microsoft.com/en-us/pricing/calculator/` or Amazon AWS `http://calculator.s3.amazonaws.com/index.html`.

on the Internet. With these, or any other number of users, the more read or write access to the data, the more cost-effective CCs become, due to the large difference of costs for local vs remote data transfer. Beyond that number of users, the CC solution has cheaper prices. In terms of costs, the local CC computing servers (virtualised servers or dedicated hosts) are clearly cheaper than Internet cloud providers. We have not considered the cost of software development and maintenance because there are several mature open-source software products for these functions. In our study, we assumed dedicated hardware, but slight additional economies of sharing can be achieved through IaaS CPR. Considering locality in terms of latency, performance, independence from Internet connectivity when it is fragile, and data protection, we can conclude that the CC is reasonably attractive for end users, and it appears to be financially viable, advantageous in cost, and therefore sustainable. There is the additional benefit of promoting local money flows, that is, contributing to local socio-economic development. Furthermore there is a preference in communities to keep data nearby, for privacy and availability reasons, away from excessive data retention and potential exploitation from cloud providers, blockade from attackers or censorship from governments. These results, combined with the discussions of other aspects that emerged in the pilot, allow to qualify the levels of feasibility and sustainability reached.

7.6 Discussion

In previous sections, we elaborated on key aspects of the governance and implementation of CCs, which determine the degree of technological readiness (feasibility) and (organisational, governance, and economic) sustainability of CCs as commons, which relate to our main research questions. Here we discuss several reflections about factors and artefacts that appeared during the collaboration and discussions, as part of the action research, with the Guifi.net community and their participants directly involved: (i) the nature of CCs as CPR, in Section 7.6.1; (ii) the development of the software implementation, in Section 7.6.2; (iii) the experience gained with the deployed system and prototype storage service as it relates to other user-oriented services, in Section 7.6.3. For each topic, we first describe the idea and its relevance, and then we discuss the analysis and lessons learned.

7.6.1 Community cloud infrastructure as a common-pool resource

Despite the lack of benefits from economies of scale in unit costs compared to large remote cloud data centres, local infrastructures have their own technological advantages in terms of latency, better connectivity with end users, partition tolerance, or faster and more regular transfer rates. As a result of local cooperation and sharing, users enjoy cheaper or even free local network traffic, cheaper local cloud infrastructure, and socio-economic advantages from local interactions, investing and contributing to the local economy and promoting local development. The most relevant factors that emerged during the pilot are detailed next.

Participation with contributions Users must be willing to participate with contributions to the CC. These contributions can be in terms of hardware, locations, maintenance, etc. The entry cost is relatively small: a low-capacity and low-power device[28] is enough to start. The installation process is relatively simple, and the devices require little maintenance. These tasks can even be delegated to a friend or trusted member of the community. A large body of research and practical experience in the past has already shown that users are often willing to donate spare computing resources to third-party propositions in exchange

[28] e.g., mini-computers or single-board computers, such as the Raspberry Pi or a NUC device.

for added value [3]. Economic or social incentive mechanisms building on that have been proposed in CCs [93] and CNs [4] research.

Access to nearby strategic locations (e.g., homes, service rooms in buildings, street cabinets, warehouses, and public data centres) is another beneficial factor from CPR clouds. Many key local public and private stakeholders can offer these locations to voluntary and commercial service providers for the local interest. The locations of the resources are valuable assets for enabling innovative locality-critical services without relying on Internet connectivity. In addition, privacy regulations and privacy protection can be more easily fulfilled if a commercial service runs on local CPR-provided cloud infrastructures due to lower costs and more opportunities to audit and control the collection of personal data. Such an approach has enormous potential to address use cases in the smart-city and IoT domains.

Locality and cooperative cost sharing Therefore, there is a local opportunity to beat or complement traditional Internet cloud infrastructure and service providers in terms of pricing or features that stem from locality and the cooperative model of cost sharing in CNs [P3], taking advantage of the shared collective network and cloud infrastructure. In such a model, local entrepreneurs can venture in setting up garage or warehouse data centres, or established organisations, like companies, governments, schools, farms, or factories, can lower their costs by venturing into the IaaS business for local cloud users.

Cost-oriented pricing for local sustainability From a business perspective, CCs offer resources and basic services according to a cooperative commons model with a cost-oriented pricing. The costs should include fair remuneration and local reinvestment to preserve the sustainability of the commons. For SMEs and entrepreneurs, the CPR is a suitable context for experimentation and learning and an opportunity to explore commercial services without a strong initial risk or capital investment. Research about cost sharing in CNs [P3] explores this factor.

