Oliver, Miquel; Majumder, Sudip

Conference Paper

Motivation for TV white space: An explorative study on Africa for achieving the rural broadband gap

2nd Europe - Middle East - North African Regional Conference of the International Telecommunications Society (ITS): "Leveraging Technologies For Growth", Aswan, Egypt, 18th-21st February, 2019

Provided in Cooperation with:
International Telecommunications Society (ITS)

Motivation for TV white space: An explorative study on Africa for achieving the rural broadband gap

Miquel Oliver
Universitat Pompeu Fabra
miquel.oliver@upf.edu

Sudip Majumder
Universitat Pompeu Fabra
sudipeee@gmail.com

Abstract:

Emergence of digital broadcasting is the key index of the new horizons of communication and media environment. In this paper we will discuss how TVWS, the resultant of digital switchover is approaching for becoming a financially rewarding solution in terms of rural areas than the other cellular technologies i.e 3G and 4G or even for upcoming 5G. We will analyze the standpoint of digital switchover around the globe and will try to the look at the white space capacity. There has been several TVWS pilot testing all over the world, specially in Africa region and we will try to evaluate their inclusive performance as they match the needs to deploy mobile broadband in rural and low-density areas. After shortly presenting the case, we will try to measure the potential of TVWS technology in terms of the other regions around the world which share the same teletraffic profile and socio-economic condition. Also we will try to present the importance of regulatory issues with ICT strategies and market development with proposed design and recommendations along with the future of of TVWS and the future of spectrum.

Introduction

According to World Bank, 75% of world's population has access to a cellular phone, while 95% of the global population now covered by mobile-cellular signal. The penetration of mobile internet is more restricted than cellular penetration. It has been revealed that 57% of the world population does not have access to the internet [1]. If we talk about internet penetration in Europe, IDATE's data show that more than 34 million rural inhabitants of the EU do not have access to either wired or mobile broadband. Data from the ITU Releases shows that, the growth in Internet usage hence the revenue growth has slowed down recently. For example, in Asia Pacific, revenue growth has slowed sharply in recent years, reflecting declining subscriber growth. Increasing competition in certain markets along with the growth adoption of IP messaging services and a challenging macroeconomic environment has a deeper impact on that.

The foremost obstacle for ensuring the global coverage and achieving the rural broadband gap is the higher cost margin. There are several technologies such as GPON, projects like Terragraph and ARIES by Facebook, Satellite Broadband, Unmanned Aerial Vehicles (UAVs), TVWS etc. Apart from cellular technologies and TVWS, other solutions strongly lack the perspective of gratifying the rural broadband gap due to higher deployment and operative cost. The cellular technology is mostly urban oriented and has been unable to efficently serve rural areas. This is because the traditional cellular models are not economical for areas with low user density and lesser revenues [2]. On the other hand, TVWS technology is a WiFi-inspired technology which are considered to be the most robust and cost-efficient solution in rural

scenarios. As the digital switchover from existing analog TV transmission to digital counterpart has already being started, and in many countries it's already being implemented, this TVWS, the underutilized portions of the terrestrial TV bands are becoming more and more evident around the globe. The essence of unlicensed spectrum is that any certified device can operate within it, with only minimal restrictions placed upon the uses to which it may be put. Unlicensed spectrum encourages manufacturers to collaborate in the development of open standards, and to compete in the delivery of low cost components and user equipment [3].
There are several TVWS pilot project which are already deployed, at least in 18 countries [4]. For all these pilots, no interference with the current broadcast TV service have been identified. It is noticeable that, most of these trials are being conducted in rural areas in underdeveloped or developing countries which have socio-economic challenges like affordability and consumer readiness.

The main problem of the rural areas are that they are very underprivileged of using the internet. So the prime principle for ensuring the connectivity will be the availability instead of performance or the any kind of ideal user satisfaction. In this paper we will discuss whether TVWS can be a viable option for fulfilling the rural broadband gap as this white-space bandwidth based technologies are low-powered and low cost techno-economic feasible solution and has a propagation of wide-range coverage with greater throughput and lower latency. In this sense, TVWS presents an excellent opportunity for bridging the so-called "broadband divide" [5]. We also make an exploratory study through all the TVWS pilots in Africa (e.g. trials in South Africa, Mozambique, Kenya, Namibia, Malawi, West Africa etc). By this investigation through all the trials and their outcomes, we will examine the justification of the TVWS for overhauling the rural broadband. We analyze the after-effect of TVWS networks using analog TV channel gaps once digital TV is fully deployed and we will shortly discuss about the possible regulatory issues and licensing framework for implementing TVWS.

Rural communities are vulnerable to poorly managed spectrum because they do not have fixed line alternatives. Currently the high cost of spectrum licenses is a major constraint on deploying new wireless services, limiting the deployment of wireless Internet services, and increasing end-user costs. High spectrum prices are also linked to the continued market dominance of the mobile operators [6]. As this rural community has commonly lower ARPU than the other region, and in most cases mobile operators are less likely to invest and deploy. All these TVWS projects are being conducted in collaboration with Microsoft, Google or Facebook. There are several vendors who provides the TVWS solutions (e.g. Carlson Wireless Technologies, ICC Networking, Adaptrum, Redline Communications etc). The motivation for TVWS movement in terms of the technical approach and pricing is very pragmatic and favorable. Considering the Africa region, it is affordable and offers reachability to connect and serve the rural and urban communities. For example, In Botswana, 43% of people in rural areas are being covered through TVWS deployment. Ghana (50%), Namibia (55%), South Africa (37%), Tanzania (70%) are also great examples of TVWS deployment [4]. The potential market for rural broadband is quite substantial. It has been shown that emerging TVWS broadband can support data speeds upto 30 to 50 Mbps. The results of TVWS trials in Africa can set a prior example for all the other geographical alike countries which share the same socio-economic condition and teletraffic profile such as South Asia (e.g. Bangladesh, Bhutan, Pakistan, Nepal etc). In the rural regions, it has been observed that, in most of the countries, especially those are in developing and under developing zone, mobile phone operators do not envision the market as much of a remunerative gain. As that market has nominal potential in terms of money-making, most of the MNOs do not want to expand the infrastructure and do as little as needed. That's where the TVWS can become the applicable solution.

