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SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

**Feasibility Study of TV White Space for Broadband Internet
Services: The Case of Rural Ethiopia**

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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other university, and all sources of materials used for the thesis have been fully acknowledged.

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Abstract

Now a day's internet is one of the most important things in our daily activities. Providing broadband internet by currently prevailing technologies for all people is challenging task especially for communities who live in rural and remote areas. One possible solution to provide broadband internet for rural areas is by using wireless technologies which work at unused spectrum. One of the candidate technologies which can minimize the problem of the rural broadband connectivity is a band which is allotted for terrestrial TV broadcasting but not used; referred as TV white space. The work of using TV white space for rural broadband internet service has been started in different parts of the world.

In order to deploy TV white space network for rural Ethiopia, the government's policy toward the use of communication media and the pattern of community settlement will affect the network architecture. In Ethiopian scenario, it is assumed that available telecom infrastructure will be used for backbone network; since Ethiopian government takes monopoly of all communication media and there will be no private service provider. From the simple mathematical computation, it is assumed that Okumura-Hata path loss model can be used for rural Ethiopia.

Even though ample amount of spectrum is allocated for terrestrial TV broadcasting in Ethiopia, only fraction of it is being used and it will be available for other secondary applications. Finally, this thesis showed that TV white space is financial feasible for rural Ethiopia compared with currently prevailing technologies even though handset cost is unaffordable.

Key Words: TV White Space; Rural broadband; Financial Feasibility; Quantitative Amount of TVWS

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Abbreviations/Acronyms

Aps	Access Points
ASO	Analog Switch-off
AAA	Authentication, Authorization, and Accounting
BS	Base Station
CapEx	Capital Expenditure
CPE	Client/Customer premise equipment
CR	Cognitive Radio
COSTECH	Commission for Science and Technology
CSIR	Council for Scientific and Industrial Research
DSO	Digital Switchover
DNS	Domain Name System
DHCP	Dynamic Host Configuration Protocol
DSA	Dynamic Spectrum Access
EIRP	Effective Isotropic Radiated Power
ECC	Electronic Communications Committee
EBA	Ethiopian Broadcasting Authority
EBC	Ethiopian Broadcasting corporation
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commissions
ISM	Industrial, Scientific and Medical
IEEE	Institute of Electrical and Electronics Engineers
ITU-R	International Telecommunication Union-Recommendation
ISPs	Internet Service Providers
LOS	Line of Sight
LTE	Long Term Evolution

MACRA	Malawi Communications Regulatory Authority
NCA	National Communications Authority
NOC	Network Operations Center
NPV	Net Present Value
Ofcom	Office of Communications
OpEx	Operational Expenditure
OMC	Operation and Maintenance Center
OSA	Opportunistic Spectrum Allocation
PoE	Power over Ethernet
PU _s	Primary Users
PMSE	Programme Making and Special Events
QoS	Quality of Service
Radius	Remote Authentication Dial-In User Service
SU _s	Secondary Users
SINR	Signal-to-Interference-plus-Noise Ratio
SME	Small and Medium Enterprise
SUI	Stanford University Interim
SSA	Static Spectrum Access
TCO	Total Cost of Ownership
TVWS	TV White Space
TVWSDB	TV White Space Database
UHF	Ultra High Frequency
VHF	Very High Frequency
WSD _s	White Space Devices

CHAPTER ONE

INTRODUCTION

At today's information communication era, internet becomes one of our basic needs for day to day activities.. In urban and dense populated areas broadband internet is mostly available. But rural and remote areas are deprived from it due to different factors. One challenge for providing broadband for rural area is high cost of laying backhaul network.

One possible solution is using wireless technologies. In the recent years, wireless communication systems have developed rapidly. The various types of services provided by the wireless networks are growing significantly causing huge volume of traffic flow. This has resulted into the ever-increasing demand of wireless spectrum. So the Radio Spectrum has now become a scarce resource. Today, most part of the existing usable spectrum has been already licensed. So the task of accommodating the demand of bandwidth with such less available spectrum is challenging.

With rising demand for bandwidth, several researchers around the world have measured and studied the occupancy of spectrum in different countries. These findings suggest that except for the spectrum allocated to services like cellular technologies, and the industrial, scientific and medical (ISM) bands, most of the allocated spectrum is underutilized [1]. Among all the underutilized portions of the frequency spectrum, TV white spaces in the Ultra High Frequency Television bands have been of particular interest owing to the superior propagation characteristics as compared to the higher frequency bands. In generally speaking, the underutilized TV channels collectively form the TV white spaces. The amount of available TV white space varies with location and time. Estimation of amount of the available TV white space has been done in several

countries at different times; in India [1], the United Kingdom (UK), [2], Europe, [3], South Africa [4] and the United States of America (USA), [5].

In this research paper feasibility study of TV white space for broadband internet services in rural Ethiopia is discussed. This study includes proposing possible network architecture, comparing different signal propagation models for rural Ethiopian scenario, estimating the amount of available TV white space (or the amount of free channel at a time at a given area), and financial feasibility and viability of the TV White Spaces technologies with respect to rural Ethiopian context. Due to lack of required data and essential software, this work comprises mostly theoretical and mathematical description.

1.1. Literature Review

There are different research papers on TV white space, since spectrum allocation and usage is different from country to country. The following are some of the literatures which resemble rural Ethiopian scenario.

Rural Broadband Trials Laikipia County Kenya, [6] shows trial TV white space (TVWS) network deployed in remote area of Kenya. This trial focuses particularly on the commercial feasibility of TVWS technology in delivering low-cost broadband in rural communities currently lacking access to both broadband and reliable electricity. A trial network in Kenya uses TVWS technology and solar-powered base stations (BSs) to deliver broadband access. The trial project has successfully demonstrated the technical viability of this model of delivery. The maximum achieved speed was 16 Mbps on a single 8 MHz TV channel at distances of up to 14 kilometers.

Timothy X Brown, et.al [7] “A Survey of TV White Space Measurements”, in this paper they have characterized the available TV white space spectrum in terms of total volume by using both detector and database access methods. From their work they have

revealed that there are significant amount of white space available for secondary use. Finally they have concluded that there is a great potential for using white space frequencies to provide two way telecommunication services in rural areas, especially in developing countries where white spaces are abundant and telecommunications infrastructure is lacking.

Sidney Roberts, et.al [8], "Connecting Africa Using the TV White Spaces: From Research to Real World Deployments," The authors in this paper started describing their work from describing that most of African countries have no broadband connectivity due to different factors and recommending using TV white space is a best solution. Authors also described why they have chosen TVWS for rural area. And they have showed from their deployed trial networks that TVWS deployments are more economical than Long Term Evolution (LTE) for rural areas in developing countries. Finally they have concluded that the TV white spaces are a unique enabler for providing Internet access in Africa.

As [9], [10], [11], [12], [13], indicates there are different African countries which have already started trial network on TV white space. Most of them have got encouraging result from their work and recommended to continue on it.

1.2. Statement of the Problem

Most of the total populations in Ethiopia lives in rural and sub-urban areas, many operate farming businesses and small and medium enterprises (SMEs) as merchants, and others. Almost all of those people who live around rural and sub-urban areas have no broadband internet connection, due to high cost of providing such service by deploying fiber cable/copper or via satellite. In order to solve this problem one possible solution is utilizing available frequency spectrum properly and using efficient technologies.

Although we have utilized this scarce resource efficiently, there is also some part of spectrum part which is underutilized due to different factors. One of the underutilized spectrum parts is spectrum allocated for terrestrial TV transmission. In TV transmission band there are some unused channels which we call it as a white space.

Thus TV white space is either temporarily or permanently unoccupied spectrum at VHF/UHF band; so white space is either unallocated spectrum or allocated and/or assigned, but under-utilized spectrum or arises naturally between used channels as a result of interference (guard band between two transmitting channels) or spectrum that is coming free due to digital dividend.

The main aim of this research is to study feasibility of these white spaces for broadband services in rural Ethiopia. Since TV transmission is at VHF/UHF band, it has important properties/features: (such as: Signal can propagate longer distance, Signal can penetrate walls and other materials, Signal cannot be easily affected by environmental factors such as rain), which make TV white space best candidate for rural and semi-urban area broadband connectivity.

Using TV white space for rural broadband connectivity has more economic and social benefits than other licensed ones. Since it is license free and signal at this band can travel longer distance it covers larger area, expenditure cost and operational cost is low if designed and planned properly. The other feature of TV white space which makes it more feasible for rural and remote area than other cellular network is its power consumption level. Since power consumption of white space transmitter is very low, we can use solar panels to generate electricity at remote areas.

1.3. Objective of the study

1.3.1. General Objective

The main aim of this thesis work is to study the feasibility of TV white space for broadband services in rural Ethiopia. It is the intension of the work to understand the special offer which this technology provides with respect to the existing technologies in the country.

1.3.2. Specific Objectives

Particularly, the thesis focuses on

- To propose the best network architecture for rural Ethiopian scenario
- To compare different propagation models and selecting one which is suitable for rural Ethiopian scenario
- To estimate the amount of available TV white space in Ethiopia
- To study economic and financial feasibility of the TV White Space technologies.

This includes

- Study of financial feasibility of deploying TV White Spaces technologies with respect to other prevailing technologies
- And affordability of the technology

1.4. Methodology

The work started with preliminary study on TV white space. On the process of reviewing related works the statement of the problem had been clearly specified.

The general methods employed to achieve the objectives of the research are:

- *Literature review*: includes reading books, articles, white papers, and other resources related to this topic.

- *System Designing*: involves selecting appropriate network architecture components of TV white space and analysing various signal propagation models that are applicable in the frequency range of TV band.
- *Analysis and Interpretation of the results*: results from each section will be analyzed.

1.5. Scope and Limitation

1.5.1. Scope of the Thesis

This thesis is a case study addressing the feasibility of TV white space for broadband internet in rural areas as generally. It should be able to indicate why TV white space is chosen over existing technologies and show which propagation model is suitable for rural area of Ethiopia. Finally, it discusses about available white space and economic and financial viability of the technology in Ethiopian scenario.

1.5.2. Limitations of the Thesis

This thesis has some limitations mainly due to lack of required data. Since, TV white space is ongoing research at many countries, and there is no regulation regarding TV white space usage in Ethiopia theoretical and mathematical analysis are done in this thesis. In addition to this, exact amount of available white space is not known, due to lack of digital map of Ethiopia. Finally, it was difficult to estimate profitability of project due to lack of data about TV white space deployment cost.

1.6. Thesis Layout

This thesis work is done in such a way that it gives a clear flow and understanding regarding the subject matter and is organized in seven chapters. Chapter one presents the objectives, scope and limitation, methodology and a short introduction with problem explanation. Chapter two presents the theoretical fundamentals of TVWS and

related works on TVWS and it includes cognitive techniques to access white spaces, TVWS regulations and standards and trial networks in Africa.

Chapter three presents proposed network architecture and propagation model used. Chapter four deals with estimating available white space and chapter five presents economic and financial feasibility of TV white space in rural Ethiopia. Chapter six discusses the results and analysis. Finally, conclusion is given followed by points of future work in Chapter seven.

CHAPTER TWO

TV WHITE SPACE

2.1. Introduction

Traditional wireless communication is based on static or fixed frequency allocation plan. That means spectrum is regulated so that most of the bands are allocated exclusively to a single system licensed to use that band in any given location, this allocation is fixed and independent from location. Unfortunately, the reserved frequencies are not in use most of the time, deriving in spectrum inefficiency. According to Federal Communications Commissions (FCC), the utilization of fixed spectrum assignment is approximately 15-85% depending on space and time [14].

In that approach different frequency bands are assigned to different users and service providers, and licenses are required to operate within those bands. From technical point of view, this approach helps in system design since it is easier to make a system that operates in a dedicated band than a system that can use many different bands over a large frequency range. In addition, spectrum licensing offers an effective way to guarantee adequate quality of service (QoS) for license-holders.

Since popularity of the wireless networks and the resulting increase in the volume of wireless data traffic has created a large gap between bandwidth supply and demand, the available frequency spectrum is running out. To optimize its use, new opportunistic spectrum allocation (OSA) techniques such as Dynamic Spectrum Access (DSA) and Cognitive Radio (CR), are being developed [14].

CR is the technology that makes possible the DSA, providing the capability to share the wireless channel with licensed users in an opportunistic manner. CR networks will offer

high bandwidth to mobile users, making it possible to first detect the available spectrum portions and other licensed users (spectrum sensing), then select the best available channel (spectrum decision), coordinate its access with other users (spectrum sharing) and liberate the channel in case that a licensed user is detected (channel mobility) [14]. The DSA depends on time, space and frequency. The following figure 2.1 describes the concept of DSA.

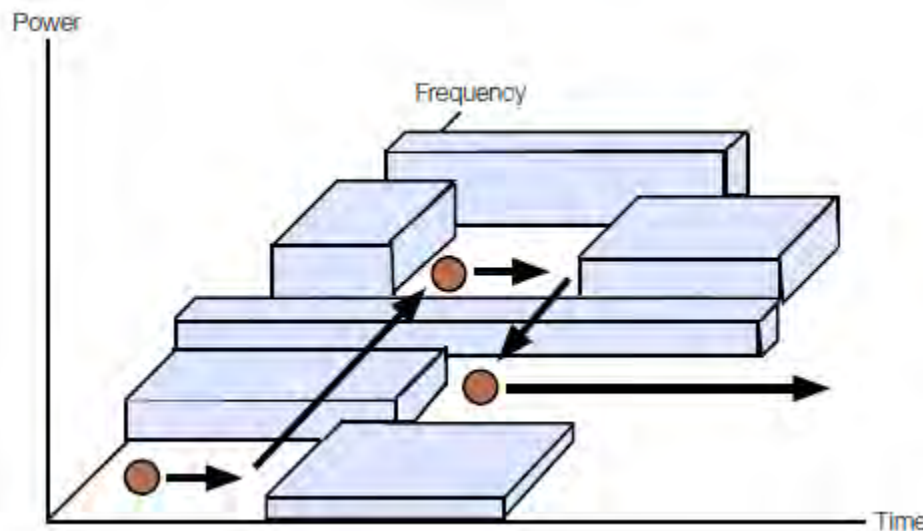


Figure 2. 1: Dynamic spectrum access concept [14]

As it was explained above, the electromagnetic spectrum is underutilized due to fixed allocation plan. This leads to the concept of a *spectrum hole (white space)* which can be defined as [15]: a band of frequencies assigned to a primary user, but at a particular time and specific geographic location, the band is not being utilized by that user. In order to improve the spectrum utilization it is possible to allow secondary users to access a spectrum hole unoccupied by the primary system at the right location and the time in question.

2.2. TV white space

As discussed above, due to static spectrum access (SSA) method there was underutilized spectrum at almost all bands. This underutilized or unused spectrum

band is referred as “spectrum hole” or “white space”. Spectrum hole or white space which is found at frequency band which is allocated for terrestrial TV broadcasting is called TV white space (TVWS) [16, 17, 18].

2.2.1. Basic Concept

TV broadcast services operate on the licensed Very High Frequency (VHF) and Ultra High Frequency (UHF) radio spectrum which have a favorable propagation and penetration characteristics and can cover a wide area with relatively small transmission power. In most cases all of those allocated spectrum are not utilized efficiently due to different reasons. The part of allocated spectrum which is not used at a given time and geographic location is called TV white space (vacant spectrum).

White Space is part of the spectrum, available for a radio communication application (service, system) at a given time in a given geographical area on a noninterfering/ non-protected basis with regard to primary and other services [19].

These vacant portions of the spectrum, known as TV white space, became available as a key research topic and future technology and business development area. For example, both the United States FCC and the Office of Communications (Ofcom) in UK proposed to exploit them by license exempt users devices to improved spectrum efficiency as long as they do not interfere any incumbent services, including TV broadcast and wireless microphone transmission. It is considered an ideal candidate solution for the spectrum shortage problem and estimated that up to 50% of the total broadcast band will be available for secondary uses in practice [20].

Figure 2.2 below illustrates the concept, showing unused ‘white spaces’ between licensed transmissions.

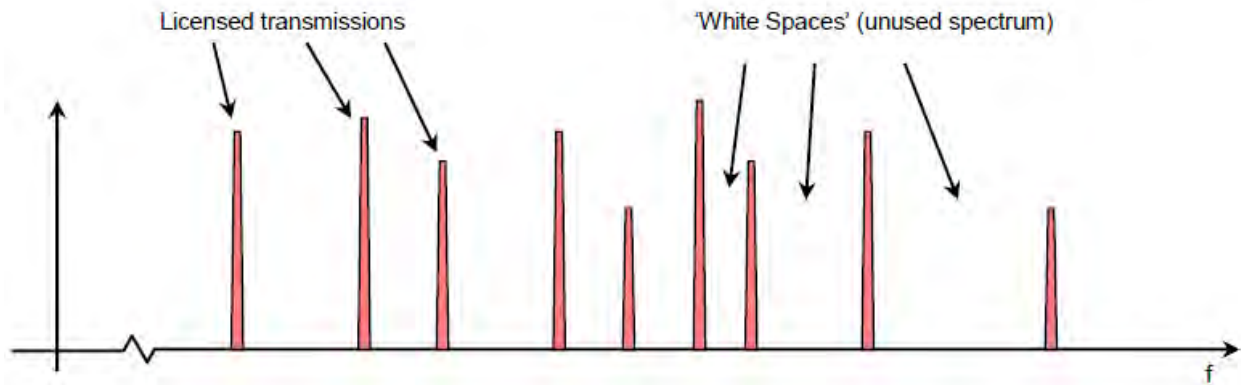


Figure 2. 2: Graphic illustration of licensed transmissions at certain frequencies, with 'white spaces' between them [6].