Voluntary and professional effort In the commons, we find coexistence and cooperation between voluntary and professional schemes. The first usually comes with no service commitment (best effort or less), while the second involves specific commitments (SLOs) in exchange for service fees. Ideally, both schemes can complement each other. Volunteers can buy and include professionally maintained resources in their voluntary efforts, and professionals can occasionally leverage from voluntary resources or efforts in their services (e.g., software tools and peer-assisted cloud services) in exchange for contributions back to the commons. This close collaboration allows pooling and growth at smaller steps with smaller upfront costs. The FBSS, for instance, can be deployed on a hybrid schema combining a stable server infrastructure with less stable resources from volunteers to handle peaks or growth at the expense of a compensation fee. Local currencies have been explored [5] to regulate these transfers without involving fiat money.

Influence of underlying conditions Community clouds can, in principle, develop over any kind of network infrastructure. While the commoditisation of hardware (low cost), software (free and open), networking (flat rates), and access to locations (facilities for deployment and right of pass) is a major enabling factor for sharing, the major barriers come from differentiation, such as with traffic-based (instead of capacity-based) charging or lack of traffic neutrality (when ISPs do traffic discrimination by throttling or blocking local servers and promote paid fast lanes for major Internet cloud and content providers), or provide asymmetric access (a TV-like Internet).

Scalability Local community commons can also benefit from economies of scale through the local aggregation of resources (e.g., pooling of needs for data stores, remote backups, server consolidation for public websites, databases, hosts, and containers). This way, a group of small and medium local cloud users can act as wholesale intermediaries and benefit from volume pricing from large Internet cloud providers. This requires interoperability and federation mechanisms to group resource needs and to transparently integrate Internet cloud providers as a backend. The wholesale access to Internet carriers or Voice over IP providers by service providers involved in the Guifi.net CN or the digital exchanges discussed in Section 7.2.1 are good real examples of that.

Second-layer organisations A cloud commons can act together as a larger organisational umbrella representing and protecting their collective interests in the face of external agents, like governments, companies, users, regulators, research organisations, investors, and standardisation bodies. Guifi.net foundation, which has played that role for the CN, sees similar challenges for CCs, and an umbrella organisation can represent and more effectively protect a group of emerging local CCs better than CCs can individually.

Validation of the CC model Regarding the validation of the CC commons model, our experience with the Guifi.net CC shows the value of the scenario of 'platform commons' (scenario *c* in Figure 7.1) but also its difficulties. We managed to work with different stakeholders, for example, many volunteers and two professionals interested in the feasibility and sustainability analysis of the file storage service. We also worked with software developers, some supported by research projects and others as volunteers, and we counted on the support of Guifi.net foundation. In the context of the participation framework, we started the dialogues for the cloud computing licence and the compensation system, and although such social processes of deliberation take time to deliver results, the interim results are positive. Therefore, we can conclude we have developed a functional organisational and governance model for a CC infrastructure as an open commons reaching technology readiness level 9 'actual system proven in operational environment' [45], in the specific environment of the Guifi.net community. Applied to other different environments, that may require adaptation, it can be considered at least a 'field demonstration' (TRL 6) or 'system prototype demonstration in operational environment'(TRL 7). From the perspective of demand-readiness levels [159], we have moved from the feeling of 'something is missing' in level 1 to 'building the adapted answer to the expressed need in the market' in level 9, in the specific environment of the Guifi.net community. Furthermore, the model and its discussion can be applied to other communities, as the only requirements are the feasibility factors described in Section 7.2.7, and then the pooling by the CC community of networking, computing, or storage resources.

7.6.2 Community cloud software platform

Throughout our research and interaction with the pilot community and other interested CNs, we identified several factors and artefacts related to the software platform that are detailed next.

Emphasis on digital self-reliance or self-determination This translates in a preference for resilient decentralised CC infrastructures, capable of continuing to deliver their services when facing functional, environmental, or technological changes to a degree that they can support and enhance other critical local infrastructures, services, and applications. We have also perceived a growing concern about the risks of extraction and exploitation of personal data. Some of the main domains we have identified, where these aspects are particularly relevant, include smart infrastructures, such as energy, transportation, waste and sewage, and communications; services for citizens, governments, and industry based on smart monitoring and control; and applications for smart communities to improve the efficiency of services and meet residents' needs.

