



ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING

**Digital Dividend and its Opportunities for Emerging Wireless
Services: the case of 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

Digital television and mobile broadband services are significantly progressing for the past three decades; this progress, in turn, is putting a burden in the available spectrum. Two of the factors that contribute to the burden are: *underutilization* of the spectrum occupied by the previous analogue television transmission and *congestion* of the spectrum due to several wireless services supported by the spectrum.

In Ethiopia, there are a limited number of terrestrial television channels and a single mobile service provider. Hence, there is no imminent challenge from spectrum scarcity at the present. However, as more television services commence in the future and the telecom infrastructure expands further, where both are in the immediate plans of the Government of Ethiopia, spectrum scarcity will likely be encountered.

Digital dividend, which creates an opportunity in making use of the underutilized spectrum, is a promising solution for the problem facing the spectrum. Digital Dividend is a free spectrum band that will be created as a result of the transition from analogue to digital terrestrial television transmission. This spectrum can be used to support emerging services from the broadcast and telecom sectors. Therefore, a proper frequency resource planning that accommodates the two wireless systems is needed sooner or later.

In light of this, this thesis shows how the resource can efficiently be used without a considerable interference impact between the two systems. As the world has sought the digital dividend as a hopeful solution in dealing with spectrum issues, this paper discusses the context of Ethiopia's spectrum issues

in proposing the analogue switchover and showing coexistence among other wireless services. The coexistence and compatibility studies help radio planners and national frequency regulator bodies to come up with new management of the frequency resource. This facilitates a way forward for designing a standard spectrum plan before many wireless services begin to operate.

In this study, the wireless environment of the City of Addis Ababa is analyzed with the possibility of applying the study for the rest of the country as well. The results obtained identify the region 700-1429 MHz band as a digital dividend out of which 795-1429 MHz band can be used for non television wireless services, particularly for broadband mobile services such as the Long Term Evaluation (LTE).

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Table of Contents

ABSTRACT	III
ACKNOWLEDGEMENT.....	V
ABBREVIATIONS	IX
Chapter One: Introduction.....	1
1.1 Introduction	1
1.2 Statement of the Problem.....	3
1.3 Objectives	4
1.3.1 General Objectives	4
1.3.2 Specific Objectives	4
1.4 Methodology	5
1.5 Literature Review	5
1.6 Scope of the Thesis	7
1.7 Thesis Organization.....	7
Chapter Two: Frequency Management and Analysis.....	9
2.1 Frequency Spectrum and its Regulation.....	9
2.2 Digital Dividend and Analogue Switchover.....	11
2.3 Digital Broadcast Standards and Modulation	13
2.4 Proposed Digital Broadcast Deployment in Ethiopia.....	15
2.5 Interference and Coexistence Analysis Methods	19
2.5.1 Minimum Coupling Loss.....	20
2.5.2 Monte Carlo Method	23

2.5.2.1 Interference Mechanisms	31
2.5.2.2 Unwanted emissions.....	31
2.5.2.3 Receiver Blocking Power	33
2.5.2.4 Intermodulation Interference	35
Chapter Three: Propagation Analysis	38
3.1 Radio Wave Propagation	38
3.2 Propagation Mechanisms.....	41
3.2.1 Reflection.....	41
3.2.1.1 Reflection from a perfect conductors.....	43
3.2.1.2 Ground Reflection (2-Ray Model).....	43
3.2.2 Diffraction	44
3.2.3 Scattering.....	46
3.3 Characteristics of Propagation Models	46
3.3.1 Distance Dependence	47
3.3.2 Large-Scale Shadowing.....	47
3.3.3 Small-Scale fading.....	48
3.4 Classification of Propagation Models	48
3.4.1 Theoretical Models	48
3.4.2 Empirical Models.....	48
3.4.3 Deterministic Models	49
3.5 Comparison of Propagation Models	49
3.5.1 Free Space Loss Model.....	49