In many countries, analogue television broadcasts are being switched off and replaced by more spectrally efficient digital television transmissions, and the white spaces that exist in the TV band have good propagation and building penetration characteristics. This potentially makes them suitable for use in rural broadband applications, where transmission links may be several kilometers in length and may involve challenging terrain such as hills, foliage, and water [6].

The USA regulator (FCC) and the UK regulator (Ofcom) have indicated that they intend to make certain parts of the TV band available for use on a licence-exempt basis [16, 22]. This represents an interesting and novel development in the management of spectrum, as it involves unlicensed transmissions being interleaved with those of licensed users such as TV broadcasters and 'Programme Making and Special Events' (PMSE) users. Several other regulators around the world are actively considering similar approaches. Figure 2.3 below shows an illustration of white space transmissions existing alongside licensed transmissions.

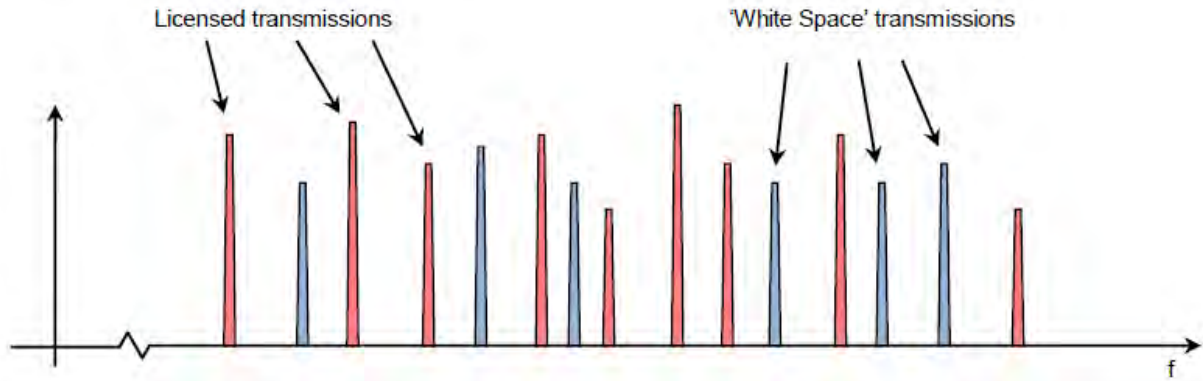


Figure 2. 3: Some of the 'white space' spectrum may be utilized by licence-exempt devices interleaving their transmissions with those of licensed users [6].

Allowing licence-exempt devices to interleave their transmissions with those of licensed users does, however, present challenges in ensuring that such unlicensed transmissions will not adversely interfere with the licensed transmissions. The approaches adopted by the FCC and Ofcom differ slightly [16, 22], but both involve the use of a regulator-approved database which White Space Devices (WSDs) will need to consult before being allowed to access the spectrum.

2.2.2. Important characteristics of TV white space

There are some unique features which makes TV white space suitable for rural connectivity. The following are some of the important signal properties at TV band.

2.2.2.1. Superior Qualities for Broadband

The availability and unique qualities of the white-space frequencies promise to make broadband faster, less expensive and more widely available, especially in rural areas, where TV white space is more abundant. The signal is robust, is unaffected by weather, works well in rugged terrain and requires little infrastructure to deploy compared with other prevailing technologies.

2.2.2.2. More Bandwidth in Rural Areas

Actual bandwidth depends on how much white space is available in a given area and how many devices make use of that bandwidth at a given time. Rural areas have higher vacant TV channels due to small TV broadcasters at the area, while suburban and urban areas have less vacant TV channels. This means that the bandwidth capacities of the white-space frequencies are higher in rural areas than in urban ones, simply because there are more available channels and fewer subscribers per square mile.

2.2.2.3. Superior Range and Coverage

In hilly regions, the area white-space frequencies can cover is typically two to six times that of Wi-Fi. This is due to the particular characteristics of the low radio frequencies, which carry farther and penetrate better. Ground waves cling to the curvature of the earth, spreading over greater distances and requiring less power to do so. For broadband use, this means that fewer base units are required to cover greater areas and that access points (APs) can serve larger areas.

2.2.2.4. Greater Signal Penetration

White-space frequencies penetrate obstacles, a characteristic that makes them particularly promising for affordable rural broadband because little new infrastructure or land alteration is required for deployment. Up to now, rugged terrain has posed the greatest challenge to using radio technology for rural broadband because microwave frequencies, like the 2.4 GHz used for Wi-Fi, require a line of sight, meaning the components of radio equipment must be visible to each other.

In mountainous or thickly forested country, this line-of-sight requirement means large towers must be built to hold transmitters, receivers, repeaters and antennas. In rural areas with only a few customers per square mile, Internet service providers (ISPs) cannot justify the expense of building large towers.

VHF/UHF frequencies, however, can travel from miles away, penetrating foliage, stone, brick and even metal to reach all the corners inside a building—the qualities that made them work well as TV signals.

2.2.3. Possible applications of TV white space

Fundamentally, spectrum being a scarce resource, white space technology is being used to meet growing local demand by using spectrum that would have otherwise remained fallow. There are many possible applications that can be used in the TV white Spaces. In fact, most generally used applications for wireless communications could potentially be used in TV white space. The following are some of attractive applications.

2.2.3.1. Rural wireless broadband networks

The ability of TVWS networks to travel seamlessly through obstructions and rough terrain is particularly beneficial for rural areas with low to zero mobile network coverage. Providing broadband service to the rural area is challenging task especially at mountains and thick forest areas. TV white space frequencies could travel from miles away and provide affordable obstacle penetrating ability, which means ISPs will not need to build new infrastructure in order to deploy broadband in rural communities.

2.2.3.2. Machine to Machine Connectivity

Since signal at TVWS propagate longer distance with small power, TV white space can be used as internet of things. Industry forecasts estimate there will be more than 50 billion connected devices by 2020 [21], with a good proportion of these communicating and sharing information wirelessly, enabling a wide range of applications. Mobile broadband is too expensive for 'things' and mobile broadband also means battery powered devices would need to be charged far too often and all those sensors would load the cellular networks to such a level that there would be little network capacity left.

In smart grids for utilities, TVWS can be used to improve meter to meter communication, especially in grids across difficult terrain. This allows operators to manage the utilities system remotely. TVWS has been described as key candidates of the 'Internet of things' (IoT) [23] because unlike mobile networks, it provides machines with dedicated communications channels and standards to cope with high numbers of user nodes and low cost and maintenance requirements. Because low-frequency broadcast requires low power, white space is ideal for connecting devices and sensors with small, long-lasting batteries [24].

2.2.3.3. Emergency and public safety network

Public agencies can have access to spectrum in the TV band; this would improve the capacity and quality of their networks, as well as facilitate their expanded use for e-government and consumer services. TVWS network can be used in emergency response and public safety organizations, such as police force, fire and medical teams responding to accidents, crimes, natural disasters and other similar events.

2.2.3.4. Local TV stations

Ofcom, the UK communications regulator, has allowed local TV channels to broadcast in the TVWS spectrum, which aren't used for existing broadcasts locally. This move is in the interest of creating content that is of relevance to local communities [25].

2.2.3.5. Providing backhaul

White space spectrum can also be used to provide backhaul links to access systems such as Wi-Fi hot spots. The 2.4 GHz and 5 GHz bands are not as well suited for backhaul due to the short range that can be achieved. In contrast, TVWS equipment can sustain links in more challenging environments without requiring a dense network of relays. Several of the trials in the UK have tested the viability of TVWS as a backhaul mechanism for Wi-Fi hotspots. In the US, TV White Spaces links are being used as a

replacement for microwave fixed links in scenarios where non-line-of-sight conditions cannot be avoided [26].

2.3. Cognitive Techniques to Access White Spaces

The main aim of any opportunistic spectrum access schemes is to utilize the white space without causing any interference to the primary user.

There has been lot of research going on in Academic and industrial world in resolving how the white space devices could find the usable frequency bands. Cognitive secondary access to TVWS involves detection of the available spectrum holes in the TV-bands and to use the spectrum based on the regulatory requirements, which basically protect incumbent services from harmful interferences. Three cognitive techniques have been proposed by Electronic Communications Committee (ECC) to help WSDs find empty channels [27]:

1. Geo-location with databases
2. Spectrum sensing
3. Beacons

2.3.1. Geo-location Databases

In this cognitive technique, the white space devices (WSDs) determines its location and accesses a 'Geo-location' database to determine which channels or frequencies can be used by them in that reported location. That means, geo-location database concept is based on the idea that before the white space device can start operating; it has to contact some known and trusted database. According to [27], Ofcom proposed that it is mandatory for a White Space Device (WSD) to provide the database only its location.

With this scheme, WSDs are not allowed to transmit before they receive notifications from the database about the available white spaces, if any, in their position. This

requires that the WSDs make initial connectivity to the database by some other way than the white space frequencies.

The database contains needed information for operating on the each geographic location. The database returns at least the usable frequency bands and allowed transmit powers on those frequencies [27].

The primary challenge with the database approach is to find accurate information since in most countries spectrum usage information can be stored in many formats, electronic and paper, and the regulator has not collected these into a useful centralized database that is publicly available. Even when available, the approach is also computationally intensive if assessing a large region [28].

2.3.2. Spectrum Sensing

With spectrum sensing techniques, WSDs try to detect the presence of the protected incumbent services in each of the potentially available channels. Spectrum sensing essentially involves conducting a measurement within a candidate channel, to determine whether any protected service is present. When a channel is determined to be vacant, sensing might also be applied to adjacent channels to determine what constraints there might be on transmission power, if any.

FCC, for instance, requires the *“TV bands devices [unlicensed WSDs] be capable of sensing analog TV signals, digital TV signals and wireless microphone signals at a level of -114dBm within defined receiver band-widths”*. So for sensing only WSD some channels may have to be permanently excluded, because the occupying service is not amenable to detection by sensing, such as passive service. For example, in the band 608-614 MHz some countries have stations for radio astronomy services which cannot be protected by sensing [27].

Spectrum sensing, if it is standalone, has very important advantage that it doesn't need connection to a centralized database server. This eliminates the need for extra communication infrastructures like the Internet.

The primary challenge with the spectrum sensing approach is the presence of detection errors where the detector either fails to detect the presence of a TV signal or gives false detections when no TV signal is present. Because of these challenges, spectrum regulators advocate the database approach [28].

The other challenge associated with the spectrum sensing scheme is that sensing signals may be vulnerable to what is called the hidden terminal problem as described below.

Hidden node problem

According to [27], hidden node problem was caused during Spectrum sensing by white space devices (WSDs). This arises because the receiver of the service to be protected is better able to receive the licensed transmissions than a WSD in a low height scenario can (due to their different spatial locations). Figure 2.4 below illustrates an example of this. For a high height scenario, i.e. WSD antennas at height of e.g. 10 or 30 meters, the hidden node problem will be reduced.



Figure 2. 4: Hidden node problem [27]

A house receives a DTT signal using a rooftop directional antenna mounted clear of surrounding buildings (path 1). Nearby is a WSD attempting to detect the same signal at street level, but it is blocked by surrounding buildings (path 2) and therefore much reduced in strength. The WSD might erroneously conclude that there are no transmissions and hence no active nearby receivers, start to transmit and cause harmful interference to the rooftop antenna (path 3).

2.3.3. Beacons

A third proposal for spectrum white space detection is using beacons. Unlicensed devices transmit only when they receive the beacons that carry information whether the channel is vacant or not. The beaconing technology is quite similar to the database method. The difference is that there is a control signal giving all the needed information to operate on the area. The control signal could be sent from an external source for example the broadcast TV stations, the radio BSs or the licensed wireless communication providers.

The WSD would not be allowed to operate before receiving this control beacon and of course applying to the setup given in the message. The benefit compared to geo-location database is that the WSD does not need to know its location and establish connection to the database which can be time consuming in some cases. The downside is that the building of the beaconing network takes time and money. The beaconing signal counters are also hard to define accurately due to location and time variation of the electric field strength [27].

From above discussed Cognitive Techniques to Access White Spaces, Geo-location with Databases assumed to be used for this thesis. This was due to above mentioned shortcomings for other cognitive access methods and the fact that most of WSD's manufactured today supports this cognitive access methods.

2.4. TV Whitespace Regulation

Generally, Radio Frequency (RF) spectrum regulation in every country is the responsibility of the government agencies, such as Ethiopian Broadcasting Authority (EBA) in case of Ethiopia.

Regulators around the world enforce spectrum management and regulation mainly through three main approaches [29]:

- ✚ Licensed spectrum for exclusive use
- ✚ Licensed spectrum for shared use
- ✚ Unlicensed spectrum

The radio spectrum has a vast amount of users and different kind of services. Those who wish to operate in the certain band have to apply for a license and pay for it, if granted. After this the band is reserved for the rightful owner and the authorities are obligated to make sure that the licensed owner's service is not interfered. For the licensed and for unlicensed operation there are certain regulations that the system has to fulfill. These regulations are meant to make it possible to for tell what kind of interferences certain systems cause and so be able to mitigate interferences between the systems [30].

While trials and deployments have flourished throughout the world, there are some regulators that have fully adopted rules for use of television white spaces: the United States, Europe (ECC), Malawi, and the United Kingdom.

2.4.1. FCC Proposal

The U.S. FCC first adopted rules for the use of television white spaces in 2008 [18]. Since then, it has amended its rules several times [16, 31]. The rules allow operation of devices on a license-exempt basis [16, 18, 31]. According to [16], the FCC rulings can be summarized as follows.

Devices may rely on either databases or sensing to avoid interference with protected services. The rules authorize private sector database operation without placing a limit on the number of database providers offering service. They also impose certain security and certification requirements on databases. They establish three classes of devices: fixed, mode I portable, and mode II portable. Fixed devices must limit their power to no more than 4 W EIRP, and personal/portable devices are limited to 100 mW. Detail proposal can be accessed at [6, 31].

2.4.2. ECC Proposal

ECC has proposed in its Report 159 [27] technical and operational requirements for the possible operation of CR systems in the TV white spaces at a given frequency band. Whereas the FCC's method was quite traditional with a fixed guard band and power, the ECC has taken different approach with much more complicated system of calculating the allowed parameters based on the estimated interference.

The approach in the ECC regulation is the coverage probability of the TV contour. The TV transmission coverage is determined by a location probability. Detail proposal can be found at [27].

2.4.3. Ofcom Proposal

The UK regulator Ofcom for the first time released a similar proposal as FCC to allow license exempt use of interleaved spectrum for cognitive devices in 2007 and proposed a number of technical parameters in a consultation published in 2009 [32]. Then after, Ofcom revised its TVWS regulation several times and Ofcom adopted current rules for the use of television white spaces in early 2015 [22]. According to [22], the Ofcom rulings can be summarized as follows.

They allow operation of devices on a license-exempt basis. They also authorize private sector database operation by one or more database providers. Ofcom will impose

certain qualification requirements on databases. They establish four classes of devices: fixed master, fixed slave, portable master, and portable slave. They establish varying maximum power levels based on the presence of incumbents and assume that devices will comply with the European Telecommunications Standards Institute (ETSI) emissions mask classifications. Ofcom's rules do not allow the use of sensing-only devices. Detail proposal can be accessed at [22].

2.4.4. The Malawi TVWS Draft Regulations

According to the Malawi Communications Regulatory Authority (MACRA), the eligibility, requirements and grant of licenses are dependent upon the different factors, according to their draft regulation. Drafted regulation to use TVWS can be found at [33].

2.5. Standards

Standards for the WSD's are still under development. The operational features of the WSD depend on the application it is targeted at and so different applications demand different standardization. If some white space application becomes widely used, then using certain standard for that application is likely to ease the interoperability.

2.5.1. IEEE 802.11af

IEEE 802.11 WLAN working group launched a TV white space project in 2009 and formalized a new standard called IEEE 802.11af which popularly known as Super WiFi/WiFi 2.0/WhiteFi [34]. The main difference from the well-known IEEE 802.11a/b/g standards is that IEEE802.11af will be a based on CR for operation in the TV white space. In order for whiteFi to be able to operate, it is necessary to ensure that the system does not create any undue interference with existing television transmissions.

2.5.2. IEEE 802.15.4m

In 2011 the IEEE 802.15 working group formed a new task group to develop an amendment to the 802.15.4 wireless personal area network (WPAN) standard for TV

white space operations [35]. IEEE 802.15.4m based devices may be used to enable many of the use cases which involved machine-to-machine communication.

2.5.3. IEEE 802.22

The 802.22 standard is targeted to be used for the rural and remote area wireless broadband access. It is assumed that good propagation characteristics of the UHF band combined with unlicensed operation enables large BS coverage and cheap implementation. This could result in providing broadband access to even sparsely populated area with low cost.

2.5.4. IEEE 802.19.1

The IEEE 802.19 Wireless Coexistence Working Group develops standards for coexistence of unlicensed devices between wireless standards. Task group 1 is working on standard 'TV White Space Coexistence Methods' to specify radio technology independent methods for coexistence among dissimilar or independently operated TV band networks and devices. IEEE 802.19.1 coexistence system consists of three logical entities, coexistence enabler (CE), coexistence manager (CM), and coexistence discovery and information server (CDIS).