Software tools and services for the deployment and operation of a CC infrastructure We observe that, similar to the operation of the network infrastructure, a set of software tools and services are needed to ease the tasks of deploying the cloud infrastructure and coordinating its operation and usage. The Cloudy software stack we developed materialises the most urgent services we have identified and facilitates the adoption of the required software components by the users, such as the common user authentication and the DADS services. Therefore, Cloudy is expected to help standardise and unify the cloud infrastructure and service level in CNs, similarly as Guifi.net has achieved through the website and other tools at the network infrastructure level.

The complexity of software However, this results in software complexity that requires a committed community of developers, maintainers, and users. The Guifi.net experience shows that an effective approach to face this challenge is through a combination of volunteers (for testing, reporting bugs, making suggestions, contributing code, documentation, etc.) and professionals (for delivering professional code). To this end, it is necessary to develop a value chain that ensures a minimum revenue stream to pay the professional developers and volunteers. Software that can be customised to work for multiple CCs creates opportunities for more sustainable crowdfunding of these developments. Moreover, this surplus must also allow maintaining, updating, and expanding the existing hardware to keep the value chain alive and avoid a spiral of decline, which is more pronounced in low-cost devices (e.g., we have experienced cases of nodes suffering from cell burnout in compact flash storage and power supply burnout).

Resilience Compared to proprietary cloud environments, community-owned clouds are prone to node failures given their more fragile environment. Replication techniques are therefore essential for resilience so that users will not lose their data. For instance, the Tahoe-LAFS data objects are typically stored on 10 nodes of the storage server pool, but only any three of these are required to retrieve the data. Obviously, this resilience has a cost in terms of network traffic and storage capacity.

Validation of the CC software platform We can conclude that we have reached TRL 9 'actual system proven in operational environment' [45], or at least TRL 7 in other different environments. Although being in continuous evolution and improvement, the software platform is applicable to other communities. Adoption by other communities will define new requirements but will also bring in new contributions. This is the case with a new community in Italy that is preparing a pilot trial of Cloudy.

7.6.3 Tailored services at the network edge and effects on users

Our exercise of working with a community is consistent with other experiences of collaborative system design. Several factors that emerged during the pilot are detailed next.

Collaborative system design Identifying requirements and proposing useful applications is a community building exercise that creates social bonds between experimenters, early adopters, and developers. Sharing knowledge with the rest of the community helps motivate developers to create new services of interest even outside the initial community.

Crowdfunding model of local services In an open environment for innovation, crowdfunding campaigns can sponsor the development of new applications of local interest or of a specialised sector. Some cases from discussions with the volunteers include services required by and for local governments, SMEs, farms, factories, schools, and citizens, regarding environmental monitoring, control of public and private infrastructures, and security or emergencies. A model based on several simple but adapted local solutions can flourish in CCs, opening new markets for the local economy. The idea of micro-services follows this trend [135].

Complementarity to traditional cloud services The presented CC model is complementary to traditional cloud service provisions and can benefit from the integration with it. The inter-cloud integration [26] has been reported to be beneficial in this regard. However, it must be considered that the resources and services at the edge are also more fragile. Thus, the SLAs and guarantees are difficult to achieve for high-demand services [119]. Therefore, interoperability with industry standards like OpenStack or APIs from Internet cloud providers are desirable to merge the benefits of services running on 'big iron' clusters and data centres with the local decentralised structures that Cloudy supports. The resulting hybrid clouds pose interesting research and innovation challenges like the federation of very diverse computing, storage, and networking resources.

Validation of the file storage SaaS Regarding this storage service, we can conclude that we also have reached not only TRL 7 but also reached TRL 9, which implies identifying and implementing the social and technological factors to bootstrap (feasibility) but also to sustain the service (sustainability). The results are relevant and applicable to other end-user oriented applications and other communities adopting the CC model. As Ostrom said [113], regimes should adapt to local conditions, not the other way around.

7.7 Conclusion

CCs at the network edge are motivated by their disruptive potential for changing the future cloud service landscape by expanding the current cloud service offerings with local cloud resources and service infrastructures open for access (usage) and open for participation (construction, operation, and governance). This chapter presents an analysis, design, and evaluation of the artefacts and enabling factors for the feasibility and sustainability of local CCs, through the development of an organisational and governance model, a system architecture, its hardware/software implementation in Cloudy, and the technical and economic experimental evaluation of a storage application. The research combines action research with a community of users from the Guifi.net CN and experimentally driven research on a real deployment.

The first key aspect is about organisational models. To this end, the chapter first reviews the mechanisms that have led the Guifi.net CN, a case of network infrastructure as open commons, to start up and become sustainable. Then, specific issues for the applicability of these mechanisms in CC-based services are discussed. The model we propose, inspired by the experience of Guifi.net but applicable to other communities, implements a CC with the IaaS and PaaS layers organised as an open CPR. A framework of tools (artefacts) to govern such a CC is presented. Some of these components have been already implemented in the Cloudy software stack.