Digital Switchover and Estimating the white space capacity

Older television technology used analogue signal for broadcasting and transmitting the audio and video. Back in 2006 Digital television transition mainly started after an ITU Conference (Regional Radiocommunications Conference, RRC06) where 104 nations agreed on a plan where this analog terrestrial television signal will be converted into digital terrestrial signal with their digital counterparts, i.e to regulate the use of a certain portion of the spectrum (174-230 MHz/Band III and 470-862 MHz/Bands IV-V) for digital TV (DVB-T) and digital radio (T-DAB) usage [7]. Since both analog and digital TV utilize the same frequency bands, DTV standards were designed so that the transmitted digital signal requires exactly the bandwidth of the legacy analog one (8 MHz in Europe, 6 MHz in the US). Therefore, a digital channel entirely replaces an analog one during the switchover procedure [8].

After Digital Switchover a portion of TV analogue channels become entirely vacant due to the higher spectrum efficiency of digital TV (DTV) [5]. These cleared channels can be reallocated again and be used by the regulators to other services. These reallocation process can be done by setting up an auctions between the stakeholders. As an outcome to switchover, the licensed operators, platform operators, network providers are more compelled, due to strict regulations they are now able to offer a range of digital channels. As per RRC06 conference, 106 nations made an agreement to finish up the Digital TV Transition process by June, 2015. But this Digital Terrestrial Television (DTT) in the UHF bands has not been implemented fully yet. It has been successfully completed in most of the countries and for other countries the implementation process has been slower or not even started yet. For example, Russia, Argentina, Bolivia, Indonesia and Singapore are planning to finish the transition in 2019. The progress made in digital technologies has permitted the evolution of terrestrial television, making it more spectrally efficient by allowing, through digital compression techniques, the transmission of multiple high-quality TV programmes in one single spectrum channel (where before it was possible to transmit only one programme per channel with analogue TV) [8]. The newly available white spaces can be used in many other useful cases such as wireless broadband applications. As the mobile broadband traffic are expeditiously growing, wireless broadband applications are getting more and more popular and favoured. The advantages of white space enabled Wi-Fi is signals using sub-1GHz spectrum can travel significantly further than signals using 2.4GHz for the same power level, and may increase the possible range of communication by a factor of 3, and correspondingly increase the area of coverage by a factor of 9. The addition of the white spaces spectrum would increase the amount of unlicensed spectrum available for high data rate Wi-Fi communication by around 9 – 22 percent in a typical location in the US, and a similar amount in other parts of the world [3].

As a result of digital switchover, several stakeholders such as Government and regulators were been able to draw a framework for further reviewing legislation and setting up a comprehensive plan for implementing an attractive consumer proposition for DTT network and DTT services. The most pragmatic key aspect for digital switchover was that there was a sufficient penetration of digital receivers – 95% is the target adopted in many cases – and good availability of receivers for consumers [9]. Outcomes of switch-over are clearly positive for the consumer, as digitization increases choice of distribution mode (people can receive programming through digital terrestrial, cable, satellite or broadband platforms) and content (digital television offers the opportunity to expand the number of media sources and programs, which can promote pluralism and encourage new voices) [10]. Due to digital switchover, in the US, it enabled the reallocation of the 700 MHz band. Australia has announced that it will also have a digital dividend in the 700 MHz band while countries in the European Union are aligning around a smaller digital dividend from 790 to 862 MHz. In these countries the digital dividend has already been, or expected to be allocated predominantly to advanced mobile cellular and mobile broadband networks using technologies such as HSPA, WiMAX or LTE. [11].

Ofcom revealed that over 50 percent of locations in the United Kingdom have more than 150 MHz of terrestrial white space available for cognitive access [12]. USA has more white spaces than the European region. A results show that at an average location in a representative European region about 56% of the spectrum is unused by TV networks, compared to the 79% in the USA [13].

Land-based terrestrial DTTV signals has prior advantages over analogue transmission like the efficient use of spectrum, getting more capacity, with better quality images and lower operating costs for broadcasters. With the evolution of time, technological advancements have emphasized the need for new trends to cope up with the emerging requirements in every field. In case of wireless telecommunication, the prospect of meeting the ever-increasing requirements due to envisaged saturation of existing cellular capabilities calls for new directions for evolution [2]**.** This released frequency channel can be used for various innovative interactive services, terrestrial HDTV and in mobile communications.

TVWS Technology and Specification

For providing broadband we can have either wired solution or wireless solution. For wireless solution, Satellite broadband can be named as an option, but definitely not an effective one. As in satellite broadband, a customer having an antenna connecting with an orbiting satellite linked to a faster internet connection back on Earth – is technically available anywhere in the country. But it is slower, and often more expensive, than wired broadband connections. And its connections are vulnerable to bad weather. For Radio connections which can serve rural broadband quite significantly. One type, called “fixed wireless,” requires customers to be within sight of a service tower, much like a cell-phone speeds can be up to 20 megabits per second. Other options just being explored involve frequency ranges that are newly available. An approach using “white space” signals would transmit data on channels previously used by analog television broadcasters. Its signals, like TV broadcasts, can travel several miles, and are not blocked by buildings. Another frequency range around 3.5 GHz, called “Citizens Broadband Radio Service,” could let rural internet companies’ use frequencies previously reserved for coastal radar – even in places far inland. [14].

Every TV Station has its own frequency channel which is entirely dedicated to them by the regulatory authority of that particular country or region. When the regulatory authority intent their radio spectrum planning, they geographically separate the TV coverage areas with different channel for broadcasting to avoid radio interference in overlapped areas. TV White Space (TVWS) refers to those TV channels which are in between those frequency band that are not used for TV broadcasting at certain locations at all times. TV white spaces (TVWS) are “portions of spectrum left unused by broadcasting, also referred to as interleaved spectrum”. Widely, TVWS are also referred to as those currently unoccupied portions of spectrum in the terrestrial television frequency bands in the VHF and UHF TV spectrum (be it analogue or digital, generally in the UHF band) [15]. In a simpler way, The TVWS spectrum represents large portions of the UHF (300MHz-3GHz) spectrum, that is hundreds of MHz, (in some countries it and also includes VHF that is becoming available on a geographical basis for sharing uses). This spectrum can be used by primary users (licensed) or by secondary users that using unlicensed equipment can, share the spectrum with the digital TV transmitters and other users such as wireless microphones [16]. The amount of available terrestrial white space depends upon various factors, such as: geographical features, the level of interference potential to the incumbent TV broadcasting service, TV coverage objectives and related planning, and television channels utilization [15].

White spaces exist naturally between actively used channels but assigning nearby transmissions to immediately adjacent channels will cause destructive interference to both. In addition there is also unused radio spectrum which has either never been used, or is becoming free as a result of technical changes. In particular, the switchover to digital television frees up large areas between about 50 MHz and 700 MHz. This is because digital transmissions can be packed into adjacent channels, this means that the band can be compressed into fewer channels, while still allowing for more transmissions [17]. Most of the countries around the globe are performing this switchover, for example for Latin America, most countries planned the switch-off of the analog TV as the last milestone of the digital dividend process between 2019 and 2025, depending on the area and the deployment of infrastructures to support the distribution of the digital TV along the country [4].