2.5.5. European Telecommunications Standards Institute (ETSI)

Technical Committee on Reconfigurable Radio Systems of the ETSI also develops standards for CR systems and reconfigurable radios (RRS). RRS are intelligent radio devices which can scan unused spectrum that open up the opportunity to negotiate the second usage. Its purpose is to make more efficient and flexible use of spectrum to enhance user experience [36].

2.6. Trials and Commercial deployments of TVWS in Africa

This section provides an overview of TVWS deployments and trials in Africa.

2.6.1. Kenya TV white spaces pilot

In 2013, Microsoft, in collaboration with the government of Kenya's Ministry of Information and Communications, and Mawingu Networks, launched a pilot TVWS project called Mawingu (Cloud in Swahili) for delivering low-cost wireless broadband access to previously unserved locations near Nanyuki, Kenya. This trial focuses particularly on the commercial feasibility of TVWS technology in delivering low-cost broadband in rural communities currently lacking access to both broadband and reliable electricity [9, 37]. A trial network in Kenya uses TVWS technology and solar-powered BSs to deliver broadband access and create new opportunities for commerce, education, healthcare and delivery of government services.

Technical Results of Mawingu project can be summarized as follows [6].

- The Mawingu project has successfully demonstrated the technical viability of this model of delivery, with interference free point to multi-point coverage of up to 14 kilometers from TVWS BSs operating at only 2.5 Watts power (EIRP measurement);
- In total this provides approximately 235 km² of TVWS coverage using multiple 90 degree BS sector antennas;
- The maximum achieved speed was 16 Mbps on a single 8 MHz TV channel at distances of up to 14 kilometers;
- There have been no reports of interference from any concerned parties;
- The trial project have demonstrated that the technology can support various media protocols such as streaming videos, emails, FTP, Skype voice and video conferencing, and high speed VPN services;

- The project partners have delivered this technology in areas with no source of electricity. In fact, the majority of the endpoints are running on standalone solar power systems – a clean and renewable source of energy.

2.6.2. Malawi TV white spaces pilot

The University of Malawi, in partnership with the regulator, MACRA, and the International Centre for Theoretical Physics in Trieste, launched a white-spaces pilot project in the city of Zomba, in southern Malawi. The pilot, which got underway in September 2013, has connected a number of different institutions including a school, a hospital, an airport and a research facility [9]. The trial uses Carlson Wireless's Rural Connect TVWS radios.

Technical results obtained from Malawi TVWS trial project can be summarized as follows [10].

- It is observed that unlike other fixed broadband services, TVWS services demonstrated 2.6 times better data rates given the same operating conditions.
- The tested functional range at the moment is 7.5 km which measures an SNR of 24.7 dB, average latency of 118 ms and maximum throughput of 420 kbps given simultaneous usage of three client stations from a TVWS BS backhauled to a 2 Mbps internet bandwidth.
- The collaboration arrangement between the University and the Regulator is worth learning from the deployment in Malawi, where the regulator understood the significance of dynamic spectrum study, re-use and re-farming through solid science research and supported the project using its Universal Access Fund.

2.6.3. South Africa TV white spaces pilots

2.6.3.1. Cape Town TV white spaces trial

Cape Town TVWS trial project was conducted to study feasibility of TVWS for broadband internet connection. The trial project was conducted for six months and launched in March 2013 in Cape Town.

The pilot was a joint effort between Carlson Wireless, the Council for Scientific and Industrial Research (CSIR), e-Schools' Network, Google Inc., Tertiary Education and Research Network of South Africa, and the Wireless Access Provider's Association of South Africa [9, 12]. Technical results obtained from Cape Town TVWS trial project can be summarized as follows [12].

- The trial offered reliable and fast broadband services
- It produced bit rates of up to 12 Mbps at distances as far as 6.5 km.
- The trial partners were also able to operate co-channel with broadcasters without causing harmful interference.
- Finally, the trial partners also observed that even in Cape Town, which was selected as the trial site because it has the highest broadcast spectrum use in South Africa and the highest potential for interference – there is significant vacant spectrum for TVWS devices to use.

2.6.3.2. University of Limpopo TVWS trial

In 2013 [9] Microsoft, 6Harmonics and The Meraka Institute, who research and develop geo-location spectrum databases, partnered with the University of Limpopo in South Africa to provide the institution and five schools in an 8km radius with internet access. Hundreds of students benefit from TV White Space network which allowed ICT to be included in the syllabus for the very first time. The project enables access to vast online

resources and allows quality education through technology which improves employment opportunities for students.

The cost of broadband remains an obstacle to internet access in rural South Africa, but by reducing the cost of broadband access millions of South Africans could get online. This creates new opportunities for education, health care, commerce and the delivery of government services across the country.

2.6.4. Tanzania TV White Space commercial pilot

The Microsoft 4Afrika initiative continued its pilot trial by setting out another deployment of TV white space in partnership with the Tanzania Commission for Science and Technology (COSTECH) and their local ISP UhuruOne, to provide internet access to university students in Dares Salaam, Tanzania [11].

The Broadband4Wote project is designed to assess the commercial feasibility of wireless broadband using TV White Space technology. The Open University of Tanzania, Institute of Finance Management, College of Business Education and Dar Es Salaam School of Journalism and Mass Communication are all connected to the network which focuses on TV White Space capabilities in urban settings [9].

The Tanzanian deployment will also hire a team of students to support the network infrastructure, devices, and software, giving students the opportunity to learn valuable technical skills and gain IT qualifications. The ongoing pilot hopes to improve student's education through access to vast online resources and boost employment opportunities through the development of technical expertise.

2.6.5. Ghana TV White Space commercial pilot

In January 2015, SpectraLink Wireless launched the first commercial broadband service in Africa leveraging TV white space technology, which provides low-cost wireless

connectivity, cloud services, and devices to students and faculty at universities in Koforidua, Ghana [13].

The project partners are Microsoft, SpectraLink Wireless, the Ghanaian Ministry of Education, and the Ghanaian National Communications Authority (NCA), are collaborating on this effort. Research partners include the CSIR Accra and the University of Southampton. The project partners have deployed a wireless network covering an entire campus at Koforidua Polytechnic, serving a student population of 8,500. The network uses TVWS-enabled radios and other wireless technologies to connect campus buildings as well as off-campus hostels where students live to ensure they have access to fast broadband connectivity.

CHAPTER THREE

NETWORK ARCHITECTURE AND PROPAGATION MODELS

Introduction

Today, two out of three people in the world do not have access to internet [38]. More than half of the population in the world lives in rural areas with almost no any access to broadband internet connectivity. It is too expensive to lay fiber / cable in rural and remote areas with low population density. Except for direct coverage by satellite where cost-effective and low latency solutions are still developing, wireless is the only practical solution in rural and remote areas with low population density.

Current technologies have been unable to provide large area wireless coverage under non-line-of-sight conditions present in rural area to build successful and viable business models [38]. This limitation of previous technologies has initiated researchers to find other possible solutions. One possible solution proposed was using under-utilized spectrum band which was previously allotted for other services. Spectrum band which was assigned for terrestrial TV broadcasting is one of the under-utilized band and favorable for rural connectivity due to its signal propagation characteristics.

Ethiopia comprises of urban, semi-urban and rural areas. In urban areas and metropolitan cities, broadband internet can be easily accessed. Rural Ethiopia has no internet access. This is mainly due to providing a backhaul network by currently prevailing technology to the entire rural part of the country may be difficult and too costly task. Another option to this issue is using wireless broad band, for which TVWS would prove a good alternative. A noteworthy point is there would not be any interference source except TV signals in these frequency bands.

3.1. Network architecture of proposed system

3.1.1. Introduction

In this section, proposed network architecture was discussed. Here we assume that TV receivers are primary users (PUs) and TVWS devices are secondary users (SUs) and geo-location with data base cognitive accessing methods are assumed to be used.

There are many TV broadcast channels that are unused in nearly every location in the world [8]. The database informs the device about the available TVWS channels, and the maximum power level it is permitted to use at its current location. The database maintains a list of all protected TV stations and frequencies across a country, so the devices can avoid causing interference to TV broadcasts and other primary services using TV band.

The network architecture for a given system can be modeled depending on the available communication infrastructure and its intended purposes. That means, the available infrastructure determines which technology and transmission media will be used to design system architecture and the purpose of given system determine how to configure and where to install different components to get the required service.

For TVWS technology there are some proposed or used for trial deployments network architecture as described below.

IEEE 802.11af [39] starts proposing network architecture by describing each entities which form entire network and by defining the specific roles each entity executes. In this paper, they have described high level network architecture and how each entity will communicate with each other with in this standard and whole document can be found at [39].

According to [40], the authors have proposed their own network architecture to provide broadband internet service for campus community by using TVWS. They have used

both optical fiber and point-to-point microwave link as a backbone/backhaul network to connect ISP and TVWS BS. Here TVWS BS and TVWS client premise equipment (CPE) are connected point-to-multi point through TV channel and end users access broadband internet from CPE as Wi-Fi or by using Ethernet cable. Block diagram can be found at [40] page 7.

The other proposed network architectures include: [10], at which 5.8 GHz microwave point to point link used as backhaul and TVWS as last mile connectivity to provide broadband internet connectivity. According to [41], TVWS proposed to be used as backhaul connection to provide high speed broadband internet connection. In [6, 42] the trial network architecture uses fiber optic for main backbone and TVWS for backhaul and last mile connectivity and 5 GHz links used for Wi-Fi connectivity.

Complete and more general network architecture for TVWS was proposed by [8]. This paper describes the network architecture to be used for developing countries specifically African continent.

For this thesis this network architecture topology is assumed, since it is more general architecture and can describe rural Ethiopian scenario.

3.1.2. Block Diagram of Network Architecture

The network architecture of a system shows all required entities to provide broadband internet service. In order to provide broadband internet connectivity for rural areas, we assume TVWS is used.

If there is no previously installed infrastructure for backhaul network, we can use TVWS for such purpose. That means, TVWS has two uses in this case. It can be used both in the backbone and in the 'last mile' distribution to end users.

For this thesis general rural area of Ethiopia assumed; hence network architecture must be general in order to be applied for all areas. Therefore, network architecture of [8] which is general and can be applied for countries like Ethiopia is proposed for this thesis. The following block diagram shows the network architecture of proposed system. The block diagram highlights the path to connect remote rural area with ISP via backhaul interconnection and TVWS core network service with data base. The backbone network from the ISP to the first TVWS BS may be any type, it depends on available infrastructure.

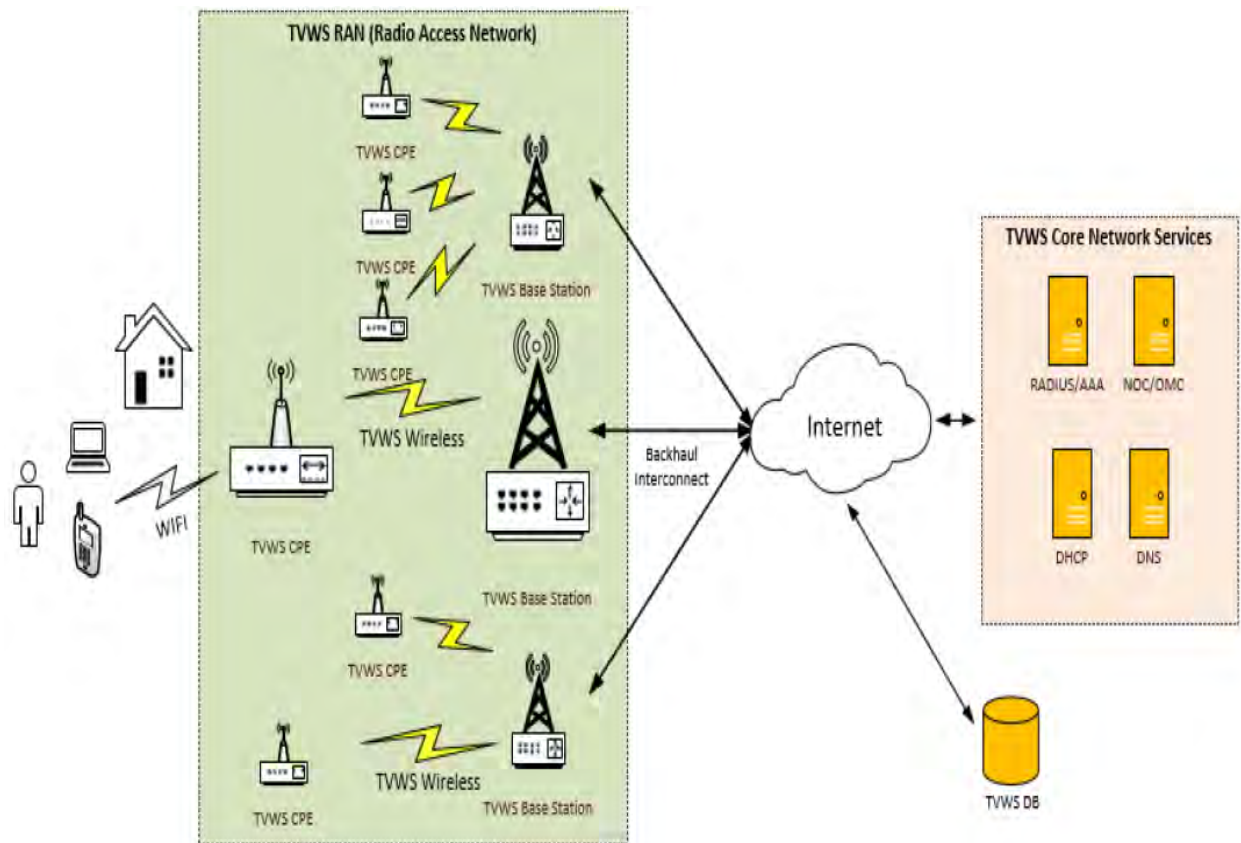


Figure 3. 1: Proposed TVWS Network Architecture [8]

Figure 3.1 above depicts a block diagram of a proposed TVWS network architecture. From left to right, the block diagram components include off-the-shelf 802.11 b/g/n/ac Wi-Fi APs, which connect directly to the TVWS CPE. The CPE, in turn, communicates with the TVWS BSs through a TVWS air interface protocol, which can be located within

several hundred meters of the CPE or many kilometers away, depending on the use case, availability of mounting radio facilities, and the location of backhaul access.

TVWS BSs again must be interconnected with Internet or ISPs via backhaul network. Backhaul/backbone network is any kind of interconnection; it can be fiber optic, micro wave, TVWS or even VSAT backhaul systems.

Finally block diagram contains two blocks at the right side, TVWS data base which controls the operation of TVWS devices and TVWS core network services. The function of core network services include some sort of Remote Authentication Dial-In User Service/Authentication, Authorization, and Accounting (Radius/AAA) for customer provisioning and billing; Network Operations Center and Operation and Maintenance Center (NOC/OMC) tools for network management and control; and Dynamic Host Configuration Protocol/Domain Name System (DHCP/DNS) for IP addressing, allocation and management [8].

3.1.3. TV white space as wireless backhaul network

In Ethiopia, typically there is a town within 20-25 km (assumption) from every village. The optical fiber network and point-to-point microwave link in Ethiopia currently provides service to most of such towns. But services provided by such networks are mostly voice and related services. Thus, it is this area and areas far from the main backbone network in which backhaul has to be provided using the TV band spectrum.

In these areas, two typical scenarios are prevalent. In one scenario, the regions between the villages are covered by highways or connecting roads with very little or almost no population, no need to provide service for such areas. Similar scenario exists when the region between two villages is separated by forests, desert areas or water bodies again no service will be provided. In this case, point to point links can be established between the relay BSs.

Finally CPE can provide broadband internet connection by either as wireless Wi-Fi or by LAN cable. The following figure 3.3 describes TVWS acts as repeater and base transceiver station.

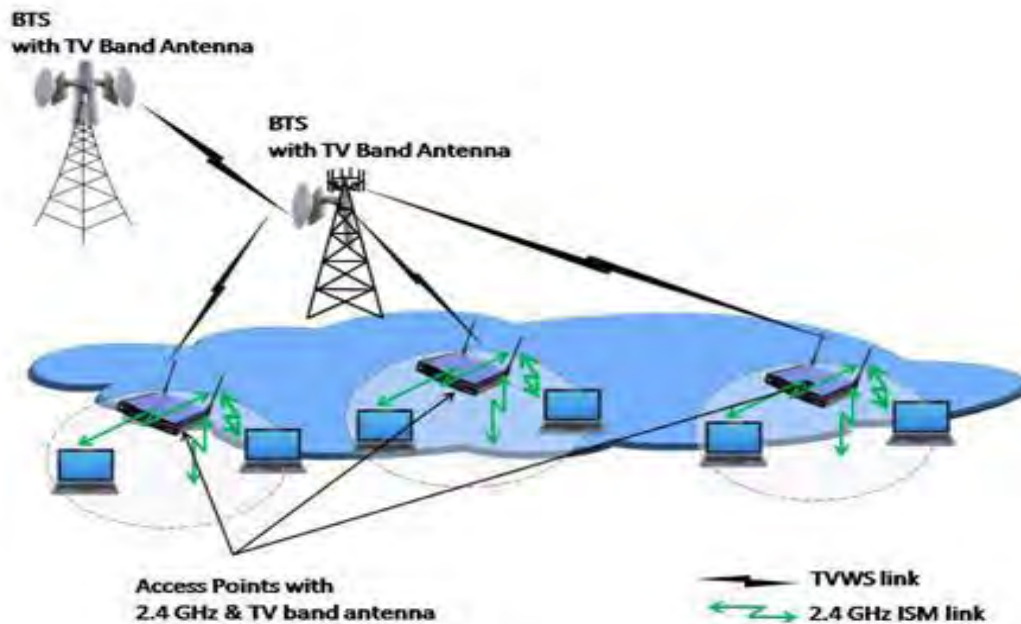


Figure 3. 3: Rural area TVWS BTs and TVWS Wi-Fi connecting to TV band backhaul [38]

3.2. Propagation Models

The performance of wireless communication depends greatly on the channel characteristic between the transmitter and receiver. An obstacle between the transmitter and receiver can seriously affect the propagated signal strength. Propagation models are used for calculation of electromagnetic field strength for the purpose of wireless network planning during preliminary deployment.