The software implementation and its deployment in the field is the second key aspect. The overall CC model, implementation, pilot deployment, and services have been put into practice in Guifi.net for more than two years of operation with about 60 end-user devices and 64 participants from the community. The results of that experimentation confirm the feasibility of CCs as open commons in a real setting (TRL 9 in the Guifi.net environment, TRL 7 for others), from the concept to the implementation and its governance.

The Cloudy software stack can be extended by its users with new application-oriented services (SaaS). As such, the third key aspect is the evaluation of a storage application service from the technological and socio-economic viewpoints to assess the technical feasibility and the economic sustainability of CC application services in comparison to commercial cloud solutions. The technical analysis shows the application can be implemented and integrated in Cloudy and it operates correctly. The economic analysis for the storage application service shows competitive long-term costs from a rather small number of users. The extended period of experimentation with the Guifi.net CC, combined with the technological and socio-economic analysis of a representative SaaS, confirms the potential for the sustainability of CCs as open commons.

In general, we identify a set of key enabling factors for feasibility (demand, early adopters, technology availability, ease of participation, and licence), and a set of governance artefacts/tools (governance: licence and collaboration agreements; socio-economic: conflict-resolution and sanctioning systems, economic compensation; and coordination: management and provisioning, and communication) for sustainable CPR CCs.

Although we provide compelling findings for an “adapted answer to the expressed need” (DRL 9), further studies are required to extend the results to other services, and evaluate replication in other regions, other socio-economic environments, other CNs, and on a larger scale. It is interesting to note that CCs as open commons, despite being inspired by CNs, can develop in diverse environments, including Internet access networks provided by commercial service providers.

From a broader perspective, our findings on the similarities between CNs and CCs in terms of the capacity of being successfully implemented as participatory CPRs suggest that this approach might be suitable for other types of infrastructure. On this basis, and taking into account the results on the scalability potential investigated in Chapter 6, we conclude that further investigation is required to (i) gain insight into the approach to other particular types of infrastructure, and (ii) derive general lessons and patrons generals, where possible, models.

Chapter 8

Generalisation

Preface

In this chapter we elaborate propose a generic model and elaborate on its applicability domain. The model we make a taxonomy of the stakeholders based on their attributes and define the interactions among them, ...

Our proposal builds on the positive results of our investigations on the capacity of the Guifi.net model to scale and its potential to be exported to other infrastructure.

8.1 Generic model

8.1.1 Fundamentals

Definitions:

Compensation TODO habitualment cost-compensation, però hi pot haver d'altres formes de compensació

Recognition The establishement of a link between an asset and an

Conflictes d'interès: 1)Els part poden tenir diferents rols, però en cas de conflicte d'interés, sempre preval el més fort.
2) en cas de conflicte d.interès es queda exclòs del legislatiu, exec i judicial. Sempre es té veu

Basic rules:

- In one location a single shared infrastructure is built and maintained.
- Neighbouring infrastructures interconnect with each other under these same rules.
- The infrastructure is build through the contributions of the participants.
- Contributions are either in kind or in cash.
- Contributions are recognised if so wishes the contributor.

  discussion: depreciation should be taken into account

- The infrastructure is available to everyone for any purpose, including, but not limited to, the commercial exploitation.
- The obligation to participation in the construction and maintenance of the infrastructure is established based on its usage.
- The ownership right on infrastructure assets only entails the right to retrieve them from the common-pool if no other participant makes use of them or, otherwise, the right is limited to be fairly cost-compensated for them.
- The ownership right entails no other right than those that are internally and explicitly recognised.
- The compensation entails the proportional transfer of the ownership right (from who receives the compensation to who makes the compensation).

  Ramon: un bé compensat ja passa a ser un common good a nivell de ownership right? sempre? entre professionals no? R: és clarament un mecanisme amb la intenció de fer créixer la propietat comuna (com les llicències víriques del software lliure), però pot ser que acabi desincentivant la compensació?

- By default all contributions are compensated. Nonetheless, the ownership right entails the right not to be compensated. In this case the ownership right is retained.
- Measures to boost the commitment to the shared infrastructure are accepted (e.g. reduction of the obligation of participation to those participants who put all their resources to the common pool).
- All rules must be predictable and non-discriminatory.
- Everyone has a voice on any matter of his/her concern.
- Default rule: The collective interest always prevails (over private interests).