For the average person residing in this region, the difference is smaller but still notable: 50% versus 63%. If restrictions also apply to the use of adjacent TV channels, only 25% of the spectrum would remain available at an average location, and just 18% for an average person in the considered region. Note also that these figures were obtained considering TV transmitters only, and including constraints related to, e.g., wireless microphones, might reduce the numbers further depending on local regulations [13].

Digital Terrestrial Television became a reality in the mid-90's, when DVB-T and ATSC A/53, the two main standards to enable terrestrial transmission of digitized TV signals, were approved and adopted in Europe and the US, respectively. Since then, various similar standards were developed for use in other countries, mainly in China (DMB-T) and Japan (ISDB-T). Going a step further, in Europe, the second generation terrestrial standard (DVB-T2), adopted by ETSI in 2009 [5]. TVWS born as a technology from Cognitive Radio studies used by the US Army, in which, the used terminals with the application of algorithms reach to connect and establish communication with other devices through finding free channels in specific instants of time. The challenge of implementation is achieve that each of the network devices can access into an unoccupied channel with the security conditions established, so that the powers do not generate negative consequences with adjacent channels [18]. The lower frequencies of TVWS bands can result in lower energy consumption compared to WiFi/Zigbee. Time-division duplex (TDD) systems are preferable to frequency-division duplex (FDD) when using TVWS, since FDD requires a fixed separation of base station transmit and terminal transmit frequencies, and this condition restricts the number of TVWS channels available. The requirement to avoid adjacent channels may be imposed if the TVWS transmitters have outof-band emissions that are too high. The combination of FDD and adjacent-free would severely reduce the amount of spectrum available and is best avoided [16].

There are many TVWS available over the world. Due to exponentially rising in data traffic, the range of applications are also growing in an utterly innovating way. The usage of this higher data traffic are spreading from public cellular system to enterprise wireless network. Nowadays, M2M communications, Internet of Things including Smart City and the industry revolution are making the whole paradigm shift. We need more internet capacity to provide robust and secure communications systems. These applications have higher bandwidth demand. Cellular networks have dedicated channels which varies upon one countries to another. The way cellular penetration and data consumptions are sloping upward, in a distant future this licensed frequency spectrum will be saturated eventually. That is where TVWS can be a viable option which will provide a secondary platform for long-distance coverage and high-capacity Internet access. TVWS has a prior advantage when it comes to propagation characteristic, as it is located at lower frequency spectrum bands than Cellular. UHF (and VHF) band allows wider communication distance and better penetration through barriers. That is why nowadays TVWS has been considered a prime option for M2M communication, super Wifi, Video Surveillance and Disaster Planning [19].

In November 2008, the FCC adopted a report setting out rules allowing licence-exempt cognitive devices to operate in TV White Spaces. In summary these rules require cognitive devices to use a combination of spectrum sensing and geolocation. The devices must be able to sense both TV signals and wireless microphones down to −114 dBm, and must also locate their position to within 50 meters accuracy and then consult a database that will inform them about available spectrum in that location. When a high power cognitive device operates in a vacant TV channel, energy leakage to adjacent channels may cause interference to TV sets that are tuned to these adjacent frequencies. To eliminate the occurrence of such adjacent channel interference the IEEE 802.22 Working Group prescribes that if channel N is occupied by an incumbent, then cognitive devices should not only vacate this channel but they also should refrain from transmitting at channels N ± 1. The paper shows that on average ~ 150 MHz of TVWS is available for access by low-power cognitive radios. This is a significant amount of spectrum, for example in comparison with the UK's 3G spectrum, which is 140 MHZ [20].

Terrestrial television operates using very high powered transmitters, which broadcast signals over a very large area. A typical DTV transmitter will broadcast using a power of hundreds of kilowatts, and can cover millions of households. In contrast, a cellular base station transmits at a power of tens of watts and can cover typically an area of a few square miles. To avoid interference, neighbouring DTV transmission areas do not use the same frequencies for transmission. This results in a large number of vacant channels in the television bands in any particular location, and these are termed the white spaces. Technology companies such as Microsoft, Dell, Google, and Hewlett-Packard, public interest organisations, and other groups have advocated in filings to the FCC that the white spaces should be opened up for the use of unlicensed applications [3].

To deploy TVWS technologies, the most crucial thing is to have a spectrum database where we will save a list of all available free channels by location. We have to remember, this available white space does not mean that a particular white space device (WSD) can freely use all of them. It has to be coordinated by the regulatory authority of that region. For example in USA, FCC allows for a variety of legislative entities to use this spectrum. In UK, Ofcom does the same. The rules and policies are determined by those entities and all of the WSD devices must maintain specifications. For example, the devices which operate according to the TV Whitespace rules are referred as TV band devices (TVBDs) by the FCC. TVBDs can be categorized in to two classes: fixed and portable/personal. The portable devices are further divided into Mode I and Mode II devices. Fixed devices are permitted to transmit up to 30 dBm (1 watt) with up to 6 dBi antenna gain, while portable devices are permitted to transmit up to 20 dBm (100 mw) with no antenna gain [17].

TVWS is basically and two way communication with longer coverage and high data throughput. TVWS spectrum database is being updated periodically that tells white space device which vacant frequencies to use. It calculates which frequencies will be the best to use, that does not interfere with active TV signal. Fixed registered WSD will be first authenticated and then connected with the database. WSD has to be able to determine its GPS location and will ask the database for the vacant channel. Afterwards, database will check the GPS location and will analyze that and then it will govern the WSD the available channel hence it will connected to the wireless broadband network. Depending on the availability of channels in an area, TVWS can offer tens of Mbps per channel over several kilometres. There is potential to increase the bandwidth to offer up to 100 Mbps by combining multiple channels. One of the attractive features of TVWS is that it uses lower frequencies compared to Wi-Fi and mobile networks, thus allowing the signal to travel much greater distances and penetrate permanent obstacles such as buildings and trees, as well as travel around terrain allowing non-line of sight connections. TVWS therefore performs best in rural areas where the spectrum is generally less congested than in urban areas [21]. Spectrum sensing and identification is the most crucial thing in terms of TVWS deployment. Vacant spectrum has to identify flawlessly so that it doesn't interfere with the primary users.