Propagation model describes the signal attenuation from transmitter to receiver antenna as a function of distance, carrier frequency, antenna heights and other significant parameters like terrain profile (e.g. urban, suburban and rural) [43].

The nature of the terrain has an impact on the radio wave propagation. In plain terrain, the radio waves propagation at UHF band can be reflected by ground surface. The tip

edge of rocks and large trees can cause diffraction of the propagated radio wave. The height of the transmitting antenna will avoid interference if placed at higher altitude.

3.2.1. Types of Propagation Models

In wireless communication the transmission medium (channel) is shared by many radio systems. The characteristics of the radio signal changes as it travels from the transmitter to receiver antennas. The signal is affected mainly by the length of the path(s) taken by the signal and the transmission environment. The interaction between the radio signal and the environment reduces the signal strength send from transmitter to receiver, which causes path loss.

Propagation Models for path loss can be categorized into three types, [43].

- ✚ Empirical Models
- ✚ Deterministic Models
- ✚ Stochastic Models

Empirical Models

During system modeling, sometimes it is impossible to explain a situation by a mathematical model. In that case, we will use some data to predict the behaviour approximately. According to [43], an empirical model is based on data used to predict, not explain a system and are based on observations and measurements alone. Some examples of empirical models include: The Stanford University Interim (SUI) model COST 231 Hata model, Hata and ITU-R.

Stochastic

This is used to model the environment as a series of random variables. Least information is required to draw this model but its accuracy is questionable.

Deterministic

Deterministic model makes use of the laws governing electromagnetic wave propagation in order to determine the received signal power in a particular location. Nowadays, the visualization capabilities of computer increases quickly [43]. The modern systems of predicting radio signal coverage are Site Specific (SISP) propagation model and Graphical Information System (GIS) database. SISP model can be associated with indoor or outdoor propagation environment as a deterministic type.

Choosing an appropriate path loss model is very important in TVWS capacity analysis because it directly affects all subsequent results and choice of secondary parameters. There are various path loss models in the literature that has been adopted for different applications, frequency range and environments. Some of the path loss models are described as follows.

3.2.2. Free Space Path Loss Model (FSPL)

The free space propagation model is the simplest model of a propagation channel, used to predict received signal strength when the transmitter and receiver have a clear, unobstructed line-of-sight path between them [20]. This model can be really useful to study the ideal performance of the CR system.

It is included in this topic to comparatively show the losses due to environmental factors that are predicted by the other propagation models in comparison with free space pathloss. The calculation is done by using the following equation [20, 43]:

$$PL_{FSPL} = 32.45 + 20 \log_{10}(d) + 20 \log_{10}(f) \quad (3.1)$$

Where: PL_{FSPL} is free space path loss in dB , d is separation distance between transmitter and receiver antenna in meter and f is operating frequency in MHz .

3.2.3. Okumura Model

This model was built by the data collected in Tokyo, Japan. This model is perfect for using in the cities having dense and tall structure, like Tokyo. Moreover, Okumura gives an illustration of correction factors for suburban and rural or open areas. By using Okumura model we can predict path loss in urban, suburban and rural area up to 3 GHz by extrapolating and distance of up to 100 km [43].

According to Okumura model median path loss model can be expressed as [43]:

$$PL(dB) = PL_{FSPL} + A_{mn}(f, d) - G(h_t) - G(h_r) - G_{AREA} \quad (3.2 (a))$$

where PL is median path loss in dB, PL_{FSPL} is free space path loss in dB, $A_{mn}(f, d)$ is median attenuation relative to free space in dB, $G(h_t)$ is BS antenna height gain factor in dB, $G(h_r)$ is mobile station antenna height gain factor in dB, G_{AREA} is gain due to the type of environment in dB, f is operating frequency in MHz, h_t is transmitter antenna height in m, h_r is receiver antenna height in m, and d is distance between transmitter and receiver antenna in km.

$G(h_t)$ can be calculated by using the following equation [43]:

$$G(h_t) = 20 \log_{10} \left(\frac{h_t}{200} \right) \quad \text{for } 1000m > h_t > 30m \quad (3.2 (b))$$

$$G(h_r) = \begin{cases} 10 \log_{10} \left(\frac{h_r}{3} \right) & \text{for } h_r \leq 3m \\ 20 \log_{10} \left(\frac{h_r}{3} \right) & \text{for } 10m > h_r > 3m \end{cases} \quad (3.2 (c))$$

Although this model is ideally suited for urban areas with high building density, it can also be used for sub-urban, rural and open areas. The gain due the type of environment (G_{AREA}) and the median attenuation relative to free space ($A_{mn}(f, d)$), are different for the various types of metropolitan areas and can be extracted [43].

3.2.4. Okumura Hata Model

Okumura Hata Model is one of the famous statistical models of signal propagation in a multipath radio environment. The simplified mathematical path loss equations are derived from measurement results for limited set of parameters (antenna heights, frequency and distance). The model works well for medium range coverage areas, but may not be suitable propagation model for distances beyond 100km. The operating frequency falls in the range of 30MHz - 3GHz [44].

The model of Okumura-Hata includes different approaches for urban, suburban and open areas propagation losses [15], as shown below for each case.

The Okumura-Hata equation in urban areas is given in dB by:

$$PL = 69.55 + 26.16 \log(f) - 13.82 \log(h_t) - a(h_r) + (44.9 - 6.55 \log(h_t)) \log(d) \quad (3.3 (a))$$

where h_t and h_r are the transmitter antenna and the receiver device antenna heights in meters respectively, f is the frequency in MHz and d is the distance between transmitter and receiver in kilo meters. The function $a(h_r)$ is the correction factor for the antenna height of the receiver device and, in the case of urban areas, it is defined by:

$$a(h_r) = \begin{cases} 3.20(\log(11.7h_r))^2 - 4.97 \text{ dB} & \text{for } f \geq 400 \text{ MHz} \\ 8.29(\log(1.54h_r))^2 - 1.1 \text{ dB} & \text{for } f \leq 200 \text{ MHz} \end{cases} \quad (3.3 (b))$$

For medium to small cities it becomes:

$$a(h_r) = (1.1 \log(f) - 0.7)h_r - (1.56 \log(f) - 0.8) \quad (3.3 (c))$$

Okumura-Hata's expression for suburban areas is:

$$PL_{sub} = PL(\text{urban area}) - 2(\log(f/28))^2 - 5.4 \quad (3.3 (d))$$

Okumura-Hata's path loss model expression for open areas is:

$$PL_{open} = PL(\text{urban area}) - 4.78(\log(f))^2 + 18.33 \log(f) - 40.94 \quad (3.3 (e))$$

3.2.5. COST-231 Hata model

The COST-231 model is an extension to the Okamura-Hata model. This model is suitable for the frequency band between 500 MHz and 2000 MHz. This model is used to calculate pathloss in three different environments like urban, suburban and rural (flat) and it provides simple and easy ways to calculate the path loss. For this model the path loss expression in dB is given by [15, 20, 43]:

$$PL = 46.3 + 33.9 \log(f) - 13.82 \log(h_t) - ah_r + (44.9 - 6.55 \log(h_t)) \log(d) + c_r \quad (3.4 (a))$$

where f is the frequency in MHz, d is the distance transmitter and receiver antenna in km and h_t is the transmitter antenna height in metres. The parameter c_r is considered to be equal to 0 dB for suburban areas or open environments, and to 3 dB for urban environments. For the parameter ah_r (receiver antenna height correction factor), some different expressions depending on the type of terrain are used. Thus, for urban environments:

$$ah_r = 3.20(\log(11.7h_r))^2 - 4.97 \text{ dB for } > 400\text{MHz} \quad (3.4 (b))$$

and for suburban or rural environments:

$$ah_r = (1.1 \log(f) - 0.7)h_r - (1.56 \log(f) - 0.8) \text{ dB} \quad (3.4 (c))$$

3.2.6. Stanford University Interim (SUI) model

The University of Stanford proposed the channel standards called SUI models, which are developed to work within the frequency bands below 11 GHz. This prediction model comes from the extension of Hata model with frequency larger than 1900 MHz. The BS antenna height of SUI model can range from 10 m to 80 m. Receiver antenna height is from 2 m to 10 m. The cell radius is from 0.1 km to 8 km. The SUI model describes three types of terrain; they are terrain A, terrain B and terrain C [15, 43]. There is no declaration about any particular environment.

Terrain A can be used for hilly areas with moderate or very dense vegetation. This terrain presents the highest path loss and can be taken as a dense populated urban area. Terrain B is characterized for the hilly terrains with rare vegetation, or flat terrains with moderate or heavy tree densities. This is the intermediate pathloss scheme. We consider this model for suburban environment. Terrain C is suitable for flat terrains or rural with light vegetation, here path loss is minimum [15, 43].

The basic path loss expression of The SUI model with correction factors is expressed as [15, 43]:

$$PL = A + 10\gamma \log_{10} \left(\frac{d}{d_0} \right) + X_f + X_h + s, \quad \text{for } d > d_0 \quad (3.5 (a))$$

where γ is path loss exponent, d is the distance in metres, d_0 is the reference distance equal to 100 metres and s is a lognormal distributed factor which takes into account the shadowing effect because of trees and other clutter on a propagations path and its value is between 8.2 dB and 10.6 dB. The parameters X_f and X_h are the correction factors for the operation frequency if greater than 2 GHz and for the antenna heights respectively.

According to [15] and [43], the frequency correction factor X_f and the correction for receiver antenna height X_h for the SUI model are expressed as:

$$X_f = 6 \log_{10} \left(\frac{f}{2000} \right) \quad (3.5 (b))$$

$$X_h = \begin{cases} -10.8 \log_{10} \left(\frac{h_r}{2000} \right) & \text{for terrain type A and B} \\ -20 \log_{10} \left(\frac{h_r}{2000} \right) & \text{for terrain type C} \end{cases} \quad (3.5 (c))$$

where, f is the operating frequency in MHz, and h_r is the receiver antenna height in m.

The parameter A is defined as [15], [43]:

$$A = 20 \log_{10} \left(\frac{4\pi d_0}{\lambda} \right) \quad (3.5 (d))$$

and the path loss exponent γ is given by [41]:

$$\gamma = a - bh_t + \left(\frac{c}{h_t}\right) \quad (3.5 (e))$$

where, the parameters λ is wavelength, h_t is the BS antenna height and is between 10 m and 80 m. The constants a , b , and c depend upon the types of terrain, that are given in Table 3.1 below. The value of parameter $\gamma = 2$ for free space propagation in an urban area, $3 < \gamma < 5$ for urban non-line of sight (NLOS) environment, and $\gamma > 5$ for indoor propagation [43].

Model Parameter	Terrain A	Terrain B	Terrain C
a	4.6	4	3.6
$b(m^{-1})$	0.0075	0.0065	0.0050
$c(m)$	12.6	17.1	20

Table 3. 1: Parameter values of different terrain for SUI model [24, 41].

3.2.7. ITU-R models

ITU-R P Recommendation series describe radio propagation prediction methods in various aspects and contrary to other models described above can predict the point to area propagation characteristics. Among them, recommendation ITU-R P.370[45] provides guidance on prediction of field strength for the broadcasting service for the frequency range 30 to 1000 MHz and for the distance range up to 1000 km, while ITU-R P.529[45] (based upon data for specific urban areas) on the prediction of point-to-area field strength for the land mobile service in the VHF and UHF bands centred around 150, 450 and 900 MHz and ITU-R P.1546-3[45] recommendation predicts terrestrial point-to-area radio propagations for frequency values 30MHz - 3GHz. The model is aimed at tropospheric radio propagation covering long-range distances (1-1000km) and

traveling over land, sea or mixed land-sea paths for effective transmitting antenna heights less than 3km. In Recommendation ITU-R P.1411[46], it defines four outdoor short-range propagation situations over the frequency range 300 MHz to 100 GHz.

The ITU-R P.1411 model described below is intended for propagation between low-height terminals where both terminal antenna heights are near street level well below roof-top height to calculate the basic transmission loss between two terminals. The parameters required are the frequency f (MHz) and the distance between the terminals d (m) and derivations steps are as follows [46].

Step 1: Calculate the median value of the line-of-sight loss:

$$L_{LoS}^{median}(d) = 32.45 + 20 \log_{10} f + 20 \log_{10} d/1000 \quad (3.6 (a))$$

Step 2: For the required location percentage, p (%), calculate the LoS location correction:

$$\Delta L_{LoS}(p) = 1.5624\sigma \left(\sqrt{-2 \ln(1 - p/100)} - 1.1774 \right) \quad \text{with } \sigma = 7dB \quad (3.6 (b))$$

Step 3: Add the LoS location correction to the median value of LoS loss:

$$L_{LoS}(d, p) = L_{LoS}^{median}(d) + \Delta L_{LoS}(p) \quad (3.6 (c))$$

Step 4: Calculate the median value of the NLoS loss:

$$L_{NLoS}^{median}(d) = 9.5 + 45 \log_{10} f + 40 \log_{10} d/1000 + L_{urban} \quad (3.6 (d))$$

L_{urban} depends on the urban category and is 0 dB for suburban, 6.8 dB for urban and 2.3 dB for dense urban/high-rise.

Step 5: For the required location percentage, p (%), add the NLoS location correction:

$$\Delta L_{NLoS}(p) = \sigma N^{-1}(p/100) \quad \text{with } \sigma = 7dB \quad (3.6 (e))$$

$N^{-1}(\cdot)$ is the inverse normal cumulative distribution function. An approximation to this function, good for p between 1 and 99% is given by the location variability function $Qi(x)$ of Recommendation ITU-R P.1546 [45]. Alternatively, values of the NLoS location

correction for $p = 1, 10, 50, 90$ and 99% are given in Recommendation ITU-R P.1411-6[46] section 4.3.1.

Step 6: Add the NLoS location correction to the median value of NLoS loss:

$$L_{NLoS}(\mathbf{d}, \mathbf{p}) = L_{NLoS}^{median}(\mathbf{d}) + \Delta L_{NLoS}(\mathbf{p}) \quad (3.6 (f))$$

Step 7: For the required location percentage, p (%), calculate the distance d_{LoS} for which the LoS fraction F_{LoS} equals p :

$$d_{LoS}(\mathbf{p}) = \begin{cases} 212[\log_{10} \mathbf{p}/100]^2 - 64 \log_{10}(\mathbf{p}/100) & \text{if } \mathbf{p} < 45 \\ 79.2 - 70(\mathbf{p}/100) & \text{otherwise} \end{cases} \quad (3.6 (g))$$

Step 8: The path loss at the distance d is then given as:

$$L(\mathbf{d}, \mathbf{p}) = \begin{cases} L_{LoS}(\mathbf{d}, \mathbf{p}) & \text{if } d < d_{LoS} \\ L_{NLoS}(\mathbf{d}, \mathbf{p}) & \text{if } d > d_{LoS} + w \\ L_{LoS}(d_{LoS}, \mathbf{p}) + (L_{NLoS}(d_{LoS} + w, \mathbf{p}) - L_{LoS}(d_{LoS}, \mathbf{p})) \frac{(d - d_{LoS})}{w} & \text{otherwise} \end{cases} \quad (3.6 (h))$$

The width w is introduced to provide a transition region between the LoS and NLoS regions. This transition region is seen in the data and typically has a width of $w = 20$ m.

3.3. Comparative Study of Path Loss with Various Existing Propagation Models and Simulation of Models

Since the main objective of this thesis was to study feasibility of TVWS for rural broadband internet service, hence here we can assume sub-urban and rural metropolitan area. The other assumptions are since Ethiopia is developing country, there are rare tall buildings at sub-urban areas, so the propagation model which works at sub-urban areas are valid for rural areas except for some cases as high mountain area and thick forest areas.

For the purposes of this computation and simulation, we fixed our operating frequency at 200 and 730 MHz; distance between transmitter antenna and receiver antenna is assumed 10 km, transmitter antenna height is 35 m in suburban area and in rural area. Let us consider 2 different antenna heights for receiver antenna i.e. 3 m, and 8 m. Even though most of the models provide two different conditions i.e. LOS and NLOS, for this thesis only NLOS condition is assumed. Here Free Space Model (FSPL) is used as a reference model in our whole comparisons. The following table 3.2 presents the parameters we applied in our comparison.

Note that, the above assumed values are randomly selected values for purpose of comparing different propagation models with each other and it can be changed.

Parameters	Value
Distance between Tx-Rx	10 km
Operating frequency	200, 730 MHz
Transmitter antenna height	35 m
Receiver antenna height	3, 8 m
Gain due the type of environment	8 dB
Median attenuation relative to free space	25 dB
Correction factor for shadowing	8.2 dB

Table 3. 2: Sample comparison parameters

For an ITU-R case the calculation was done according to the given information and the following equation used.

$$PL(d, p) = L_{NLOS}(d, p) = 0.5 + 45 \log_{10} f + 40 \log_{10} \frac{d}{1000}$$

3.3.1. Path loss and analysis of simulation results

For this calculation, we set 2 different antenna heights (i.e. 3 m, and 8 m) for receiver, 2 different operating frequency (i.e. 200, 730 MHz) distance varies from 250 m to 10 km and transmitter antenna height is 35 m. The numerical results for different models in sub-urban/rural area for different operating frequency and for different receiver antenna heights are shown in the Figure 3.4 below.