8.1.2 Capital expenditures and compensation

The construction of the infrastructure (CAPEX) is done through resource pooling

ownership, initial contributors can:

1) keep the ownership

NB: maintanace is cosidered OPEX

8.1.3 Stakeholders

ownership holders

8.1.4 Body of normative

8.1.5 Appropiation

8.1.6 Cost-sharing

8.2 Expected benefits

8.3 Applicability

8.3.1 Extensible infrastructure

Definition: infrastructure that is relatively easy to expand and maintain in contrast to those naturally limited or hard to expand such as natural resources.

Examples:

8.3.2 Other infrastructure

* traditional infrastructure

TODO

Chapter 9

Conclusions

With the ambition to contribute in the search of innovative models for infrastructure development and management that allow to overcome the limitations of the currently used, in this dissertation we investigated more participatory models for financing, deploying and operating network and cloud computing infrastructure. More efficient models are necessary to attain and accelerate the delivery of minimum services worldwide, including a decent access to digital infrastructure. Improvements in efficiency translate into a reduction of the consumption of natural resources, reducing waste and environmental impact. Accordingly, several international organisations are tackling the challenge of improving infrastructure management efficiency. In the ICT sector some examples are IEEE and ISOC, and more comprehensively, advances in infrastructure development and management are key for attaining many of the UNESCO's SDG.

We focused on participation because we believe, and our results so indicate, more participation in the infrastructure affairs eventually translates into more efficient management. According to our view, the main underlying problem of the current dominant models of how infrastructure is currently handled is the lack of social involvement in addressing the challenges infrastructure management poses. According to our view, the detachment between society and infrastructural affairs has resulted in a vicious circle: the bigger the gap is, the more hermetic the processes through which infrastructure is planned, designed, deployed, etc. are, which, in turn, enlarges the gap. Even more, we suspect that the current trends to present public affairs as more transparent and accountable, just contribute to worsen the problem. The main basis for these suspicions is our direct practical experience: during the course of our research, we witnessed the evident differences in treatment by public authorities between bottom-up initiatives and the major corporations.

Extending this logic further, as a consequence of the aforementioned vicious circle, there is currently an excessive influence of the private sector. This excess of influence is detrimental to the optimal planning, execution, and exploitation of infrastructure for the following two main reasons. First, because, in order to evade social control, a very narrow and technocratic conceptual vision of infrastructure management is established. Second, because, in the aim of reducing competion, any potential alternative is systematically marginalised. Consequently, in our comparative studies, we took the private sector model as a reference, putting aside the PPP and public sector models.

A satisfactory answer to our research challenges demanded a multidisciplinary approach and a substantial amount of field work and interaction with communities of practice. Our technological background us to focus our effort on acquiring the necessary competences in social sciences, economics and law. In consonance with the holistic approach required, in this dissertation, the term *model* is used in a broad sense, including planning, design, finance, procurement, deployment, operation, maintenance, commercialisation, and service delivery, unless otherwise indicated. Three other concepts play a central role in it: *governance*, *common-pool resources (CPRs)*, and *community networks (CNs)*. Governance refers to all internal processes of ruling and managing a community undertakes. CPRs are systems of resources collectively built and managed in a participatory and open manner. CNs are bottom-up initiatives aimed that building network infrastructure by pooling resources and managing it collectively

Our major underlying concerns were to understand (i) how CNs communities organise themselves, (ii) how can they deploy NGA technology in areas traditionally deemed as unattainable without massive public subsidies (the so-called unprofitable areas), and, more importantly, (iii) whether they were just non-relevant isolated cases that have not the ability to extrapolate, or, on the contrary, (iv) these were experiences from which models and standards could be developed and applied to other network infrastructure, or even to other type of infrastructures, and if so, (v) if we could contribute to make them more efficient. The bulk of our research focused on Guifi.net, which is widely recognised as the largest and the most sophisticated CN.

We selected action research as the main research methodology for its suitability for dealing with communities of practice and for coping with research challenges not explicitly defined since the very beginning. More precisely, the research methodology we followed falls into the domains of ethnographic action research and network action research variants combined, in many occasions, with components of experimentally-driven research. These methodologies also align well the requirements of the industrial doctorate plan under this dissertation has been developed.

After significant interaction and critical analysis of the intermediate results with the practitioners, we eventually formulated the following RQs:

RQ1 Does the approach followed by Guifi.net outperform the private sector model?

RQ2 Does the Guifi.net case have enough unique and beneficial features to be considered a model on its own?

RQ3 Does the Guifi.net model apply to other infrastructures?