3.5.2 Irregular Terrain Models	51
3.5.2.1 ITM model	52
3.5.2.2 The ITU P 452 Model	58
3.5.3 City Models.....	63
3.5.3.1 Okumara Model.....	63
3.5.3.2 Hata Model.....	65
3.5.3.3 COST-231 Hata Model	66
3.5.3.4 ECC-33 Model	67
3.5.3.5 Erickson Model	68
3.5.3.6 ITU-R P.1546-5 Model.....	68
Chapter Four: Results and Discussion	70
4.1 Coexistence Requirements	70
4.2 Interference Scenarios.....	76
4.3 Interference Mitigation Techniques.....	84
4.4 Proposed National Frequency Plan for Telecom and Broadcast services	91
Chapter Five: Conclusion and Recommendation	95
5.1 Conclusion.....	95
5.2 Recommendations.....	96
References	98
Appendix I.....	102
Appendix II.....	103

ABBREVIATIONS

ADSL	Asymmetric Digital Subscriber Line
ATSC	Advanced Television Systems Committee
BTS (BS)	Base Transceiver Station (Base Station)
COFDM	Coded Orthogonal Frequency Division Multiplexing
CR	Cognitive Radio
DD	Digital Dividend
DL	Down Link
dRSS	Desired Received Signal Strength
DEM	Digital Elevation Map
DTM	Digital Terrain Map
DVB	Digital Video Broadcasting
eUTRAN	evolved UMTS Radio Access Network
HDT	High Definition Television
ICT	Information and Communication Technology
iRSS	Interference Received Signal Strength
ITU	International Telecommunication Union
ITU-R	ITU-Radio Sector
LTE	Long Term Evolution
MCL	Minimum Coupling Loss
MCIT	Ministry of Communication and Information Technology
MPEG	Moving Picture Experts Group
MS	Mobile Station

NLOS	Non Line of Sight
OFDM	Orthogonal Frequency Digital Modulation
PDF	Probability Density Function
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RR	Radio Regulations
SEAMCAT	Spectrum Engineering Advanced Monte Carlo Analysis Tool
SFN	Single Frequency Network
SINR	Signal to Interference plus Noise Ratio
SIR	Signal to Interference Ratio
TV	Television
UHF	Ultra High Frequency
VHF	Very High Frequency
UL	Up Link
UMTS	Universal Mobile Telecommunications System
WRC	World Radio Conference
3G	3 rd Generation Mobile Technology
4G	4 th Generation Mobile Technology

Chapter One: Introduction

1.1 Introduction

Fixed and mobile broadband wireless telecommunication systems are technologies that make use of the radio waves spectrum for their transmission. Since the beginning of 3rd Generation (3G) technologies like Universal Mobile Telecommunication System (UMTS), there were predictions that the strain on the wireless spectrum due to more data demand will be little [1]. However, it only took a few years for the spectrum demand to surpass the predictions now putting tremendous stress on wireless systems as a whole. Trends unambiguously show that wireless data demands continue to increase at phenomenal rates. In fact, the International Telecommunication Union (ITU) highlighted that mobile broadband subscriptions now exceed fixed broadband subscriptions [2]. Wireless networks are now expected to provide capacity for mass multimedia connectivity just like fixed networks, with some projections showing a 30-fold increase in wireless data capacity requirements over the coming few years [1]. Continual enhancements in devices, expansions of applications, improvements in network performance, and evolution toward a cloud computing environment also contribute to the heightened explosion in mobile broadband data usage [2].

Terrestrial television (TV) transmission (broadcasting) is another technology that makes use of the radio waves for its signal transfer. Terrestrial television is now in a transition from analogue to digital transmission. Digital TV broadcast offers viewers a highly improved audio and picture quality benefits. Its compression techniques,

modulation and coding schemes have enabled the digital terrestrial TV to be efficient in frequency spectrum usage and leave much area of the spectrum free. Compared to analogue technology, digital technology is also able to transmit more television programs in the same amount of radio frequency spectrum, enabling the provision of additional television services through multi channeling. This is simply reflected in its capacity of supporting 20 channels per 8MHz bandwidth as opposed to a single channel support by the same bandwidth in the analogue type TV transmission [2].