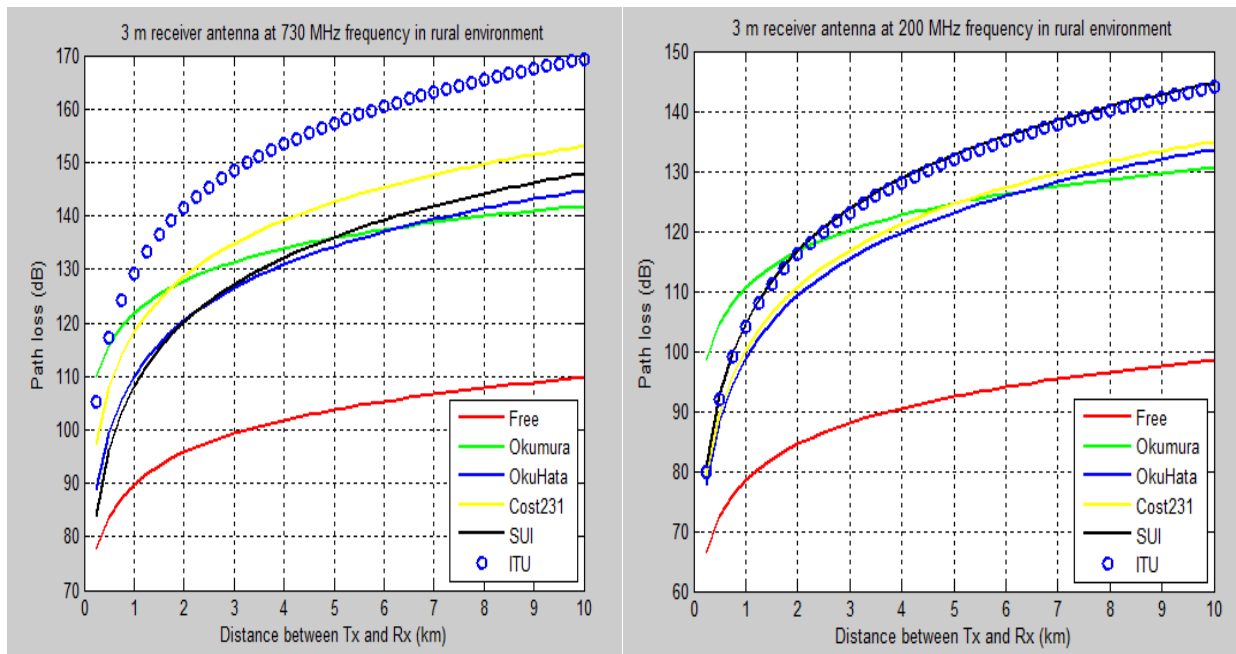


Figure 3. 4: Path loss in sub-urban/rural environment at 3 m receiver antenna height and operating frequency of 200 and 730 MHz.

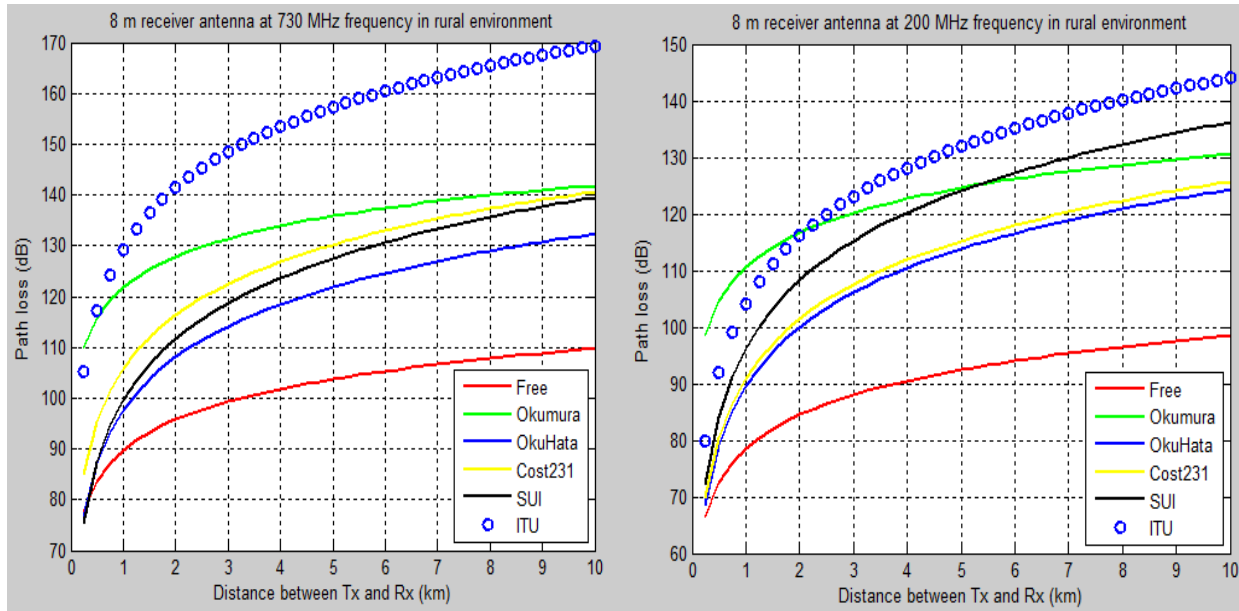


Figure 3. 5: Path loss in sub-urban/rural environment at 8 m receiver antenna height and operating frequency of 200 and 730 MHz.

From the above simulation graph of different propagation models (figure 3.4 and figure 3.5); the result shows that for lower operating frequency path loss is also low for all cases. Except ITU-R and free space path loss models, all other models showed significant fluctuations in path loss due to change in the receiver antenna heights. From the graphs above we can also observe that, for a constant receiver antenna height if we increase the operating frequency, the path loss also increase.

From the above graphs, in this environment Okumura-Hata path loss model showed the lowest path loss prediction for all cases, as shown figure 3.4 and figure 3.5 above. For a lower receiver antenna height Okumura path loss model shows second lowest path loss and for higher receiver antenna height Stanford University Interim model shows second lowest path loss. In all cases, ITU-R path loss model shows highest path loss. Therefore, from the above graphs for this thesis Okumura-Hata path model is assumed for rural part of Ethiopia.

CHAPTER FOUR

ESTIMATING QUANTITATIVE AMOUNT OF AVAILABLE TVWS

INTRODUCTION

In order to use TVWS for other purposes, it is necessary to estimate the amount of available white space. Estimating the available white space can be done either by measuring the signal level or using other relevant methods. In this paper estimating available white space is done via mathematical methods by using some known parameters. Since, there was no white space regulation in Ethiopia; FCC rules are used as necessary for mathematical computation.

4.1. TECHNICAL CONSIDERATIONS

In this section, some important technical and theoretical parameters are discussed. At first the relation between TVWS and digital migration are discussed followed by spectrum access methods. Finally, type of TV transmission and utilization of allocated TV band are discussed.

4.1.1. Relationship between TVWS and the Digital Migration Process

Digital migration or Digital Switchover (DSO) or analog switch-off (ASO) is a process of replacing existing analog terrestrial TV transmissions with their digital counterparts; a procedure which has been successfully completed in various countries and is in progress in others [6, 12]. 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 analog one. Therefore, a digital channel entirely replaces an analog one during the switchover procedure.

This analog shut-off requires that the viewers must obtain digital receivers to continue viewing the content they used to enjoy with their analog TVs. Thus, digital migration process requires three phases:

- **Digital Switch-on:** The rollout of digital terrestrial television (DTT) services.
- **Double illumination / Simulcast:** The period when television services are available in both analogue and digital terrestrial formats.
- **ASO:** The switching off of analogue transmitters to complete the transition. After ASO, terrestrial television services shall be available only in digital form.

In Ethiopia, a significant portion of television broadcast spectrum is unused at any one place because analogue TV transmitters require significant physical or spectral separation to avoid interfering with each other or because there is more unassigned broadcast spectrum than is needed to prevent broadcasters from interfering with one another.

Based on the recommendations of International Telecommunication Union (ITU) for developing countries, for migration of analog TV broadcasting to digital TV broadcasting, the Ministry of Communication and Information Technology of Ethiopia has announced to start migration process (DSO of analog terrestrial TV) by 2016 and expected to be completed by 2020 [47].

Thus, it is expected that this switchover will free up large blocks of spectrum. In analog terrestrial transmission, lot of bandwidth is wasted as guard band which is inevitable in analog mode. But the digital switchover overcomes this problem resulting in a large amount of unoccupied bandwidth in the TV band. This unoccupied bandwidth in turn results in *more white spaces* in TV band.

Enabling use of TVWS does not need to be tied to the digital migration process and TVWS technology can be utilized before, during and after digital migration. Further,

database technology can instantaneously direct devices to use whatever TVWS channels are available at the time; even as television broadcast stations are being relocated [6].

4.1.2. Geo-location Databases vs Spectrum Sensing

The main aim of these spectrum access methods is to utilize the white space without causing any interference to the primary user. The main advantages and drawbacks of each access method were described in section 2.3 above. Most of national regulators around the world, [6, 8, 12, 18, 22, 26, 27, 32, 33], mandated geolocation databases scheme to access vacant TV channel. The following paragraphs explain why regulators around the world choose geo-location database over spectrum sensing.

Geolocation approach provides greater flexibility for TVWS networking and seems safer for licensed TV broadcasters which should be relieved to see that their service area is geographically “fenced”.

On the other hand spectrum sensing approach alone has more drawbacks. For instance, according [48] spectrum sensing approach has two main draw backs. First, since this method uses extremely low detection thresholds, this results in a heavy under-estimation of the actual white space area. Very weak TV signals coming from distant transmitters are detected and the associated channels are ruled out, although practically no TV receiver in the area can actually demodulate and decode them. Second, the authors in [48] explain why spectrum sensing can lead to an overestimation of protected areas of even 3.5x in comparison to a well-laid out geolocation mechanism; this is a considerable drawback, leading to waste of valuable spectrum.

For this study we assume TVWS networks, which solely use a centralized geolocation-based mechanism. Indeed, in a scenario with fixed TV transmitters, whose geographical location is known and unchanged, it is reasonable to assume that the calculation and

employment of a set of fixed maps with allowable TVWS network locations for every channel is a well-established and fully justified approach.

4.1.3. TV Transmission in Ethiopia

In Ethiopia, there are three basic types of TV transmissions. These are terrestrial transmission or broadcasting, unencrypted satellite or Free To Air (FTA) and Internet Protocol (IP) TV. Terrestrial transmission or broadcasting is main interest of this paper.

Ethiopian Broadcasting corporation (EBC) (former ETV, ERTA) is an Ethiopian public service broadcaster. EBC operates not only TV channels but also FM radios (FM Addis 97.1 and FM 104.7 MHz) and AM radios (National Radio). There are also some regional public broadcasters, such as Oromia TV, Amhara TV, Southern TV and Tigray TV. Currently EBC operates three main TV channels including EBC 1, EBC 2 (Addis TV), and EBC 3. Among all these EBC 1 is most popular channel. The usage pattern of these channels depends on geo-location, rural or urban area and time.

4.1.4. TV band utilization in Ethiopia

As per the Ethiopian frequency allocation plan 2001 figure 4.1 below, [49], the spectrum in the frequency band 174-230MHz and 470-862MHz is earmarked for Broadcasting Services on a primary basis. Ethiopia is a part of the ITU Region 1 terrestrial spectrum allocations, and the 790-862MHz band has been earmarked for International Mobile Telecommunications applications [50]. Currently the TV transmitters operate both in the 174-230MHz band in the VHF band and 470-862MHz band in the UHF band [51].

ETHIOPIAN FREQUENCY ALLOCATION (MHz)

CORE OBJECTIVES OF THE LICENSING AND FREQUENCY MANAGEMENT AS INDICATED IN THE TELECOMMUNICATION PROCLAMATION (PROC. No. 49/1996 AND COUNCIL OF MINISTERS REGULATION ON TELECOMMUNICATION SERVICES (REG. No. 47/1999)

To manage, assign, authorize and register frequency allocated to Ethiopia in accordance with international conventions to be used for telecommunication, radio-communication services, broadcasting and others.

To coordinate the use of Frequencies both locally and internationally, and monitor the proper use of the same.

To prepare a national frequency list (database)

To give permission to import, possess, install or operate radiocommunication and other telecommunication equipment.

To prepare draft directives on national radio regulation.



ETHIOPIAN TELECOMMUNICATION AGENCY
July 2001

Tel: 251-11-466-82-82
Fax: 251-11-465-57-53
E-mail: tele.agency@ethionet.et



Produced by Licensing and Frequency Management Department

Figure 4. 1: Ethiopian frequency allocation plan of 2001[49]

In Ethiopia, EBC is the sole terrestrial TV service provider at TV band which currently transmits in three channels in most parts across Ethiopia and there are some state monopole public TV channels at regional levels. As of 2012, [51], EBC (former ETV) and regional TV broadcasters use both VHF and UHF band for transmission.

Current TV band utilization in Ethiopia may change after DSO process and the new ITU rules WRC-12 [50]. The following table 4.1 shows main new WRC-12 resolutions and recommendations regarding Ethiopia for TV band.

Frequency band	Primary allocated service	Secondary allocated service
174-223 MHz	Broadcasting	Fixed and Mobile services
470-790 MHz	Broadcasting	
470-582 MHz	Broadcasting	Fixed services
790-862 MHz	Broadcasting, Fixed & mobile (IMT)	

Table 4. 1: Summarized Ethiopian TV band allocation plan according to WRC-12 [50]

Even though, there was no recorded data of measured spectrum occupancy rate regarding TV band utilization in Ethiopia, we can conclude that small portion of the allocated spectrum is used and the vast majorities are wasted; since there are limited (almost 54 national TV transmitters [51]) national transmitter sites across the country.

4.2. TV White Space Availability in Various Countries

The amount of available TV white space varies with location and time. The available TV white space depends on regulations such as the protection margin given to the primary user, height above average terrain, transmission power of secondary users, and separation of unlicensed user from the licensed ones. Since the actual availability of TV white spaces varies both with location and time, operators of secondary services are interested in the amount of available white space. TV white space estimation has been done in several countries; for instance in India [1], the United Kingdom (UK), [2], Europe, [3], South Africa [4], and United States of America (USA), [5]. For instance, in South Africa, [4], results indicate that spectrum occupancy remains fairly constant for the UHF bands at approximately only 20%. According to [3], 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.

Regulators in the certain countries of the world have adapted rules to utilise TVWS. For instance, FCC regulations in the US, [16, 18, 31], and Ofcom regulations in the UK, [22, 32], have allowed for secondary operations in the TV white spaces. According to [18], FCC regulations declare a band as unutilized if no licensed-user (primary) signal is detected above a threshold of -114dBm. Under this provision, a secondary user can use the unutilized TV spectrum provided it does not cause harmful interference to the TV band users and it relinquishes the spectrum when a primary user starts operation.

4.3. METHODOLOGY & ASSUMPTION USED FOR ESTIMATING AVAILABLE TVWS

In Ethiopia, VHF band III (i.e. 174 - 230 MHz or channel 4-13) and UHF band IV and V (i.e. 470 - 862 MHz or channel 21-69) are primarily used by analogue broadcast services for the 8 MHz channel spacing. In this work, TVWS is defined in terms of the coverage area of the TV broadcast system. The TV coverage area is the geographical area within the TV noise limited grade B contour, that is, where the received signal strength for channels 14 through 69 exceeds 64 dBu and 41 dBu for analog and DTV systems respectively [18].

The mathematical quantification of TV white space in Ethiopia will be addressed in this section. Currently, there are no TV white space regulations in Ethiopia. The regulations of FCC (USA) are used for the estimation of TV white space in Ethiopia.

There are few assumptions of this study that should be made. Firstly, Microphones and other wireless devices using TV band are ignored for this computation due to lack of available information. Secondly, it is assumed that the Okumura-Hata path loss model predict the reality on the ground to a fair degree, as shown in section 3.3 above. Thirdly, only UHF band (470-862 MHz) is considered since, according to [51] all 54 national TV

transmitters use UHF band. Fourthly, analog TV broadcasting is assumed, since DSO does not take place in Ethiopia before 2020 [47].

The following parameters are required for all TV transmitters to estimate amount of available TV white space.

- i. Position of the tower
- ii. Transmission power of the TV transmitter,
- iii. Frequency of operation,
- iv. Height of the antenna

The above parameters of all the TV towers operating UHF band are not available, but [51] gives us some basic data required and others are assumed.

Let's consider the TV tower located at the mount Furi station near Addis Ababa. According to [51], the tower at the mount Furi station operates in the 638-646MHz band (channel 42) at a height of 60m and power of 25kW (73.98dBm), for analog TV broadcasting.

Using the TV transmitter information and the propagation model assumed previously, quantifying available TV white space in the UHF TV band was done in three different approaches. The first and second methods utilize the protection and pollution viewpoints respectively while the third one utilizes technical specification made by the FCC. These methods used for calculating TV white space have been introduced by Mishra and Sahai [52] and their method is reviewed in this section and utilized for this work for obtaining TV white space availability in the Ethiopia.