Spectrum sensing techniques can be divided into two groups: individual sensing; and cooperative sensing. Individual sensing approach are further divided into energy detection, cyclostationarity based sensing, radio identification based sensing, waveform-based sensing and matched filtering. Matched filtering is the more reliable in terms of performance though the architecture design is rather sophisticated [16].

If we want to look for the current standards for TVWS devices, currently, the development of standards for devices intended to operate in TV white spaces is centered on two major types of applications:

1) **Wireless Regional Area Network (WRAN):** This standard refers to the low-power devices which are capable of delivering broadband connectivity mainly in rural areas. Similar to IEEE 802 family of standards which covers Wi-Fi devices, IEEE 802.22 the specific version for devices operating in TVWS. The main objectives of this standard concentrates on interference protection of the incumbent television broadcasting service both digital and analogue, considering the shared-basis operation of TVWS devices with the primary TV broadcasting service. There is also a specification under the standard 802.11af, which focuses on cognitive radio techniques for TVWS [15]. .] This standard system operates on frequencies below 1 GHz and for accessing the TV band it uses geo-location database. A customer premise equipment (CPE) device using WRAN can connect to an access point, possibly to an ISP network that ranges over 20-30 kilometers or even more.
2) **Machine-to-machine communications:** M2M communication consists of very low-power radio transmitters used for low-data rate industrial and commercial applications such as monitoring, tracking, metering and control (a realization of the concept of "smart machines"). A proprietary open specification for M2M devices intended for operation in TVWS has been agreed in UK under Special Interest Group (SIG) [15]

There are several vendors which provides TVWS solutions around the world. All of the TVWS pilots are being conducted by them with the supervision of the government and the regulatory authority. The main vendors are Adaptrum, 6Harmonics, and Carlson Wireless. The prices for the devices currently range between £1200 and £4500. These are 1st generation devices and the prices expected to drop significantly when volumes build and the technology becomes more mature [21]. [22] Summarizes the technical information from the vendors which have identified having TVWS equipment, including the main characteristics of their performance.

Table 1. TVWS Vendor's comparison

Vendor Name	Product Name	NLOS coverage	Throughput	Frequency Range	Latency
Carlson Wireless Technologies	RuralConnect Gen 3	10-40 km	72 Mbps base station throughput Up to 24 Mbps client	470 to 698 MHz (US) 470 to 786 MHz (internat.)	25-35 ms (Round Trip)
ICC Networking	RaptorXR	24-32 km	Full-duplex data rates up to 45 Mbps	VHF Model: 174-216 MHz, Channels 7-13 UHF Model: 470-698 MHz	<20 ms
Adaptrum	ACRS 2.0	10 km	Up to 35 Mbps	400MHz - 1GHz	<15 ms
Redline Communicat.	Redline PTP TVWS	50 km	186.6 Mbps (base) 15-25 Mbps (client)	470-698 MHz	<10ms

Case Study: Pilots in African Countries

At the household level Internet penetration is estimated at 77% in Europe by the ITU, compared with just a 7% in Africa. Two major reasons for these inequalities are the limited distribution in many areas of basic Internet infrastructure (international and national backbones and last mile/local networks), and the high cost of access [6]. Due to connectivity challenges in Africa, important companies like Microsoft, Google and Facebook are very much interested and already have invested in many projects for the experimentation with TVWS in Africa.

There are numerous pilots trial program that are currently running or being successfully completed around the world. TVWS are perfectly suited for providing broadband in rural region. In terms of pilot trial, Africa continent is the apotheosis. Africa has a wide range of rural areas with different variations in terrain morphology which pleases the mantra of 'Coverage Everywhere' including the profile of adoption of mobile services.

TVWS deployment can illustrate the difficulties in providing cost-effective solutions to cover a huge part of their broadband market that is not currently covered by traditional wired or mobile technologies. Africa is the second largest continent in the world and covers 6% of the earth's total surface area. Africa covers about 11.7 million square miles with the adjacent islands included. By 2016, Africa had a population of 1.2 billion people which is about 16% of the world's population [41]. The interesting fact about Africa continent is the variation of land area between the countries of them. For example, we have Algeria which has nearly 2.4 million square kilometer, South Africa has 1.22 million square kilometer and on the other side, Tanzania (0.9 km2), Namibia (0.8 km2), Botswana (0.5 million km2), Ghana (0.2 km2) have much lesser area. Despite the fact that Africa is one of the most resource-rich continent, but most of the countries lack economic stability. Africa has been identified as the world's poorest inhabited continent. But for the last few years, there has been a lot of swelling in terms of economic growth, so as per the World Bank, most African countries will reach "middle income" status (defined as at least US$1,000 per person a year) by year 2025 [23]. When we think about the population density of Africa, it is also very shifting.

For example, South Africa has only 116 inhabitants/km², Rwanda has 1100 inhabitants/km², Tanzania has 147 inhabitants/km², and Namibia has only 7.8 inhabitants/km² [24]. In terms of nature, Africa has the most absence of uniformity. Botswana covers an area of 224,610 square miles with over 70% of the country being in the Kalahari Desert. Libya has about 6.4 million people translating to a population density of 9.2 persons per square mile, the second lowest in Africa. The low population density is attributed to the remoteness of the country with a large percentage of the country being covered by desert [25]. There are currently 960 million mobile subscriptions across Africa - an 80 percent penetration rate among the continent's population. Internet penetration is at 18 percent with 216 million internet users, according to the latest Jumia mobile trend report for Africa [26]. Users in Africa are up by more than 20 percent, with the reported number of internet users in Mali increasing by almost 22 times since January 2017 [27]. The African telecom market will grow on average by 6.7% during the next years. They also expect that mobile data usage will grow four times faster (19.6%) than mobile voice (4.7%), and smartphone penetration will grow to 26% in 2018 [28]. It has been observed that, countries with higher incomes have more users accessing the internet. According to GSMA Mobile Economy report 2018, Sub-Saharan Africa has 44% subscriber penetration which will reach to 52% in 2025. And mobile internet penetration is only 17% which will reach to 40% in 2025. In terms of number of mobile connections, with the entrance of 4G and 5G, it will play a major role in the lead mobile network technology and will continue to dominate over the period to 2025. Of the 2.5 billion new 4G connections over the next eight years, 1.1 billion will come from three major markets in Asia (India, China and Indonesia) and a further 1 billion will come from Latin

America, Middle East and North Africa, and Sub-Saharan Africa [29]. Though Africa has one of the fastest growing rate in terms of telecommunication sector, it's still in the early phase of development.