To answer the above RQ we conducted the following research activitys (RAs):

RA1 Gathering of performance indicators of Guifi.net

RA2 Description of the differences between the Guifi.net approach and the private sector model

RA3 Formalisation of the Guifi.net model

RA4 Identification of key factors in CNs scalability and related patterns

RA5 Analysis of the suitability of the Guifi.net model for cloud computing infrastructure

RA6 Proposal of a commons-based participatory model for financing, deploying and managing extensible infrastructure

In RA1, in addition to gather representative information on the standard indicators of the sector, which mostly focus on depicting the infrastructure put in place (technologies, coverage), the investment made (total amount, ROI periods), the commercial offerings (type of services, prices, number of competitors), and the level of adoption (penetration), we also looked into the aspects related to opportunities for participation. To the best of our knowledge, these aspects are frequently ignored or addressed partially at best. Due to the lack of standard indicators, we had to investigate which aspects were the most relevant and which indicators were the most appropriate to characterise them. The aspects we finally selected and analysed, both from the potential an effective implementation angles, revolve around the participation in the governance and the economic systems, and the alternatives to engage in the construction and use of the infrastructure beyond commercial options.

Although a systematic and extensive research was out of scope since the beginning due to time constrains and the difficulty of data collection, in our opinion, the information gathered suffices to give an unequivocal positive response RQ1: beyond doubt, many of the results achieved by Guifi.net outperform those achieved by the private sector model in similar conditions, and the rest are not worse. More precisely, we found that Guifi.net provides more effective means for (i) the inclusion of the civil society in the governance system and the inclusion of local SMEs in the economic system, (ii) the activation and aggregation of local funding and financing capacity (even in terms of units of €), deploying in areas so-called unprofitable even without any public support (although the contribution of the public sector –which not necessarily must be in terms of funding support– can accelerate the deployments in an extraordinary manner), (iii) the development of equal conditions for competition (we claim that a commons-based participatory infrastructure results in a single market with nearly perfect competition conditions), and (iv) the enablement of alternatives to the professionals for participating in the deployment and operation, such as associations and coops of users, DIY, etc. Following the comparison with the private sector, we learnt that the two options deliver similar broadband capacity (although not in the same places, as the private sector leaves the less profitable areas unattended), and similar service prices (it must be taken into account that in the private sector model the only existing option for accessing the services is the commercial offerings while in Guifi.net alternative options exist and it is open to the integration of newer ones).

While addressing RA2, we determined that the differences discovered in RA1 are due to profound differences in the most fundamental concepts, starting with the underlying reason for being (*raison d'être*) of each of them. While the genuine ultimate goal of any private (for-profit) initiative is to maximise the profit of the investors and, hence, infrastructure assets are just another resource to achieve this end, the underlying motivation of Guifi.net is to maximise the size and use of the network infrastructure, which is understood as a CPR. These profound differences shapes immeasurably the strategies, investments, planning, etc. and, ultimately, on the features of the resultant infrastructure and how it is exploited. While in Guifi.net terms such as cost-oriented, inclusive, sustainable, redistributive, and local apply, terms such as directional pricing, extractive, market failures, speculative, transnational are representative of the private sector model outcomes.

In accordance with our findings on the uniqueness in nature of the driving principles, in the size of the network deployed, in the quality of the services delivered, in the diversity of participants, in the degree of complexity of the organisational structure and the interactions among the participants, we concluded that the Guifi.net approach deserves to be considered a model on its own, thus, we responded affirmatively to RQ2 and undertook RA3 as the first step to address RQ3. Given that during the literature review we were not able to find any suitable framework for formalising infrastructure models from a broad perspective, we decided to tackle the challenge of formalising the Guifi.net model based on what we had learnt during our interaction with the community combined with the key components we believe a generic framework should have. Following this methodology, we first identified and classified the stakeholder groups, and described their roles, to then look into the organisational rules. As for the stakeholders, we identified three main categories and a score of groups. The organisational rules are structured around a comprehensive set of internal regulation, ranging from the ground rules, which establishes the scope and the driving principles of the project and sets the legal basis for protecting the entire project, to a collection of sets of good practices. A crucial piece of the set of internal regulation is the *Agreement model for economic activities and for the participation in the compensation system*, an agreement that all the for-profit participants (the *professionals*) must sign (among other participants). This agreement model regulates the *cost-compensation system*, the key success factor, in our opinion, of the fruitful economic system developed by Guifi.net as we discovered during the development RA1.