4.3.1. TV WHITE SPACE USING THE PROTECTION VIEWPOINT

Protected area or coverage area is the broadcast coverage area with no interference from other transmissions. Within protected area, the nominal received TV SNR is greater than the target signal-to-interference-plus-noise ratio (SINR). In the protection

viewpoint, when a secondary user operates, it must not cause any interference to the primary receivers in its surrounding areas. This is illustrated in Figure 4.2 below.

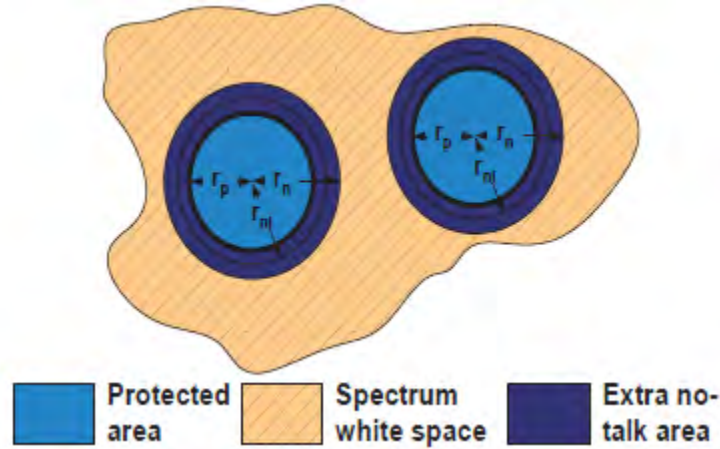


Figure 4. 2: Protection radius, separation distance and the no-talk radius [52]

The protected area is defined using the following SINR equations. Let P_t be the transmit power of primary in dBm, $PL(r)$ be the path-loss in dB at a radial distance r from the transmitter, N_o be the thermal noise in dBm, and Δ be the threshold SINR in dB. Then, the protection radius r_p is defined by the following SINR equation [52]:

$$P_t - PL(r_p) - N_o = \Delta \quad (4.1)$$

Let us assume, at every distance from the TV transmitter there exists a fading margin of “ $\Psi(r)$ ” which protects the TV receiver from bad fading events. Then modified equation for r_p becomes:

$$P_t - PL(r_p) - N_o = \Delta + \Psi \quad (4.2)$$

The no-talk radius r_n is defined as the distance from the primary transmitter up to which no secondary user can transmit, i.e. secondary user can only transmit if it is outside the no-talk area of the primary transmitter in question. In order to calculate r_n we must first have to calculate the value of $r_n - r_p$ i.e. we need to calculate the distance r_n such that a transmission from r_n results in a SINR of Δ at r_p . The separation distance $r_n - r_p$ is then calculated such that:

$$P_s - PL(r_n - r_p) = \Psi \quad (4.3)$$

where, P_s is the secondary transmitter power in dBm.

In this paper, let's assume multiple simultaneous secondary users are ignored and only one secondary device transmitting around the primary receiver is considered.

In the protection view point, for each 8MHz TV channel, the 'white space' can be defined as all area that is not within any relevant tower's no-talk radius.

A TV receiver which is tuned to particular channel has not only co-channel tolerance limit on the interference level but also adjacent channel. Hence WSD should only transmit in a given band if TV receivers in the co-channel and in the adjacent channels can be protected. According to the [18, 52], TV receiver can tolerate more adjacent channel interference than co-channel interference. Therefore, a fading margin of 27dB higher than the desired signal as the [18] FCC specifies for the adjacent channel interference is provisioned.

Let's take as an example TV tower located at the mount Furi, to determine protection radius and no-talk radius. The parameters used in computations for calculating the available TV white space by using the protection viewpoint are given in Table 4.2.

Parameters	Assigned value
Target fading margin (Ψ)	1dB specified by FCC [18]
Additional fading margin in adjacent channel	27dB specified by FCC [18]
Required SINR for primary receiver (Δ)	45dB
Thermal noise in a 8MHz band = N_o = $10 * \log_{10}(k * T * B)$	$\sim -105dBm$

Transmission power of TV transmitter	25kW (73.98dBm)
TV tower height	60m
Receiver antenna height	5m
Transmission power of secondary device	36dBm
HAAT of secondary device	30m

Table 4. 2: parameters used for calculation of TVWS using protection viewpoint

In section 3.3 above, different propagation path loss models are compared and Okumura-Hata path loss model showed lowest path loss and assumed to be used for rural Ethiopian scenario. Okumura-Hata path loss model for urban area is suitable for TV tower located at the mount Furi. The required mathematical equations to calculate protection and no-talk radius are as follows:

$$P_t - PL(r_p) - N_o = \Delta + \Psi \text{ and } P_s - PL(r_n - r_p) = \Psi$$

$$PL(r_p) = 69.55 + 26.16 \log(f_c) - 13.82 \log(h_t) - a(h_r) + (44.9 - 6.55 \log(h_t)) \log(r_p)$$

$$a(h_r) = 3.2 \times (\log(11.75 \times h_r))^2 - 4.97 \text{ where } f_c = 639.25\text{MHz}$$

From the protection viewpoint, if a fading margin of 1dB is provided, the protection and no-talk radius in channel 42 are 16.35 km and ~16.35 km respectively. If we consider an additional fading margin of 27dB in the adjacent band, the no talk radius in the adjacent channel is ~99 km. This implies that if a secondary device operates within a distance of 16.35 km in channel 42 and 99 km in the adjacent channels, the primary user receiving on channel 42 will experience interference.

4.3.2. TV WHITE SPACE USING THE POLLUTION VIEWPOINT

In the pollution viewpoint, the spectrum is available for white space if the noise from the primary transmitter is below the tolerable interference level of the secondary

receiver. That means, primary user transmissions are considered as raising the noise floor from the point of view of the secondary user. In this case, each television tower can be viewed as having its pollution radius around it in which the spectrum is unattractive for secondary use due to high noise.

Therefore, in the pollution view point a location is considered available for white space operation in a given TV channel if it does not fall within the pollution radius of any transmitter of that channel.

Let us assume γ is the interference tolerable by the secondary receiver, then pollution radius, r_{pol} is given by:

$$P_t - PL(r_{pol}) = N_o + \gamma \quad (4.4)$$

where P_t is primary transmitter power in dB, $PL(r_{pol})$ is path loss at distance r_{pol} from primary in dB, N_o is the thermal noise in dBm and γ is interference from primary to secondary in dB.

Similar to the protection viewpoint, there are adjacent channel interference conditions in the pollution viewpoint as well for secondary operation as white space. As stated in [52], secondary device can tolerate up to 45dB of interference if it is operating in the adjacent channels and up to 15dB pollution level was inferred from current IEEE 802.11g systems of interference if it is operating in the co-channels.

Assuming the TV tower located at the mount Furi, let's determine the pollution radius. The parameters used in computations for calculating the available TV white space by using the pollution viewpoint are given in Table 4.3 below.

Parameters	Assigned value
Maximum tolerable interference (γ) by	15dB specified for 802.11g

secondary	systems [52]
Maximum tolerable interference (γ) by secondary (adjacent channel)	45dB [52]
Thermal noise in a 8MHz band = N_o = $10 * \log_{10}(k * T * B)$	$\sim -105dBm$
Transmission power of TV transmitter	25kW (73.98dBm)
TV tower height	60m
Receiver antenna height	5m

Table 4. 3: parameters used for calculation of TVWS using pollution viewpoint

In the Okumura-Hata path loss model used for path loss calculations, as an example Furi has been considered as an urban city, since it is near Addis Ababa. The required mathematical equations to calculate pollution radius are as follows:

$$P_t - PL(r_{pol}) = N_o + \gamma$$

$$PL(r_{pol}) = 69.55 + 26.16 \log(f_c) - 13.82 \log(h_t) - a(h_r) + (44.9 - 6.55 \log(h_t)) \log(r_{pol})$$

$$a(h_r) = 3.2 \times (\log(11.75 \times h_r))^2 - 4.97 \quad \text{where } f_c = 639.25MHz$$

Using the pollution viewpoint, for a 15dB tolerable interference in channel 42 (638-646MHz), the pollution radius for the tower is calculated to be 33.36 km, and for a tolerable interference of 45dB in the adjacent channel, the pollution radius is 4.2 km.

What this means for a secondary device is that the interference level is more than the allowable limit in a region of 33.36 km in channel 42 and 4.2 km in the adjacent channels around the tower.

4.3.3. TV WHITE SPACE USING THE FCC RULES

Spectrum regulator in the USA, FCC, has developed their own approach to determine the no-talk radius around a TV tower. They assume that the protected radius is the same as the Grade B contour and the interference level at the protected radius (r_b) should be 23dB lower than the signal level [18, 52]. The required field strength ($E_{r_b}(dBu)$) at the Grade B contour is defined by the FCC for ATSC signals [18] as shown table 4.4 below. For example, in the UHF band r_b is the distance from the TV tower where the field strength of the primary signal falls to 64dBu, for analog TV band transmission.

Type of station	Protected contour		
	Channel	Contour (dBu)	Propagation curve
Analog: Class A TV, LPTV, translator and booster	Low VHF (2-6)	47	F(50, 50)
	High VHF (7-13)	56	F(50, 50)
	UHF (14-69)	64	F(50, 50)
Digital: Full service TV, Class A TV, LPTV, translator and booster	Low VHF (2-6)	28	F(50, 90)
	High VHF (7-13)	36	F(50, 90)
	UHF (14-51)	41	F(50, 90)

Table 4. 4: Protected contour for digital and analog TV services [18]

The required field strength is converted from dBu to dBm using the following conversion formulas [52] as shown in table 4.5 below.

Channels	Formula to convert from dBu to dBm
2 - 6	$P(dBm) = E(dBu) - 111.8$
7 - 13	$P(dBm) = E(dBu) - 120.8$
14 - 69	$P(dBm) = E(dBu) - 130.8 + 20 \log_{10} \left(\frac{615}{\frac{f_H + f_L}{2}} \right)$

Table 4. 5: dBm to dBu conversion values for various frequencies [52]

where, $P(dBm)$ is transmit power in dBm, $E(dBu)$ is the field strength in dBu, f_H is the upper frequency-limit of the channel in MHz, and f_L is the lower frequency-limit of the channel in MHz.

In order to calculate the separation distance, $r_n - r_b$ i.e. distance beyond r_b where no secondary device can transmit, we have to calculate r_n at which received TV signal level located at r_b becomes $E_{r_b} - 23dBu$.

For the TV transmitter located at the mount Furi, the protected radius and no-talk radius is 6.8 km and 40.6 km respectively by using parameters in table 4.2 above. This implies that, according to FCC white space rule a secondary device cannot use channel 42 within 40.6 km from the primary transmitter.

CHAPTER FIVE

ECONOMIC AND FINANCIAL FEASIBILITY OF TVWS IN ETHIOPIA

Introduction

Ethiopia, second most populous country in the African continent, located at the horn of East Africa has a varied geographic topography which resulted in various climates. The country has various ethnic groups with their own respective languages. Over 63% of the total country's population is aged below 24 years and 85% of the country's population is employed on agriculture and the country is on the list of UN least developed countries.

Communication in Ethiopia is less developed and mostly controlled by government. Internet provision in Ethiopia has been very poor and Ethio telecom is only ISP in the country. According to a report in 2014, only 3.7% of total population use internet. Main reason for low penetration of internet in the country was due to costly existing delivering methods and lack of adequate infrastructure. Possible solution to deliver relatively cheap broadband internet in Ethiopia is by using TVWS.

5.1. Background research

In this section background information about demographics, economics and communications use in Ethiopia are presented.

5.1.1 Ethiopia general background

Ethiopia, officially known as the Federal Democratic Republic of Ethiopia is the world's 27th largest country located in the United Nations Eastern Africa sub-region. It lies between the latitudes 3rd parallel North and the 15th parallel North and longitudes 33rd meridian East and 48th meridian East.

Ethiopia is a landlocked country and has a varied geography including vast highland complex of mountains and dissected plateaus divided by the Great Rift Valley, which

runs generally southwest to northeast and is surrounded by lowlands and semi-desert. The great diversity of terrain determines wide variations in climate, soils, natural vegetation, and settlement patterns.

5.1.1.1. Population

Ethiopia's population is highly diverse, containing over 80 different ethnic groups that include most major ethnic and linguistic groups found in Africa. The ethnic composition of the nation is: Oromo 34.4%, Amhara 27%, Somali 6.2%, Tigray 6.1%, Sidama 4%, Gurage 2.5%, Wolaita 2.3%, Hadiya 1.7%, Afar 1.7%, Gamo 1.5%, Gedeo 1.3%, Silte 1.3%, Kefficho 1.2%, other 10.5% [53].

Ethiopia's various ethnic groups typically speak a language specific to their own communities. According to 1995 constitution of Ethiopia, all languages enjoy equal state recognition and Amharic is recognized as the official working language of the Federal Government and each of the regional states are free to determine their own working languages. English is the most widely spoken foreign language and is the medium of instruction in secondary schools and Universities.

According to UN Department of Economic and Social Affairs, Population Division [54], the country has a youthful population, with 63% of residents aged below 24 years. Rapid population growth is continuing, from 18.128 million to 87.562 million inhabitants over the last 6 decades which is 3.83 fold increases and is projected to rise to 243 million by 2100, driven by high fertility rates and increasing life expectancy. This youthful population will present a number of economic opportunities for the country by creating a large labour pool. However, improving education and health outcomes is critical to making the most of Ethiopia's demographic potential.

According to the UNICEF report, [55], the primary school enrolment ratio is at 87.4% (2008-2012) and adult literacy is 39%. However, stunting amongst children is highly prevalent (44.4%) which has serious impacts on productivity in later life.

5.1.1.2. Economic

Ethiopia's economy is largely based on agriculture, which accounts for 46.6% of the gross domestic product (GDP) and 85% of total employment; but the government is pushing to diversify into manufacturing, textiles, and energy generation. Coffee is a major export crop. The agricultural sector suffers from poor cultivation practices and frequent drought. Although recent joint efforts by the Government of Ethiopia and donors have strengthened Ethiopia's agricultural resilience, changes in rainfall associated with worldwide weather patterns continue to create food insecurity for millions of Ethiopians [53].

Ethiopia is one of the world's poorest countries. The country's per capita income of \$550 is substantially lower than the regional average. The main export partners for Ethiopia include China 17.1%, Germany 7.6%, US 7.2%, Belgium 6.8%, Saudi Arabia 6.7% (2014) and main import partners include China 19.2%, US 11.4%, Saudi Arabia 6.7%, India 5% (2014) [53].

According to the latest World Bank Group's economic analysis, [56], Ethiopia's economy is estimated to have grown by 10.2% in 2015 and is projected to grow by 10.2% in 2016. The resilience is likely to continue with the economy expanding at 9.0% in 2017 and 9.0% in 2018.

5.1.1.3. Income and inequality

Ethiopia still receives high substantial bilateral and multilateral aid, is on the UN list of Least Developed Countries [57]. There are large disparities between rich and poor, with significant levels of wealth at the top of the economy and a sizable middle class.

Inequality in Ethiopia is high. The Gini coefficient of Ethiopia's income is 33 suggesting that a large part of Ethiopia's income is concentrated in a small number of hands [53]. This is reflected in Ethiopia's low score in the human development index of 0.442, which ranks 174th out of 188 countries [58].

In Ethiopia according to [59], the household survey evidence shows more inequality in rural than urban areas. The survey again shows that within rural areas, there is more inequality across households using land ownership than using total household consumption expenditure as a key variable of interest to rank households. Again the same report informed that inequality between rural and urban Ethiopia has decreased.

The economy of the country still faces ongoing problems of corruption. According to a report Ethiopia ranks 103rd out of 167 nations in Transparency International's Corruption Perception Index for fiscal year of 2015 [60].

5.1.2. Communications in Ethiopia

The introduction of telecommunication in Ethiopia dates back to 1894. Ethiopian Telecommunications Corporation is the oldest public telecommunications operator in Africa. In those years, the technological scheme contributed to the integration of the Ethiopian society when the extensive open wire line system was laid out linking the capital with all the important administrative cities of the country [61]. The rate of penetration of telecom service of the country is among the lowest being compared with African countries and even among Sub-Saharan African countries.

Internet provision in Ethiopia has been very poor, largely due to the lack of a widespread fixed infrastructure. Ethio telecom, only ISP provider in the country, is currently attempting a broad expansion of access throughout the country. These efforts have been hampered by the largely rural makeup of the Ethiopian population and the government's refusal to permit any privatization of the telecommunication market.

According to [53], in 2014 there are 820,000 fixed telephone line subscribers and 30.5 million cellular mobile telephone subscribers in Ethiopia. There are 3.7 million internet and Facebook users in the country on November 15, 2015 [62]. This shows that mobile telephone subscription grows at high rate compared with others with in the country.

5.2. Economic Significance of the Internet and Existing Delivery Methods in Ethiopia

Globally, the growth of mobile voice subscribers and internet users is amazing. In 2015 there are more than 7 billion mobile cellular subscriptions worldwide, up from less than 1 billion in 2000. Globally 3.2 billion people are using the Internet of which 2 billion are from developing countries [63]. Unlike mobile voice subscribers and internet users, fixed telephone users are diminishing; for example there are 1.261 billion users in 2006 and now in 2015 it was 1.063 billion users worldwide.

According to [53], in 2014 there are 0.82 million fixed telephone users and 30.5 million mobile voice subscribers in Ethiopia and according to [62] there are 3.7 million internet users (3.7% penetration rate) in Ethiopia.