Telecom market of Africa was influenced by poor fixed lined infrastructure. It has enormous geographical challenges with the seas, hills, mountains, rivers or in case of volcanoes. But as the cellular technology has solely been dominated around the globe, there has been a great amount of expansion and improvement in the mobile sector. As most of the African nations has an underinvestment legacy in telecom infrastructures, most 4G establishment in Africa are from a few leading countries mostly in northern and southern Africa. The latest regional appendix to the upcoming Ericsson Mobility Report forecasts that LTE subscriptions will expand by 47 percent from 30 million in 2017 to 310 million by 2023 in Sub-Saharan Africa. The first 5G subscriptions in the Middle East and North Africa are expected from 2020, reaching around 17 million subscriptions by the end of 2023. [30]. According to the report of OpenSignal.com in 2017, South Africa has 68.30% 4G LTE penetration, Morocco has 61% and Algeria has 41% 4G LTE penetration whereas in the South Asian region India has 86%, Pakistan 69% and Sri Lanka has 45% 4G LTE penetration [31].

Geographic pattern, availability of white space and the cellular traffic profile is indispensable factors for getting the output of TVWS implementation. There are several case studies around the world where we can see that, with the minimum cost of deployment we are able to achieve greater data rate and being able to serve more people with broadband internet and other services [18] summarizes a study about TV White Spaces (TVWS) current state in Ecuador, how this can solve coverage problems in difficult to reach geographic zones in comparison with other kind of technologies, facilitating the access to basic services such as Internet and Smart Grids support. There are so many TVWS pilots being conducted successfully with positive outcome in Africa. There was a trial case study from Google which was managed in Cape Town, South Africa. The trial became operational on March 25, 2013. Ten installations located on Stellenbosch University's campus in Cape Town will deliver broadband Internet service to ten primary and secondary schools within a 10 kilometer radius. This trial can be considered as a demonstration to South Africans that broadband access can be delivered effectively and affordably over TV white spaces.

The trial project of Mozambique was launched on the 8th of August 2015; the established network uses 6Harmonics TV white spaces base stations to deliver broadband access and create new opportunities for the education sector, whose access is hindered by the distance between the urban fiber optic and the municipality of Boane. Project Kgolagano trial was conducted in Botswana which were in collaboration with Microsoft, the Botswana-UPenn Partnership (BUP), Global Broadband Solutions, Vista Life Sciences, BoFiNet, Adaptrum and USAID-NetHope.They launched a TV White Space (TVWS) pilot project to provide internet connectivity and telemedicine services to local hospitals and clinics. Project Kgolagano is made possible under an authorisation from the Botswana Communications Regulatory Authority (BOCRA) to transmit using TV white spaces. It is also operating with the support of the Botswana Ministry of Health and the Ministry of Infrastructure, Science and Technology. World's largest TV white space pilot was conducted in Namibia with a collaboration of MyDigitalBridge Foundation in partnership with Microsoft and Adaptrum and support from the Millennium Challenge Corporation (MCC) and Millennium Challenge Account (MCA)-Namibia. It successfully trialled the Namibian TV White Spaces (TVWS) pilot project. The intention was to provide a blueprint of broadband internet connectivity countrywide. Called 'Citizen Connect', the pilot consists of a network deployed over a 62km x 152km (9,424 km²) area covering three regional councils: Oshana, Ohangwena, and Omusati, and connecting 28 schools in northern Namibia. This makes it the biggest TVWS project of its kind in terms of area coverage.

Accra TVWS pilot network was the first trial in West Africa which ran in March 2014, called SpectraLink Wireless, under authorization from the Government of Ghana's National Communications Authority (NCA), and in collaboration with the Meltwater Entrepreneurial School of Technology (MEST) deployed a pilot network to offer free wireless broadband access for its community of Entrepreneurs in Training. The trial has proven the viability of SpectraLink's platform in delivering high speed Internet connectivity through this medium. The purpose of the pilot with MEST has been to test the efficiency of using TV white spaces for Internet radio networks, in an urban environment that presents multiple sources of interference. The network has been successfully tested on channels adjacent to active television channels, over a 10 km link, with no interference observed [32]. There are plenty more TVWS trials which were conducted successfully to serve the rural broadband. For example, Koforidua Polytechnic TVWS trial, University of Limpopo TVWS trial, Malawi TV white spaces pilot, Dar es Salaam TVWS trial and Kenya Mawingu TVWS pilot.

First TVWS Deployment in Malawi, a new WhispPi device was introduced, which tried to replace an 20.000 US$ device that consists RF explorer spectrum analyser, USB GPS and very convenient 4200 mAh battery and maximum error was recorded of 4 dBm only. ASCII 32 is an example of another stand alone high speed device that can be used in TVWS deployment. Safari.com has 78% of the mobile market in Kenya and 18% of the country's GDP flows through that company. It is vital that alternative forces can come into play, in Kenya and elsewhere in Africa. The wide deployment of WiFi is largely because of the fact that it uses unlicensed spectrum and its low cost [33].

Benchmarking TVWS with other existing technologies

Usually, our home network consists of a single access point, but the commercial business network has a tendency to use wide range of multiple access points to provide connectivity throughout the workplace. White space enabled Wi-Fi can categorically reduce the number of access points where 2.4GHz signal does not propagate well. Say, for an isolated island or in a wild area, it will absolute impossible to establish the physical infrastructure for cellular coverage. TVWS will be the perfect choice with multiple hotspots to provide the connectivity.

TVWS bandwidth can be used as a low-power, wide range wireless networking in a strictly localized manner without interfering to licensed DTV transmissions. In general, indoor TVWS devices have less energy consumption compared to ISM ones. For secondary TVWS use, we can mention Sensor and ad-hoc/mesh networks, Regional-area networking, especially suited for providing affordable Internet and integrated services access to citizens in rural/underdeveloped areas not covered by wireline networks and in Femtocell deployment, i.e. TV-band operation of 3G/4G femtocells, eliminating interference to the operator's cellular network [5].

As we previously discussed how spectrum identification, sensing and geolocation database need to be furnished for TVWS deployment. In a recent study it has been shown that pilot channel (beacon) can be a more advantageous solution for protection of the incumbents. Pilot channel is basically a dedicated channel which will be used to notify every WSD about the current spectrum and all about the available free channels.

Rural communities are especially vulnerable to poorly managed spectrum because they are less likely to have any fixed line alternatives. But although there is also more spectrum available in rural areas because there are much fewer existing spectrum users, this has not translated into better spectrum access [6]. Plus due to digital switchover more vacant spectrum will be added. None of the TVWS Pilot trials have been reported with any sort of interference issue [34]. This investigative paper explains the trial that was conducted around the conservation area of Llanarth. The application was made following recommendations by Peter Williams of Welsh Government's ESNR-ICT Infrastructure section to make a visit to the Isle of Arran where TVWS technology is being actively deployed. A company specialising in the deployment of line of sight wireless technology (LOS) and TVWS was commissioned for the pilot, Broadway Partners Ltd. The deployment was using a hybrid solution of 5 GHz LOS and TVWS technologies.