Our detailed analysis of the organisational system of Guifi.net revealed the centrality that the proper management of the conflicts of interest has in the whole organisational architecture. The participants are allowed to have multiple roles and always have a voice. However, the exclusions due to conflict of interest always prevail over the right to participate in the decision-making processes. Consequently, the professionals can neither be members of the governance bodies nor of the system operators. Similarly, the volunteers, or any other stakeholder group including the system operators, cannot dictate on the matters that only concern the professionals. Another direct consequence of the centrality of the proper management of the conflicts interest is the difference in treatment between the professional activity directly related to the CPR (the network) and the professional use of it. The first, in order to avoid conflicts of interest is fully standardised (tasks, prices, times, etc.). The second, in compliance with the fundamental principle of freedom of use of the network, is liberalised, thus, any professional is free to charge what they feel is most appropriate (although, there are rules preventing from dumping practices).

With the model in hand, we were ready to address RQ3, the RQ on the applicability of the model to other infrastructure. Following an incremental strategy, in RA4 we first investigated its scalability through the comparison of Guifi.net with other CNs that is to say, keeping the infrastructure domain (IP networks), and similar social conditions (bottom-up collaborative initiatives). The comparison with less developed CNs let us to better identify and understand the key enabling factors of the Guifi.net scalability. Combining these factors with the evolution of the indicators gathered in RA1 and the knowledge on the improvements that are being introduced we had, we concluded that not only the model does not pose insurmountable scalability limitations, but it can also be replicated and nested.

RA5 pursued a twofold objective. On the one hand we wanted to learn about the degree of exportability to a *not so different type of infrastructure* in similar social conditions, namely whether the general approach were appropriate and the number and type of changes required, and on the other hand we wanted to start researching on the possibilities to extract a more general model. Under the scope of action research as the general research methodology, in RA5 the experimentally-driven research components was explicitly present as we designed, implemented and deployed in the Guifi.net community a product, a GNU/Linux distribution (*Cloudy*), as a central piece of our research. Although its adoption by the Guifi.net community was moderate, in our opinion, the results of our investigation as a whole validated the feasibility and sustainability of a cloud computing infrastructure managed as a participatory CPR.

We believe that the moderated adoption of Cloudy is due to the fact that the focus of the Guifi.net community is on network infrastructure, and not on cloud computing. Consequently, Cloudy was adopted by some of the active participants because it better meet their cloud computing needs, and attended our collaboration requests, but did not get actively involved in its development and promotion. This experience confirmed that the scope of Guifi.net is limited to network infrastructure, which for us is one of its success factors. Notwithstanding the moderate adoption, our particular assessment of having chosen Guifi.net as the community to conduct our experiments of RA5 is positive taking into account that our familiarity with the community saved us a lot of time and eased a lot the interaction.

Combining the results in terms of the capacity for scaling (RA4) and for being exported (RA5) led us to reply in the affirmative to RQ3. More precisely, as a result of our exploratory work in the generalisation of the model, we proposed the attribute *extensible* to refer to infrastructure that is relatively easy to expand and maintain in contrast to those naturally limited or hard to expand resources such as natural commons, and argued that the generalised model is valid, at least, for any infrastructure meeting this requirement.

At this point, we have enough arguments to state that the private sector model is not the most appropriate to deal with the governance of infrastructure due to the imbalance between the goals of a private sector initiative and the mission of an infrastructure. To put it simple, at best, the alignment of the profit maximisation of the investors with the maximisation of the social profit of the infrastructure assets can only happen by coincidence. We claim that such a critical resource for society as infrastructure cannot be left on the hands of the coincidence, specially when alternatives exist. In this regard, we argue that the Guifi.net model, or more generally, the model derived from the conception of infrastructure as a participatory CPR, better deals with the conflict of interest by design and, as a consequence, it is in a much better position to confront many of the gaps of the private sector model without diminishing effectiveness in the areas where the last performs satisfactorily. Furthermore, considering that the Guifi.net model does not preclude the private sector initiative at all but it just limits its capacity of influence on the governance affairs, we consider that the generally used term *private sector model* is misleading and we propose to refer to it as *private sector-driven model*, in contrast with the *participatory CPR model*.

To conclude, we believe that this dissertation brings enough supportive arguments to claim that: (i) at least, network infrastructure can be successfully developed an operated as a CPR at the scale of hundreds of thousands of nodes, (ii) in many aspects the results outperform those from the private sector model or, at worst, it delivers similar results, and (iii) that this approach has the potential to be implemented in many other types of infrastructure.