The switch from analog to digital TV transmission brings in an opportunity for having additional free spectrum band. The digital television transmission allows the release of much of the spectrum region that was once occupied by the analogue transmission. The released spectrum band is the one that constitutes the digital dividend. Accordingly, the *digital dividend* may be defined as the amount of spectrum made available by the transition of terrestrial television broadcasting from analogue to digital in very high frequency (VHF) and ultrahigh frequency (UHF) bands [1]. This free spectrum region will be used to satisfy the spectrum requirement of the mobile broadband such as Long Term Evolution (LTE); moreover, as the waves in the UHF band offer the possibility of long-range transmission, it allows a larger coverage radius with few infrastructure. However, digital dividend requires proper analysis of interference as a result of simultaneous transmission by digital TV and LTE in adjacent channels having a particular frequency band.

Many countries around the world have been working on the switching-off of terrestrial TV transmission of the analogue type technology in their attempt to replace it with digital type transmission since the 2010 statement made by the ITU in its frequency harmonization plan [2]. The trend is the same in the case of Ethiopia

and the Government is putting efforts to expand the number of digital TV transmissions and also the number of broadband mobile subscribers. Hence, the country will look forward in demanding freer spectrum in the future as the Information and Communication Technology (ICT) starts to advance at its fullest extent and more TV channels commence to air. Therefore, the country needs to have an appropriate frequency plan before hand and much can be studied about the current status regarding this issue.

1.2 Statement of the Problem

In principle, digitization of services in electronic communication sector has gained approval from responsible bodies and the Federal Government of Ethiopia [3]. However, it appears that the country is yet to implement the digital terrestrial television broadcast. There is a demand for having more TV channels to a big country like Ethiopia with more than 90 million people and enormous ethnic and cultural diversities.

In an attempt to achieve this goal, there is a need to have a proper planning of the scarce frequency resource that plays a great role for broadcast transmission. Besides, without having proper frequency planning, the incumbent and emerging telecom operators will be significantly affected while they attempt to provide the virtues of the 4G and beyond wireless technology as a result of the limitations in accessing free spectrum and interferences that might occur with other radio wave propagating services.

The telecom industry in Ethiopia, which is currently government owned, appears not to face such a problem in this regard for the time being. However, the problem is

inevitable in the years to come through introduction of latest digital technologies and possible emerging private service providers. This research, therefore, aspires to explore options for a new and suitable spectrum reframing for radio planners in both the telecom and broadcast industries and studies coexistence between the two systems.

1.3 Objectives

1.3.1 General Objectives

The overall objective of this thesis is to study the opportunities of the digital dividend for Ethiopian television broadcast and wireless broadband services.

1.3.2 Specific Objectives

The thesis intends to accomplish the following specific tasks in realizing the general objective:

- understanding the concept of digital dividend;
- studying the current situation of the Ethiopian analogue switch-off plan;
- studying various propagation models that will work out for the radio environment of the city of Addis Ababa;
- identifying the deployment parameters used by the telecom operator to expanding mobile broadband;
- analyzing coexistence and interference scenarios between mobile broadband and digital television services using the SEMCAT (Spectrum Engineering Advanced Monte Carlo Analysis Tool) software;

- analyze results and recommend for possible band plans for the two wireless services.

1.4 Methodology

The methodology used for this research involves:

- analysis of various propagation models;
- use of the SEAMCAT simulation for compatibility and coexistence study;
- use of collected data from Ethio Telecom, Ethiopian Broadcast Agency, Ministry of communication and Information Technology.

1.5 Literature Review

Recently, few researches are conducted under the topic of digital dividend. Various authors have done great works to show roadmaps for different countries and global ITU regions to help smoothen the transition of analogue TV transmission to the digital one so that the countries benefit from the digital dividend. Besides, some articles by the ITU have addressed the issue in helping various countries pave the way to realize the switch over.

The opportunities that the digital dividend spectrum brings ranges from helping to serve society's greater needs in various wireless services to encouraging innovations in mobile broadband, improvement in devices and their applications.

Coexistence and compatibility between the digital television transmission and wireless broadband have also been carried out along with the digital dividend studies. The authors in [4] showed their study of analogue switch off for South Korea

and indicated that the digital dividend, which will be obtained after the transition from analogue to digital transmission, can be available for other wireless systems. They have also emphasized on the need to take into account the interference effect of one wireless system on to the other and recommended solutions to ensure their coexistence.