There is a great potential for leveraging white space frequencies to provide badly needed two way telecommunication services in rural areas, especially in developing countries where white spaces are abundant and telecommunications infrastructure is lacking. The foremost advantage of TVWS is, it has much lesser costing in installation and maintenance than the other technologies. Though it lack throughput compared with LTE/LTE-A but considering the target user TVWS can gives data rate upto 15-72 Mbps which is quite sufficient. Ajer estimates the cost comparison of Rural Broadband Connectivity between TVWS and other Wireless & Wired (Fiber optic) connectivity in Bangladesh and it has been observed that, for TVWS broadband wireless connectivity cost for throughput 22 Mbps & 44 km coverage distance (approx.), the monthly cost consumption per site becomes between 10-12 thousand USD. Where as for the other wireless & wired connectivity cost for throughput 10Mbps & 11Km coverage distance (approx.), the monthly cost per site becomes more than 50 thousand USD. TVWS has wider propagation characteristic. It has 5-7 times better coverage for both downlink and uplink direction compared with other wireless (WiMAX/Wi-fi) technology [22]. The cost of the spectrum is a major issue which needs to be considered while making the cost analysis. If the spectrum cost is equivalently higher then the TVWS will become more cost efficient. In [35] authors illustrated two examples where the impact of spectrum price can be seen for higher levels of bandwidth, For the low spectrum price levels (Sweden case) a small increase can be observed but for the high price levels (India case) the networks costs increase dramatically.

With the leadership of Cisco and principal partnership with the University of Strathclyde, 32 other organisations including BBC R&D, Microsoft, BT, 5GIC, Parallel Wireless, Lime Microsystems, Zeerta Networks, the Agi-EpiCentre and Scottish Futures Trust, a project is aiming to create a complete end-to-end rural 5G testbed system for trials of new wireless and networking technologies, in which case, an LTE base station makes use of TVWS and results have shown that downlink speeds up to 45 Mbps can be achieved successfully, albeit with specialized user equipment [22]. Rural and urban areas have lower population and the inhabitant consume very little volume of data and voice traffic. That is why MNOs are not captivated to lay out their network infrastructure spending too much their money compared to Low Average Revenue per User (ARPU). To achieve the universal coverage, wired solutions are always expensive. And project like ARIES, Terragraph or UAVs and Loon have a huge drawback of excessive deployment and operational cost.

Business model and regulatory issues with ICT strategies and market development

When we talk about the regulatory issues with ICT strategies for developing the market and the business model, for the regulators and the other stakeholders burning questions would be to determine the needful during the occurred situation for TVWS service providers and users with regard due to TVWS deployments in the recently agreed digital dividend extension in ITU-R Region 1 and the possible situation in ITU-R Regions 2 and 3 in their digital dividends. Also deciding which party (or parties) would be accountable for funding the costs of TVWS service providers and users in potential scenarios of migration or reallocation of TVWS devices [17]. The white space varies geographically, so bidding them for an auction will be very complex, this may discourage the newer bidders and depress any return to the taxpayer. Main tasks of a national regulator with respect to deployment of TVWS devices would be to ensure their compatible operation with incumbent services and licensed applications. The establishment, maintenance and dynamic update of such databases may represent an added complexity for national authorities and would require thorough studies and trials. For maintaining the database it is important to track the status of border areas, where the knowledge about radio systems used in the neighboring country is pivotal [17]. The outcome of the TVWS trials would be to bring socioeconomic benefits for rural citizens. For regulations purpose ITU assembles 193 countries (grouped in three ITU Regions) to assure, among others, rational use of the spectrum/orbit resources through the consensus-based decision process, "taking into account the special needs of developing countries". As [36] states, ITU mission involves with ensuring meeting the specific needs of countries through mechanism of the World and Regional Radio Conferences, International Conventions/Agreements, etc by coordinating the efforts to eliminate and prevent harmful interference between radio stations of different countries. Also it involves studying and recommending technical and operational standards by Radiocommunication Study Groups and assemblies other tasks include global standardization and development. In case of international regulations as the spectrum/orbit resources are public, the uses of these resources are based on the common administrative regulations and allocations of frequency bands (and orbital parameters for satellite communications). These regulations and allocations are set through the mechanism of international consultations, negotiations, and consensus [37].

The licensing frameworks for regulatory issues includes a thorough co-ordination of the spectrum resource through licensing and registry for both national and international perspective. The purpose of coordination is obvious, to ensure the harmful interference through the establishment of license parameters and the technical compatibility between different services within a band or in adjacent bands. The framework must have to provide a stable regulatory environment for spectrum users in order to encourage investment and innovation [17].

In rural regions with sparsely distributed population, the low consumer base characteristics with potentially more challenging geographical features, has contributed to the lack of connectivity in such areas. Reaching these regions by means of fixed-line infrastructure is capital-intensive; therefore low short-term ROI levels would discourage providers from considering such an option. A wireless alternative is a more viable choice; especially those alternatives than can achieve large coverage areas with fewer base stations (and therefore lowering the cost of infrastructure). Such alternatives can include mobile networks in lower frequency bands (i.e. the UHF bands below 1 GHz, which propagate further, thus achieving larger coverage) as well as satellite-based solutions, and lower-frequency fixed broadband wireless access (or combinations of all these alternatives)

Related to the design and implementation of the system, the radio equipment must support wide band operation and the overall system needs to be cost efficient. [38] analyzes the business feasibility of mobile broadband access (MBBA) services using secondary access of spectrum in the TV bands.

Future of TVWS and future of Spectrum

The strict regulations of the high occupancy of primary spectrum holders eventually diminished the windows of opportunity for the application of TVWS technology. Ongoing controversy and discourse in the US region also making an impact on TVWS regulation. But considering the TVWS solution an unorthodox approach and comparatively new technology, considering the market trend, it is very soon to declare it as a practicable and commercial solution. As radio frequency spectrum is a global parameter, it is then a matter of public policy to ensure an effective spectrum regulatory framework that nurtures harmonization; as well as balancing innovation and scalability of ICT ecosystems. Comprehensive spectrum strategies and policies need to be developed towards sustainable mid and long terms, considering the international regulatory developments; or else spectrum bottlenecks will arise as demand continues to grow. TVWS utilization needs to be assessed within such strategies [17].