5.2.1 Commercial impacts of the internet

According to [64], the global e-commerce industry saw impressive growth in 2014 with goods and services worth \$1.5 trillion bought by shoppers via desktops, tablets and smart phones. Advertisers are now spending an increasing proportion of their marketing budgets on Internet advertising. This ad spend is forecast to surpass \$160 billion in 2015, of which more than \$58 billion will be spent on Display advertising.

The internet has also had a substantial effect on our industrial organisation. Broadband allows workers to work increasingly from home, often resulting in higher productivity and lower costs.

5.2.2. Social impact of the internet

Today globally, the use of social networking is the most popular activity using the internet. For the majority of internet users its social aspect is perhaps most prominent. According to [65] there are over 1.2 billion Facebook registered users, over 645 million Twitter registered users, 300 million Instagram users and 200 million LinkedIn users and according to globally email statistics report [66], there are over 4.1 billion email accounts worldwide in 2014. Access to broadband internet also allows access to other communications platforms such as the global telephone network and SMS messaging through services such as Skype Viber, Line and so on. According to [62], there are 3.7 million internet and Facebook users in Ethiopia on November 15, 2015.

The internet is home to a vast repository of knowledge and information, much of it accessible at no cost. It is also increasingly the arena in which scientific research and academic debate occurs. The internet has become the primary source of news in many countries around the world and various forums are also used to organise social and political action. Governments are increasingly delivering services and information to their citizens using the internet.

5.2.3. Existing Broadband Delivery Methods in Ethiopia

According to ITU report in 2015 [63], 3.2 billion people are using the Internet globally, 4 billion people from developing countries remain offline, representing 2/3 of the population residing in developing countries, of the 940 million people living in the least developed countries only 89 million use the Internet, corresponding to a 9.5% penetration rate. In Ethiopia there are only 3.7 million internet users which correspond to 3.7% penetration rate at the end of 2015, [62], which is below the average of least developed countries.

The current wave of growth in the usage of fixed and, especially, mobile broadband will certainly introduce a large number to the internet. However, our existing methods of broadband delivery are costly, limiting their take-up in densely populated areas and preventing roll-out altogether in more sparsely populated areas.

5.2.3.1. Challenges Associated with Existing Broadband Delivery Methods

A. Limited affordability of broadband

The cost of broadband access is a major factor limiting its uptake. The International Telecoms Union (ITU) has set a target for 2015 that broadband access should cost no more than 5% of income [67]. Broadband is becoming more affordable over the five years since the creation of the Broadband Commission in 2010; fixed broadband prices as a share of GNI per capita have dropped by 65% on average worldwide.

According to ITU report of 2015 [63], Broadband is now affordable in 111 countries with mobile-broadband less expensive than fixed-broadband. The report shows that by 2014, most countries in the world had reached the Commission's target of basic fixed-broadband service at less than 5% of monthly GNI per capita. However, in many of the world's poorest countries, where broadband could potentially have the greatest benefit in terms of bridging development gaps, even basic broadband service remains prohibitively expensive.

Again, according to the ITU report of 2015 [63], the global average price of a basic fixed broadband plan is 1.7 times higher than the average price of a comparable mobile-broadband plan. In developing countries, average monthly fixed broadband prices are 3 times higher than in developed countries; mobile broadband prices are twice as expensive as in developed countries.

The price of fixed and mobile broadband in Ethiopia is shown at appendix A. As the tables shows the price for monthly package of mobile broadband is more expensive

than that of fixed broadband. The price of mobile broadband is higher than fixed broadband due the fact that mobile network infrastructures are built mainly by external loan. This implies that, unlike most of other countries, in Ethiopia fixed broadband is more affordable than mobile broadband in terms of price.

B. Limited availability of broadband

There are only a few countries in the world in which universal availability of fixed and mobile broadband is a practical reality [67]. Such countries include a number of wealthy densely populated nations, such as Luxembourg, Denmark and Singapore and some larger nations, such as South Korea and Japan with substantial public subsidy.

According to the some reports, [67], Even in the developed markets of Europe and North America broadband is not universally available. For example, in the USA, 4% of the population, that means 11 million people, cannot access fixed broadband and in Europe fixed broadband is not available to 4.7% of the population, which is around 23.5 million people, of whom 18 million are in rural areas.

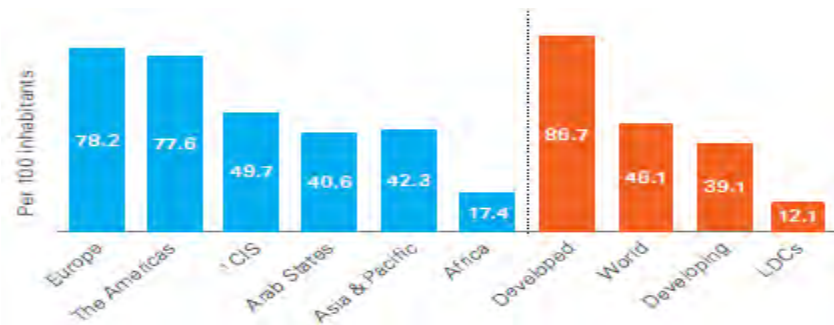


Figure 5. 1: Globally mobile broadband subscriptions [63]

In much of the developing world there is very little broadband coverage. According to ITU report [63], mobile-broadband penetration in Europe is 78.2, America is 77.6, Asia & Pacific 42.3, Africa 17.4 and least developed countries 12.1 active subscriptions per 100 inhabitants, figure 5.1 above; and for fixed-broadband penetration in Europe is 29.6, America is 18.0, Asia & Pacific 8.9, Africa 0.5 and least developed countries 0.5 active

subscriptions per 100 inhabitants, figure 5.2 below. This shows that developing countries has least broadband penetration rate.

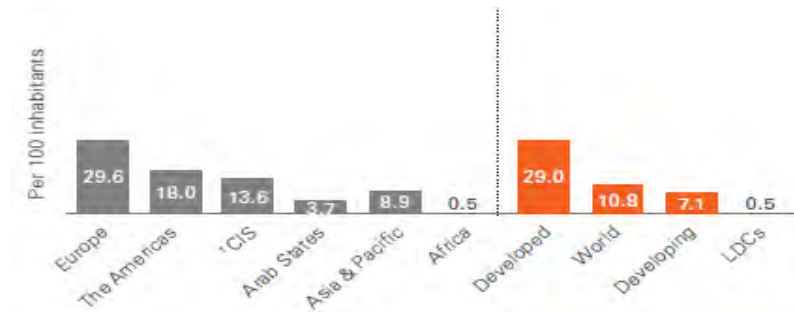


Figure 5. 2: Globally fixed-broadband subscriptions [63]

In Ethiopia broadband connectivity is limited to main cities in the country [68]. According to the data obtained from ethio telecom website mobile broadband is now only available in Addis Ababa and regional main cities where the 4G/3G network is available.

5.2.3.2. The high costs of existing models of broadband delivery

In Ethiopia, ethio telecom provides broadband services using either fixed line (such as Fixed Wireless Broadband- Aironet, fiber, cable, ADSL) or wireless broadband options (such as Broadband VSAT, which is more expensive than others and mobile broadband, which is delivered using EVDO, 3G and 4G mobile technologies) [68]. The detail tariffs for each of the ethio telecom’s broadband types are found at appendix A.

A. Fixed networks

Currently in Ethiopia, the fixed broadband infrastructure is an upgrade of previously deployed fixed networks, such as the copper based phone, providing ADSL services. In order to boost capacity and availability of broadband, new fixed networks based on optical fiber are being deployed in limited quantities in parts of the main regional cities.

In order to provide broadband by using fixed networks, construction of fixed networks is a supremely costly proposition. According to [67], most expensive element is that of

providing the last mile, or the final connection to the consumer. Other high costs include the installation of customer premises interfaces, the cabling to be laid and the construction of sub-stations to aggregate the cable ends.

Ethio telecom, only telecom operator in Ethiopia, provides fixed broadband by using Fixed Wireless Broadband- Aironet and ADSL (copper or optical fiber). A broadband service provided by ADSL is less expensive than others in Ethiopia [68].

B. Mobile networks

In Ethiopia, ethio telecom provide mobile broadband by using 3G networks (such as HSPA+, HSPA and EVDO) and 4G/LTE network. Even though the costs of building a mobile network are substantially lower than those of a fixed network, the price of the same monthly package is more expensive; this is mainly due to the fact that mobile network infrastructures are built by external loan.

Currently in Ethiopia, mobile broadband packages have played an important role in extending mobile broadband coverage to market segments that have not traditionally been able to afford fixed broadband.

5.2.3.3. Using TVWS for Delivering Broadband internet in Rural Ethiopia

As discussed above, the deployment of fixed and cellular networks requires highly expensive equipment and is limited to main regional cities in Ethiopia. By contrast, technologies that use licence-exempt spectrum, such as TVWS, are cost-effective and can be deployed easily and with less cost.

Using TVWS for broadband internet services in rural Ethiopia is the best option relative to the currently available mode of delivery methods. The main reason to choose TVWS for rural connection is due to its affordability with respect to other technologies. That means, the cost of providing the service will be cheap compared with existing

technologies due to the signal characteristics at this band and other factors such as low licence fee.

In addition, licence-exempt networks such as TVWS will be used to extend cost effective broadband to places that are not covered by fixed and mobile networks.

5.3. Cost Analysis of TVWS Technology Deployment

This section covers the analysis of the total cost of deployment of a core service station, backhaul, BS and client station model in a rural setting. The costs for setting the actual network, includes design costs, deployment costs, maintenance costs, and infrastructure costs for BSs, client stations, and APs.

The cost structure consisted of two parts: Capital Expenditure (CapEx) cost and Operational Expenditure (OpEx) cost. CapEx costs refer to all the infrastructure and network element investments, including implementation costs for building the network. OpEx costs represent the costs needed to keep the network up and running. The combination of CapEx and OpEx led to the estimation of the total cost of ownership for each scenario for a study period.

5.3.1. Capital Expenditure (CapEx) Analysis

CapEx cost is the cost that once made cannot be recuperated. This cost will include all the infrastructure and network element investments, engineering studies, labor, and transportation, training, and implementation costs for building the network.

For simplicity, CapEx cost further will be divided into four categories, which consists of the cost of deployment of core network services, cost of deployment of backhaul/backbone network, cost of deployment of a BS, and the cost of deployment of CPEs.

5.3.1.1. Core network services cost

Capital cost of TVWS core network services includes cost of designing core network, cost of installation and deployment, connection setup between TVWS data base and each core network services, procurement of equipment. According to proposed network architecture in section 3.1.2 above, the TVWS core network services are:

- i. *RADIUS*: is a networking protocol that provides centralized AAA management for users who connect and use a network service.
- ii. *Network Operations Center and Operation and Maintenance Center (NOC/OMC)*: is a place from which administrators supervise, monitor and maintain a whole TVWS network. They are the focal point for network troubleshooting, software distribution and updating, router and domain name management, performance monitoring, and coordination with affiliated networks.
- iii. *Dynamic Host Configuration Protocol (DHCP)* is a client/server protocol that automatically provides an Internet Protocol (IP) host with its IP address and other related configuration information such as the subnet mask and default gateway.
- iv. *Domain Name System (DNS)* is a hierarchical decentralized naming system for computers, services, or any resource connected to the Internet or a private network. DNS translates domain name to numerical IP addresses.

5.3.1.2. Backhaul cost

Regarding the last mile backhaul, capital investments included installation and deployment, connection setup, procurement of equipment such as transceivers and antennas. Backhaul network connects ISP with BSs and even BSs with each other. The actual cost for backhaul network depends on the type of backhaul network used and the way of obtaining the backhaul network.

For rural Ethiopian case there are three possible ways of providing backhaul network.

- i. *Using TVWS*: in this case we can use TVWS as backbone network. This method is more cost effective if there is required amount of white space is available since TVWS is licence-exempt spectrum. Providing backhaul network in this method requires building/leasing towers, installing TVWS radio devices
- ii. *Using point-to-point Microwave link*: providing backhaul network by using this method requires building/leasing towers/masts and installing microwave radio devices. In addition to these costs, there is additional licence fee for microwave spectrum.
- iii. *Using currently available backbone links*: in this scenario we can lease available backbone network from telecom service provider in the country, ethio telecom. Currently ethio telecom uses mostly fiber optic and point-to-point microwave link for a backhaul network. If this option is supposed for backhaul network, there would be no capital cost, since rent fee is paid after service is provided.

5.3.1.3. Base station deployment cost

BS deployment requires high engineering design task, because accurate and efficient BS deployment location not only decreases capital investment but also keeps quality of service at a required level. Thus, the analysis of capital cost on the BS deployment starts from choosing best location for network deployment.

Capital cost on the BS deployment includes all cost required to build it. As explained above in section 3.1.2 and 3.1.4, almost all of the components required to deploy BS are listed below.

- *Civil engineering studies prior to the network deployment*. It includes trips to sites, terrain analysis for the BS tower, area analysis for CPE installation, and initial network deployment reporting
- *Transportation cost*: Shipping of materials & transportation of the equipment to sites.
- *Labor cost*: this cost includes wages, materials, training, and tools

- *Telecommunications equipment*: cost of the antennas, cables, protective devices
- *Cost of the tower structure*: this includes cost of construction materials, electric cabling, telecommunication testing equipment
- *Lightening shielding*: costs for grounding and lightning protection system
- *Backup power*: this includes costs for UPS or diesel generator in case of primary power failure

5.3.1.4. CPE deployment cost

Regarding capital cost of CPE deployment, capital investment includes installation and deployment, connection setup, procurement of equipment. CPE deployment cost depends on the type of service provided and customers need. Each required components of CPE deployment are listed below, according to proposed network architecture in section 3.1.4 above.

- *RF to LAN*: the RF equipment that converts radio signals to digital signals. It includes LNA (Low Noise Amplifiers)
- *Yagi Uda antenna (CPE)*: high directional antenna, pointing to the omnidirectional BS antenna
- *Access points (POPs)*: The Wi-Fi routers that converts digital signal to 2.4 GHz of radio signals in unlicensed band OR DSL router that is used to access broadband internet by Ethernet cable
- *Cable*: Coaxial cables connecting CPE to the POPs
- *CPE structure*: The structure required to mount CPEs
- *Labor*: labor cost associated with deploying CPEs and cables
- *Switch*: Networking switch to divide data between POPs.
- *Lightening shielding*: grounding and lightning protection system for CPEs.

5.3.2. Operational Expenditure (OpEx) Analysis

Operating costs of TVWS operator are the expenses which are related to the operation of a business, or to the operation of a device, component, and piece of equipment or facility. They are the cost of resources used by an organization just to maintain its existence.

The operational costs for the proposed TVWS operator include all costs after network deployment. These costs include the cost of operating and maintaining TVWS core network services, operating and maintaining backhaul network, BSs and CPE and customer sides. Some of the main operational costs can be summarized as follows.

- *Site running costs*: These include utility bills such as electricity & site leasing costs.
- *TVWS core network services*: this cost includes all running and operational and maintainace expenditure on core networks. This includes software updating, provisioning, customer acquisitions, billing and so on.
- *Base station*: regarding BS, OpEx includes network operation personnel for the BS for maintenance and engineering tasks.
- *CPE*: operational cost for CPE side includes costs for network engineer and networking device engineer at the CPE side.
- *Backhaul cost*: running costs included transmission and operation and maintenance costs, as well as leasing fees for the leased case.

5.3.3. Techno-Economic Models

Currently there are different competing wireless technologies are made available for customers, a new technology that is about to be introduced to a market needs to have a significant advantage both in technological and economic terms, in order to justify its investment.

The method used for evaluating the economic feasibility of complex technical systems is called techno-economic modeling. It involves the processes of modeling, analysis,

evaluation and finally assessment. Based on the calculated costs and revenues, a number of indicators are used to determine the profitability of the scenarios, including for example payback period, net present value (NPV) and internal rate of return [69].

The main objectives of techno-economic modeling and different economic models can be found at [69, page 39-43] in detail.

5.3.3.1. Total Cost of Ownership (TCO)

Total cost of a network is cost required to build and operate certain network. The cost of a network directly depends on different factors; such as coverage, capacity and traffic demand requirements. Large coverage area requires more BSs and network elements which influences the network cost, denser area requires more stations as well which increases the cost of network while higher traffic demand require more capacity from network which raises the network cost as well.

As discussed above TCO is combination of CapEx and OpEx. Each of the required CapEx and OpEx parameters are discussed in section 5.3.1 and 5.3.2 above for this scenario.

$$TCO = CapEx + OpEx \quad (5.1)$$

In generally, there are two cost modeling methods i.e. top-down methods and bottom-up methods, differing in their starting point for the modeling process. The detail and diagrammatic representation for each method can be found at [69, page 45 & 46].

5.3.3.2. Profitability Analysis

One of the main reasons for carrying out techno-economic analysis is to estimate whether or not the investment project in question is profitable or not. There are some commonly used methods to calculate the profitability of the project. These are project's net present value, internal rate of return and payback period.

a) Net Present Value (NPV)

According to [70], NPV is the difference between an investment's market value and its costs, or it can be defined as the future stream of benefits and costs converted into equivalent values today. The NPV of a project is calculated as the difference between the discounted value of the future incomes and the amount of the initial investment. If the NPV is positive, the project is assumed profitable and otherwise project is failed.