From the scientific perspective, our main contributions fall under the fields of infrastructure management and of the study of the commons. In summary, in the field of infrastructure management, we: (i) conducted the case study of an essentially human-made infrastructure managed as a CPR, (ii) proposed the concept of *extensible* infrastructure, and (iii) proposed a model for the development and management of infrastructures of this type. In study of the commons, we: (i) provided a case study that belongs to an unexplored area (the intrinsically artificial commons –with substantial CAPEX) and has an unusual size (hundreds of thousands of beneficiaries and hundreds of participants with very diverse roles and interests), and (ii) corroborated the validity of the E. Ostrom's principles for our case study, We would be glad if these contributions contributes to strengthening of relations between these two fields, because, on the one hand we are firmly convinced that the concept of participatory CPR has strong potential in the development of more efficient infrastructure models, and because, on the other hand, we think that the community researching the commons should expand its focus to other goods and services, and look at them from other angles.

As for the communities of practice we worked with, we wish that, through our scientific approach, we contributed to better structure their information and refine some of their processes. It is our hope that theses contributions are at least partially proportionate to the contributions they proportionate to us.

Finally, we hope that our work eventually translates into the implementation of more effective infrastructure management procedures.

9.1 Future work

Considering the contributions proposed in this dissertation and with all the insight gained during the process, we believe that the following research directions can be of interest.

Could the Guifi.net model be applied to the whole Internet? The main subquestions we foresee are (i) to elucidate the scalability limits of the Guifi.net model and the limiting factors, (ii) investigate on the changes it requires to be able to cope with a very-large-scale scale network, and (iii) the viability of the implementation of the resulting model.

We have a sound suspicion that the current state of the model (it must be kept in mind that is in constant evolution –we recommend to follow closely the future evolution of the current discussions within the Guifi.net community is suitable for a bigger order of magnitude than in the existing deployed an operated infrastructure under this model (some tens of thousands of nodes). In our view, the scalability potential of the model is not only due to the capacity to organise infrastructure in a single instance but also for the possibilities for being federated, nested, etc. In our opinion, an aspect this study should include is a risk assessment of the model because the type and extend of risks are very much related to the size of the infrastructure. In this regard, for instance, we have our doubts about whether the Guifi.net foundation is taking an exceedingly leading role, hence, it can become a single point of failure. We are also particularly concerned about the scalability of Guifi.net's current legislative power organisation (direct democracy) and we wonder if novel participation models such as liquid democracy could contribute in this regard without undermining the core principles.

Despite that we have not conducted a specific research on the scalability limits, gaining insights on these limits of the Guifi.net model in its natural domain (network infrastructure) is essential to assess the usefulness of our generalisation model because the last is based on the first.

Further investigation on our generalised model As it has already been clearly stated along the dissertation, the work presented in Chapter 8 is preliminary and requires further investigation. We envisage at least three lines of inquiry to this end: (i) validation and refinement of the generalised model, (ii) validation of appropriateness of the attribute *extensible* to specify the infrastructure to which the model can be applied, and (iii) investigation on the reusability of the model beyond extensible infrastructure. On this basis, a number of specific questions can be posed. For instance: is it possible to develop a commons-based participatory model for civil infrastructure? Is this type of models suitable for infrastructure involving sensitive information like the health systems? How would the massive adoption of these models affect research and innovation?

As in our research, we believe that the research fields presented above demand a substantial level of multidisciplinary. Although, they may require less fieldwork, at least during the initial research stages, and technological skills, they require deeper knowledge in economics and law in general, particular knowledge about other infrastructures.

In our research we have also identified the following points related to the communities of practice that, in our opinion, require further attention (mostly) by the practitioners:

- In many CNs we have observed a noteworthy refusal to for-profit activities. The lack of a commercial option translates into the exclusion of those who either are not skilled enough or do not have the time. Frequently it also often involve a poor or not reliable network service. Based on the lessons learnt in Guifi.net, we believe that preconceptions against for-profit should be reviewed. This recommendation does not necessarily imply they that must adopt the Guifi.net economic system. On the contrary, the positive effects of local solutions advocate for the adaptation of any of the existing or the development of new ones.
- We have also observed a generalised excessive dependency on specific individuals. We perfectly understand that small communities have very little room for manoeuvre, but we believe that for the rest, adopting measures to reduce this dependency would be beneficial in the long-term. We see Guifi.net as particularly affected by this thread.

To conclude, this dissertation has been written as part of an industrial doctorate, thus, it has a strong knowledge transfer component, hence, we consider that the bulk of its contents can be of interest of communities of practice and other players directly involved in the development and management of infrastructure. However, its academic approach may make it too cumbersome for the general public. Thus, we are considering drafting a shorten version focused on the most practical aspects.

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