5G is about to launch very soon. Likewise 4G & 5G, the scenario for bringing resources into effective action for the rural communities will still be unchanged in 5G. Commercial deployments of 5G mobile technologies are planned in South Korea in 2019 and Japan and China in 2020.

Asia Pacific are expected to deploy 5G services, covering a third of the region's population by 2025. By this time, 5G connections (excluding IoT) are anticipated to reach 670 million across the region, accounting for just under 60% of global 5G connections. Considering the cellular penetration, it has been observed that, revenue growth in Asia Pacific has not been increased at the same rate, rather slowed sharply in recent years. Increasing competition in cellular markets and growing of IP messaging services, the cellular penetration has became almost saturated, with minimal opportunity for future subscriber growth. In the region as a whole, total revenues grew by 3% in 2016, down from 9% in 2013 [39]. Considering the mobile connectivity index such as infrastructure, affordability, consumer readiness and mobile internet penetration, TVWS can serve the rural community to minimize the connectivity gap. As an advantage, TVWS has lower cost of capital expenditure (CAPEX), longer coverage with better penetration, lower cost of operating expenditure (OPEX) with license exempt spectrum and comparative better performance with lower latencies, reduced security risk. There has been studies, which shows, in terms of CAPEX, 90% cost can be minimized using TVWS. Though, for the higher channels antennas are small. As TVWS is generally lies within the smaller band of spectrum, long antennas are can be an obstacle for portable devices. Lots of studies are being running to address the issue, and as the technology is advancing, there are lot of innovations about to come.

All the pilots of TVWS trial had a common undertaking that is to serve the rural people so that they can be connected to the broadband internet. If we look at the TVWS trial in India, it was focused in the city of Mumbai which has an enormous population density of 21000 person per square kilometer. But the drawback of the region is almost 34% is either filled with water or forest. Assuming 4 cells with radius < 500m, about 12Gbps per cell capacity will be required. The current wireless technologies including Long Term Evolution (LTE)/LTE-A will be unable to address this. One of the solutions, therefore, would be to deploy small cells such as dense Wi-Fi hotspots. However, due to non-availability of ubiquitous fiber, backhauling of small cells is a challenge. [40] This paper proposed that TV UHF band radios can be used to backhaul these dense Wi-Fi cells.

Is there enough TVWS globally to deploy such scenario? The answer is Yes, The overall usage of the analyzed spectrum ranges from 4.54% in Singapore to 22.57% in Barcelona, Spain. TV white space estimation has been done in countries like the United States (US), the United Kingdom (UK), Europe, Japan, and India. For instance, in Japan, out of 40 channels, on an average, 16.67 channels (41.67%) are available in 84.3% of the areas. The available TV white space by area in Germany, UK, Switzerland and Denmark on an average ranges between 48% to 63 out of the 40 TV channel bands [40].

What will be the next steps that entity like Ofcom and FCC should proceed? There are still some gray areas in device licence exemption and building up the spectrum databases. Operational parameters of WSD should be calculated more efficiently. For example, Ofcom are currently working to improve some other technical requirements with the exchange of data between the databases that will need to be specified.

Acknowledgement

This work was partially supported by the Spanish and Catalan Governments through the projects TEC2016-79510- P and 2017-SGR-1739, respectively.

Conclusions

After numerous trials, the burning question would be, why TVWS trials have been set for years but not without commercial application. Considering the tight market power of the MNOs, it has been observed that, the government and the regulators are least keen to lodge this concept of deployment. For example back in 2013-14, there has been a movement of TVWS deployment funded by Microsoft in Bangladesh. But no regulatory movement was expressed by the government of Bangladesh on TVWS that time. The credible reason behind that, all the MNOs were busy on starting its 4G licensing during that period. Commercial deployment TV white spaces, specially 470-698 MHz are not being allowed as it has an odds to go through de-licensing, except for research purposes.It is quite interesting the fact that companies such as Facebook, Google etc are focusing on satellite solutions and systems such as HAPS (High-altitude platform station). The use of satellites and aerial platforms has been suggested to address this long-standing problem aka community networking. The potential for rural broadband all over the world is quite significant. For example, potential market for rural broadband based on TVWS in rural area can save 10-15 billion dollars in America, according to Microsoft. The report of Voices for Innovation Advisory Task Force estimates that connecting rural Americans to the internet via TVWS technology will be 80 percent less expensive than the wired solution and 50 percent less expensive than using the wireless technology. As broadband penetration has an unbending impact on GDP growth. An increase of 10% points in broadband penetration increased the GDP of 1,21 to 1,38 for developed and developing countries. Outcomes of TVWS trials in Africa can be an apotheosis of the true perspective of TVWS and its philosophy. The more reachability of the rural community, the more impact to the GDP, Job market creation and support to innovation and entrepreneurship in various sectors. In Africa TVWS has been beneficial for the rural inhabitants. Deployments in Botswana shows that despite the limitations of the region, with the help of the national regulators positive results can be achieved. In future, a lot innovations will take place and more and more TVWS trials will materialize.

References

[1] (2018, September 28). Retrieved from https://www.cio.com.au/article/585061/57-world-population-can-t-access-internet/