NPV is calculated according to the dynamic investment evaluation method that considers the life cycle of the investment (I), the positive cash flow in particular year (D), the interest rate (r) and the initial investment [69].

$$NPV = \left[\sum_{t=1}^n \frac{D_t}{(1+r)^t} \right] - \left(\sum_{t=0}^n \frac{I_t}{(1+r)^t} \right) \quad (5.2)$$

where n is study period of time t.

b) Internal rate of return (IRR)

Internal rate of return is defined as the discount rate that makes the NPV of an investment equal to zero. This rate is called the "internal" rate in the sense that it only depends on the cash flows of that particular investment, not on rates offered elsewhere [70]. If IRR is used as profitability, then an investment is accepted if the IRR exceeds the required return, otherwise it should be rejected [70]. If the IRR is greater than the discount rate used for the project, then the investment is judged to be profitable.

c) Payback Period

Payback period, which is a number of years to wait until the accumulated discounted cash flows from the investment equal or exceed the cost of investment (i.e. when the NPV turns from negative to positive value) [70]. When using the payback rule in investment decisions, all projects that pay themselves back before a defined cutoff date are considered profitable.

CHAPTER SIX

RESULTS AND ANALYSIS

In this chapter each of the parameters which is presented in previous chapters are analyzed. First the proposed network architecture is discussed followed by the signal propagation results for TV tower located at the mount Furi, the example transmitter.

The available white space channels are then estimated, illustrating the amount of white space available. Finally economic and financial viability for the case of rural Ethiopia are discussed.

6.1. Proposed Network Architecture

In general, network architecture for a given system depends on different parameters. For example, the type of the intended service, type of the communication media will be used, location where the service will be provided and service provider; can determine network architecture.

In this thesis, TV white space is used to provide broadband internet service for rural Ethiopia. Assuming current Ethiopian government control on telecommunication sectors, it is difficult to think about private service provider in near future. Taking this in to consideration, the assumed service provider may be ethio telecom or other government agency.

Therefore, in this thesis any communication infrastructure which is owned by any government agency is assumed to be used; if it is suitable for this purpose. For example, if there is any deployed optical fiber/copper passing through a given location, it is assumed it can be used as backhaul network.

Taking all these assumptions in consideration, the proposed network architecture in section 3.1.2 figure 3.1 (page32) can be represented in block diagram as follows.

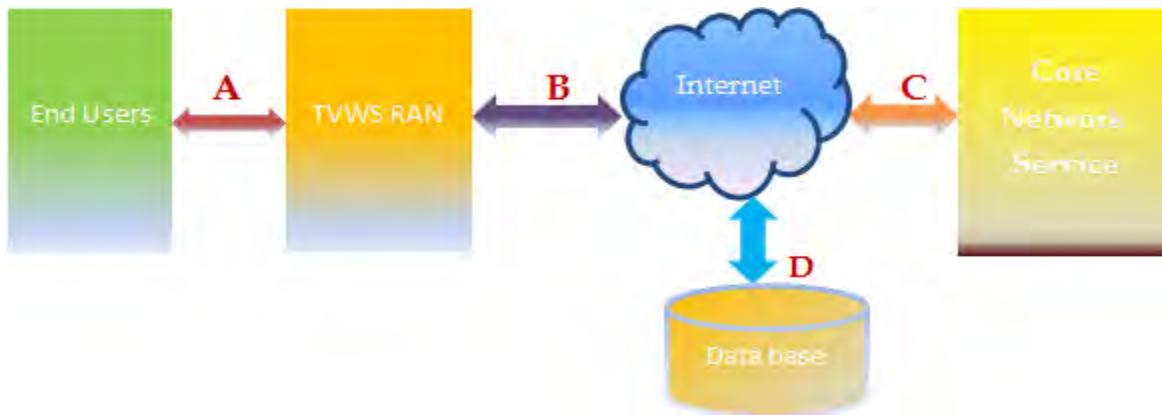


Figure 6. 1: Block diagram of TVWS network architecture

Each block and path are discussed more detail in section 3.1 above and summarized below.

Starting from the left block, end users are customers who access internet service by using any kind of devices from TVWS CPE. Path A shows the method how end users are accessing internet. Accessing method is either as WiFi or using Ethernet cable. TVWS RAN consists of both TVWS BS and TVWS CPE. The interface between TVWS BS and TVWS CPE is air.

From the diagram above, path B shows the link (backhaul) between internet and TVWS RAN. This backhaul may be any kind of available media as described in section 3.1.3 above (page 33-34). Path C and D show the interconnection between internet and data base and core network services.

6.2. Propagation Models

In general, propagation models are used for calculation of electromagnetic field strength. At a given point electromagnetic field strength is affected by different environmental factors; such as the type of environment, nature of the terrain, weather of the environment.

In section 3.2 above (page 35-44), different propagation models are described and in section 3.3 above (page 44-47) each model are simulated with randomly selected variables. Numerical result from the figure 3.4 and figure 3.5 above in section 3.3 (page 46-47), shows that Okumura-Hata path loss model is suitable for sub-urban and rural Ethiopia.

Now let's consider the TV tower located at the mount Furi station near Addis Ababa. According to [51], the tower at the mount Furi station operates in the 638-646MHz band at a height of 60m and power of 25kW for analog TV broadcasting. Assume distance between transmitter antenna and receiver antenna is assumed 15 km, receiver antenna height is 5 m.

Let's assume TV transmitter at mount Furi is considered both urban environment and semi-urban environment for computational purpose. From section 3.2 above (page 35-44), the mathematical representation and parameters for each model for this scenario used and simulated using Matlab. The numerical results for different models in urban area and rural area for given operating frequency and for receiver antenna heights are shown in the Figure 6.2 and Figure 6.3 below respectively.

From the graphs below, for both environments there is different path loss model which gives lowest path loss prediction for each case, as shown figure 6.2 and figure 6.3 below. If the TV station is considered located at urban area, Stanford University Interim model shows lowest path loss for small separation distance and Okumura model shows lower path loss. If the TV station is considered located at sub-urban area, Okumura-Hata path loss model gives lowest path lowest path loss.

Therefore, for this thesis it is assumed to use Okumura path loss model for urban area and Okumura-Hata path model for rural area of Ethiopia.

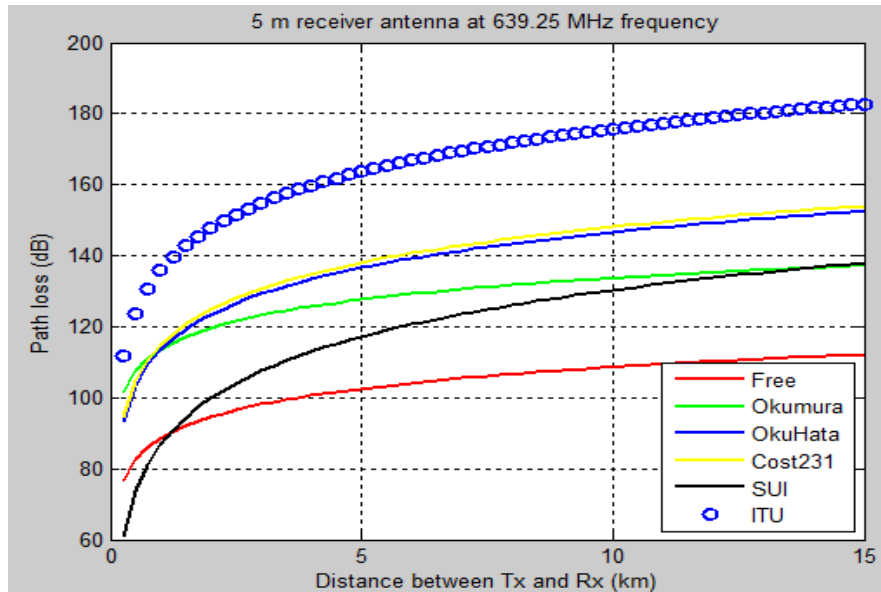


Figure 6. 2: Path loss in urban environment at 5 m receiver antenna height and operating frequency of 639.25 MHz

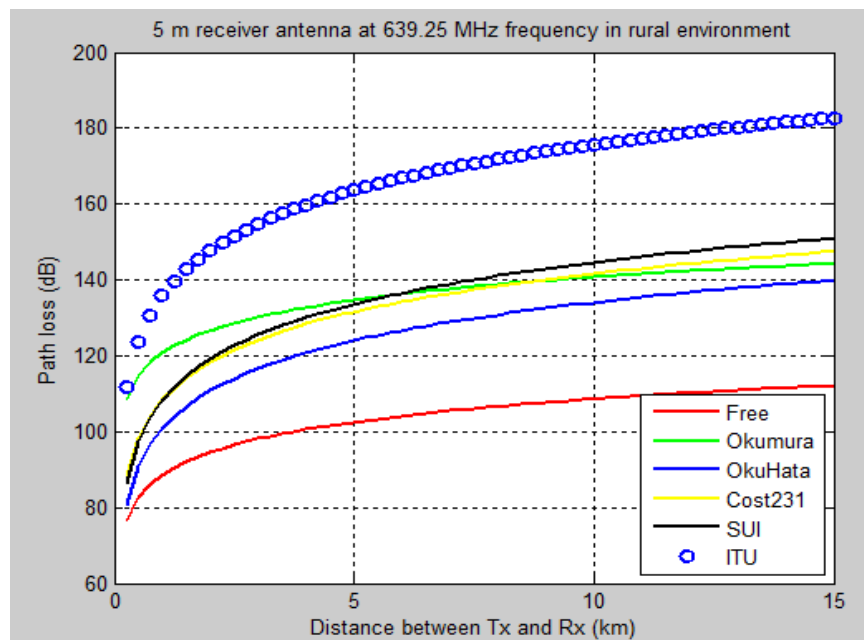


Figure 6. 3: Path loss in rural environment at 5 m receiver antenna height and operating frequency of 639.25 MHz

6.3. Estimating Amount of Available TVWS

Estimating the available TV white space can be done in different ways, depending on the country's regulation. In this thesis estimating the available white space was done mathematical in three different methods.

Each of the three methods discussed in section 4.3 above (page 55-62) uses a real data from each transmitting sites to determine either protection radius and no-talk radius or pollution radius. Knowing these radiuses helps us to determine separation where we can use that specific channel as a white space.

In Ethiopia there is limited number of terrestrial TV broadcasters and all of terrestrial TV transmissions are controlled by the government. According to [51], in Ethiopia terrestrial TV broadcasting will cover 80% of total area. That means, 20% of total area in the country can't receive terrestrial TV. Thus, all channel allocated for terrestrial TV broadcasting are available white space for 20% total area in Ethiopia.

In section 4.1.3 above (page 51) terrestrial TV broadcasters in Ethiopia are discussed and in section 4.1.4 above (page 51-52) spectrum band which is allocated for TV transmission in Ethiopia are discussed. From these discussions we can observe that only fraction of spectrum is used for terrestrial TV broadcasting and most TV channels can be available as white space for a secondary use.

For example, if we take some area in Amhara region, from totally allocated channels only three (3) channels are occupied for terrestrial TV broadcasting (EBC 1, EBC 3 and Amhara regional TV) at a time and other TV bands can be available as a white space.

6.4. Economic and Financial Analysis

In chapter 5, economic and financial analyses are discussed in detail. As we have observed from different reports, Ethiopia is still least developed country in the world. As a result, it is difficult to finance any new project.

But in this thesis, it is assumed that it is required to provide broadband internet for rural area of Ethiopia. There are two ways of providing broadband for rural community: either using currently available technology or using TV white space. In section 5.2.3.2 (page 71-72) it was shown that delivering broadband for rural area using currently available technology is more expensive and in section 5.2.3.3 (page 72) TVWS is recommended for such scenario. Again researchers in [8] showed that, the cost of an off-the-shelf TVWS BS radio is only 1/10th of an LTE BS radio, if both are compared.

Therefore, TV white space is financial feasible for rural Ethiopia compared with currently prevailing technologies.

A key assumption in determining financial feasibility is the leasing available backhaul network and masts (rather than construction of new backhaul and masts) of space on existing backhaul and masts for transmission of whitespace services from ethio telecom and others. And other assumption made was if there is no available backhaul network, TVWS can be used as backhaul.

In general, for providing broadband internet for rural Ethiopia have several challenges. Providing electricity and cost are two important challenges.

Electricity:

According to [8], in Africa alone, over 600 million people lack electricity. Hence, if there is no commercial power source solar power system is recommended, since in general TV white space devices consume low power compared with currently available

technology. Again customers must have a place to recharge their devices at solar power source, if there is no commercial power around.

Cost:

Costs are both broadband affordability and device costs. According to the report [8], for more than 60% of Africans, handset based mobile broadband is unaffordable and costs more than 5% of household expenditure. And as shown in section 5.2.3.1 (page 69), broadband is not affordable for Ethiopia and least developed countries. In Ethiopia, handset based broadband devices are very expensive compared with average daily earnings of the people. For example, minimum price of new laptop is over 9000 birr and minimum price of mobile phone which supports 4G network is over 8000 birr.

CHAPTER SEVEN

CONCLUSION AND FUTURE WORKS

7.1. Conclusion

This thesis has described issues related with TV white space usage for secondary application. In order to provide broadband internet for rural and remote areas, feasibility of TVWS was done. The feasibility of TVWS was compared with currently available broadband providing methods.

The network architecture for proposed system was modeled from taking the reality of available communication infrastructure. In proposing network architecture, it is assumed that the service will be provided by some government agency; since telecommunication sector in Ethiopia is controlled by the government and proposed network may use available infrastructure from ethio telecom and others. This decreases the cost for constructing new masts and backhaul network.

Different signal propagation methods are compared for rural Ethiopian scenario. From the sample simulation result, Okumura-Hata model was selected for rural areas, since it showed less path loss. But for urban area Okumura path loss model showed lower path loss and selected for urban environment.

TV band spectrum utilization was discussed and analyzed for Ethiopian case. As discussed above in Ethiopia there are a few terrestrial TV broadcasters and huge amount of channels are allocated for TV terrestrial transmission. This implies that most of the allocated TV channels are vacant and can be utilized for secondary application without affecting primary user. Thus in Ethiopia, there is huge amount of TV white space availability, since currently maximum of four channels can be simultaneously used in anywhere in the county.

Finally, economic and financial feasibility of TV white space in Ethiopia was discussed. Financial feasibility is compared with currently available broadband providing methods. Even though, there is no actual cost comparison for both technologies, from general reality TV white space technologies are less expensive. Hence, TV white space is financial feasible to provide broadband internet for rural Ethiopia.

Therefore, TV white space is best option to provide broadband internet service for rural Ethiopia, since there is high abundant of white space and low cost of deployment compared with currently prevailing technologies in the country.

7.2. Future Works

This thesis work solely focuses on theoretical and mathematical analysis of feasibility of TV white for broadband internet in general rural area of Ethiopia. For the future, specific area will be selected and detail analysis will be done. Spectrum occupancy rate is not known for TV band in Ethiopia and if the required material is available, this can be measure and calculated. Finally, economic feasibility and financial viability will be calculated using exact cost required to deploy TV white space network and other competing technology network.

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Appendix A: Ethio telecom broadband tariffs [68]

Monthly Package	Above bundle usage tariff	Out of package usage
1 GB	165	35 cents/MB
2 GB	320	
4 GB	600	
8 GB	1000	
10 GB	1200	
20 GB	2200	
30 GB	3000	
50 GB	4900	
80 GB	7600	
100 GB	9300	

Table A. 1: 3G/4G tariff

Monthly package	Access Speed	Monthly Package fee in Birr	Out of package usage
2GB	512 Kbps	250	23 cents/MB
4GB	1 Mbps	400	
6GB	2 Mbps	550	

Table A. 2: Limited ADSL tariff

Access Speed	Monthly usage fee in Birr without VAT	Out of package usage
256 Kbps	475	Unlimited
512 Kbps	950	
1 Mbps	1,700.00	
2 Mbps	3,075.00	
3 Mbps	4,775.00	
4 Mbps	5,550.00	

Table A. 3: Unlimited ADSL tariff

BB Internet with Aironet CPE					Local MPLS VPN WITH AIRO NET CPE			
speed	AIRO net point to point		AIRO net point to multi point		local MPLS VPN with AIRO net point to point		local MPLS VPN with AIRO net point to multi point	
	Subscription fee in Birr	Monthly Usage charge in Birr	Subscription fee in Birr	Monthly Usage charge in Birr	Subscription fee in Birr	Monthly Usage charge in Birr	Subscription fee in Birr	Monthly Usage charge in Birr
256 Kbps	70,860.50	1,552.30	14,446.48	2,006.73	71,890.94	1,908.55	15,476.92	2,362.98
512 Kbps	70,860.50	2,027.30	14,446.48	2,481.73	71,890.94	2,739.80	15,476.92	3,194.23
1 Mbps	70,860.50	2,777.30	14,446.48	3,231.73	71,890.94	4,052.30	15,476.92	4,506.73
2 Mbps	70,860.50	4,152.30	14,446.48	4,606.73	71,890.94	6,458.55	15,476.92	6,912.98
3 Mbps	70,860.50	5,852.30	14,446.48	6,306.73	71,890.94	9,433.55	15,476.92	9,887.98
4 Mbps	70,860.50	6,627.30	14,446.48	7,081.73	71,890.94	10,789.80	15,476.92	11,244.23

Table A. 4: Fixed Wireless Broadband- Aironet tariff

Access Speed	subscription fee without VAT and fixed line charges	Monthly usage fee without VAT and fixed line charges
256Kbps	47,000	7,400
512Kbps	47,000	13,400
1Mbps	47,000	25,600
2 Mbps	47,000	49,800

Table A. 5: Broadband VSAT tariff