[2] M. Khalil, J. Qadir, O. Onireti, M. A. Imran and S. Younis, "Feasibility, architecture and cost considerations of using TVWS for rural Internet access in 5G," 2017 20th Conference on Innovations in Clouds, Internet and Networks (ICIN), Paris, 2017, pp. 23-30.
[3] (2018). Retrieved from https://ecfsapi.fcc.gov/file/7020039036.pdf
[4] Oliver, M., & Salas, F. (2017). TV White Space as a Feasible Solution to Spread Mobile Broadband. SSRN Electronic Journal. doi:10.2139/ssrn.2944184
[5] Quantifying TV White Space Capacity; A Geolocation-based Approach. (2018). Retrieved from https://www.iit.demokritos.gr/sites/default/files/quantifying_tv_white_space_capacity.pdf
[6] THE ROLE OF TV WHITE SPACES AND DYNAMIC SPECTRUM IN HELPING TO IMPROVE INTERNET ACCESS IN AFRICA AND OTHER DEVELOPING REGIONS. (2018). Retrieved from http://wireless.ictp.it/tvws/book/8.pdf
[7] (2018). Retrieved from https://www.oecd.org/sti/broadband/37669293.pdf
[8] The ITU report "Exploring the mobile bandwidth¢ Value and Economic Valuation of Spectrum" provides further insights into the economic value aspects of spectrum: http://www.itu.int/ ITU-D/treg/broadband/ITUBB- Reports_SpectrumValue.pdf
[9] (2018). Retrieved from https://www.gsma.com/spectrum/wp-content/uploads/2013/02/Digital_Switch-Over_Guide_Plum.pdf
[10] (2018). Retrieved from http://openaccess.city.ac.uk/1768/1/mapping_digital_media.pdf
[11] B. P. Freyens and M. Loney, "Digital switchover and regulatory design for competing white space usage rights," *2011 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN)*, Aachen, 2011, pp. 32-40.
doi: 10.1109/DYSPAN.2011.5936222
[12] M. Fitch, M. Nekovee, S. Kawade, K. Briggs and R. MacKenzie, "Wireless service provision in TV white space with cognitive radio technology: A telecom operator's perspective and experience," in *IEEE Communications Magazine*, vol. 49, no. 3, pp. 64-73, March 2011.
doi: 10.1109/MCOM.2011.5723802
[13] J. van de Beek, J. Riihijarvi, A. Achtzehn and P. Mahonen, "TV White Space in Europe," in IEEE Transactions on Mobile Computing, vol. 11, no. 2, pp. 178-188, Feb. 2012. doi: 10.1109/TMC.2011.203
[14] Reaching rural America with broadband internet service. (2018). Retrieved from https://theconversation.com/reaching-rural-america-with-broadband-internet-service-82488
[15] (2018). Retrieved from https://www.itu.int/en/ITU-D/Conferences/GSR/Documents/GSR_paper_WhiteSpaces_Gomez.pdf
[16] Fitch, M., Nekovee, M., Kawade, S., Briggs, K., & Mackenzie, R. (2011). Wireless service provision in TV white space with cognitive radio technology: A telecom operators perspective and experience. IEEE Communications Magazine,49(3), 64-73.
doi:10.1109/mcom.2011.5723802
[17] Badri Raj Lamichhane, Ranju Kumari Shiwakoti - TV White Spaces: Challenges for Better Managing Inefficiencies - published at: "International Journal of Scientific and Research Publications (IJSRP), Volume 5, Issue 8, August 2015 Edition"
[18] O. S. Peñaherrera, J. L. Delgado, L. F. Guerrero and J. P. Inga, "TV White Spaces. A case study in Ecuador," 2017 IEEE Conference of Russian Young Researchers in Electrical and Electronic Engineering (EIConRus), St. Petersburg, 2017, pp. 198-203. doi: 10.1109/EIConRus.2017.7910528

[19] S. W. (2016). TV white space: The first step towards better utilization of frequency spectrum. Piscataway, NJ: IEEE Press.
[20] (2018). Retrieved from https://pdfs.semanticscholar.org/92a3/136307a5e32551bb6bf127459055e828dc02.pdf
[21] (2018). Retrieved from www.nominet.uk/what-is-tv-white-space
[22] (2018). Retrieved from https://static1.squarespace.com/static/5a02330280bd5ebd052c8a40/t/5b847f9d40ec9a5ac9b76916/1535410141534/CPRLATAM2018.pdf
[23] Despite Global Slowdown, African Economies Growing Strongly— New Oil, Gas, and Mineral Wealth an Opportunity for Inclusive Development. (2018). Retrieved from http://www.worldbank.org/en/news/press-release/2012/10/04/despite-global-slowdown-african-economies-growing-strongly-world-bank-urges-countries-spend-new-oil-gas-mineral-wealth-wisely
[24] List of African countries by population density. (2018, August 28). Retrieved from https://en.wikipedia.org/wiki/List_of_African_countries_by_population_density
[25] Sawe, B. E. (2017, June 08). African Countries By Population Density. Retrieved from https://www.worldatlas.com/articles/african-countries-by-population-density.html
[26] Africa: Mobile Penetration in Africa Hits 80pc. (2017, May 17). Retrieved from https://allafrica.com/stories/201704251054.html
[27] Zakład tapicerski Aleksander - trendtj.com. (n.d.). Retrieved from http://www.trendtj.com/en/baza-firm/podlaskie/zaklad-tapicerski-aleksander,bf159
[28] Baza firm. (n.d.). Retrieved from http://www.trendtj.com/en/baza-firm/podlaskie/zaklad-tapicerski-aleksander,bf159
[29] [(2018). Retrieved from https://www.gsma.com/mobileeconomy/wp-content/uploads/2018/05/The-Mobile-Economy-2018.pdf
[30] P. (2017, November 25). 4G-LTE subscriptions in Sub-Saharan Africa are expected to grow by 310 million in 2023 -. Retrieved from https://www.techjaja.com/4g-lte-subscriptions-in-sub-saharan-africa-are-expected-to-grow-by-310-million-in-2023/
[31] February 2018). (n.d.). Retrieved from https://opensignal.com/reports/2018/02/state-of-lte
[32] (2018). Retrieved from http://dynamicspectrumalliance.org/wp-content/uploads/2016/01/Pilots-and-Trials-Brochure_Jan-16.pdf
[33] (2018). Retrieved from http://wireless.ictp.it/tvws/book/10.pdf
[34] (2018). Retrieved from http://monmouthshire.biz/wp-content/uploads/2018/02/Final-Report-for-the-TV-White-Space-Broadband-Trial.pdf
[35] Markendahl, J., Sanchez, P., & Moelleryd, B. (2012). Impact of deployment costs and spectrum prices on the business viability of mobile broadband using TV white space. Proceedings of the 7th International Conference on Cognitive Radio Oriented Wireless Networks. doi:10.4108/icst.crowncom.2012.248449
[36] Takavarasha, S., & Adams, C. Affordability issues surrounding the use of ICT for development and poverty reduction.
[37] Zennaro, Marco & Pietrosemoli, Ermanno. (2013). TV White Spaces, a pragmatic approach.
[38] Markendahl, P. Gonzalez-Sanchez and B. Mölleryd, "Impact of deployment costs and spectrum prices on the business viability of mobile broadband using TV white space," 2012 7th

International ICST Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM), Stockholm, 2012, pp. 124-128.
doi: 10.4108/icst.crowncom.2012.248449
[39] (2018). Retrieved from
https://www.gsmaintelligence.com/research/?file=336a9db2ab3ed95bc70e62bf7e867855&download
[40] A. Kumar et al., "Toward enabling broadband for a billion plus population with TV white spaces," in IEEE Communications Magazine, vol. 54, no. 7, pp. 28-34, July 2016.
doi: 10.1109/MCOM.2016.7509375
[41] (2018). Retrieved from https://www.worldatlas.com/articles/which-are-the-10-largest-countries-of-africa-by-size.html