The paper in [5] has shown how efficiently the digital dividend can be used by identifying the interference criterion and developing coexistence model. The coexistence model determines minimum separation distance and frequency separation to ensure compatibility of the two wireless systems in 790-822 MHz frequency range.

The paper in [6] showed how the switchover process could be advanced. As this process varies from one country to another, some countries, like the USA, have issued a direct subsidy to be provided to households to cover part of the cost of acquiring a set-top box or digital TV. Others, like the case of the United Kingdom and Spain, have promoted additional High Definition TV channels and interactive TV services as part of the digital package to provide incentive for viewers to switch.

Based on the papers reviewed, this research aspires to ensure coexistence between the two systems in adjacent channels with bands suitable for Ethiopia's current and future TV landscape and broadcast scenario.

The Spectrum Engineering Advanced Monte Carlo Analysis Tool (SEAMCAT) simulation is used in this research. The simulation makes use of the wireless parameters of the LTE and Digital TV (DTV) in its analysis to evaluate the

interference situations. It is then recommended on how to deploy the two systems according to the level of interference that might occur between them.

1.6 Scope of the Thesis

The thesis will help frequency planners to give insight in looking at various parameters when dealing with broadcast and telecom services in Addis Ababa and further to other parts of the country. This will be a significant benefit for broadcasters when the country aims at airing more TV channels and for new telecom operators if permitted to start services.

As the research applies SEAMCAT software in its methodology, there is a limitation to employing the digital terrain map of Addis Ababa city. Instead some parameters are used for JAVA plug-in that more or less approximate the climatic, terrain and radio factors of the city.

1.7 Thesis Organization

The thesis is composed in such a way that it gives a progressive insight on the concept of digital dividend and frequency allotment until it finally shows the results of the interference scenario between broadcast and telecom services. The first chapter deals with the introduction and statement of the problem followed by the objectives, scope, and methodology used to carry out the research. It's in this chapter that related paper works regarding the topic have been explicitly reviewed.

Chapter Two focuses on the frequency analysis for broadcast and telecom services in accordance with the overall frequency management adopted. In Chapter Three various propagation models and their comparisons used for planning in the telecom

and broadcast sectors have been discussed. Chapter Four discusses interference scenarios in the broadcast and telecom services and their mitigation techniques. It also discusses the methods used to show interferences in the SEAMCAT simulation.

Chapter Five is on the results of the thesis and recommendations for broadcast and telecom services planning. It shows the supposed frequency management accordingly.

Chapter Two: Frequency Management and Analysis

2.1 Frequency Spectrum and its Regulation

Wireless or radio transmission is one way by which information can be conveyed from an information source to a destination or receiving node. Electromagnetic signals play significant role for the transfer of information and are mainly characterized by the frequency occupied and power level of the signal in the channel. Table 2.1 and Table 2.2 show list of radio frequency (RF) bands of common use and the microwave ranges, respectively.

Acronym	Name of Band	RF Band
HF	High Frequency	3 MHz - 30 MHz
VHF	Very High	30 MHz - 300 MHz
UHF	Ultra High	300 MHz - 3 GHz
SHF	Super High	3 GHz - 30 GHz
EHF	Extra High	30 GHz - 300 GHz

Table 2.1 Common RF bands.

Name	Microwave Band
L band	2 GHz-1GHz
S band	2GHz - 4GHz
C band	4GHz -8GHz
X band	8GHz - 12GHz
Ku band	12GHz - 18GHz
K band	18GHz - 27GHz
Ka band	27GHz - 40GHz

Table 2.2 Microwave ranges.

Frequency is a national resource like water, land, gas and minerals. However, it is a reusable resource. Frequency becomes a scarce resource as we keep on using it for broadcasting, wireless telecommunication services, emergency services, transport, and scientific research and consumer devices. Therefore, there is a need to have a spectrum management policy for the purpose of mitigating radio frequency interference and maximizing the benefit of usable radio spectrum. Access to radio frequency spectrum is controlled by assigning rights to specific license holders or to certain classes of users.

The regulation and monitoring is carried out by the ITU at the international level and national regulators at a state level. In Ethiopia currently Ministry of Communication and Information Technology (MCIT) is mandated to do the regulation in accordance with the international policies. Ethiopian Broadcast Agency is also the responsible body in giving licenses of spectrums for wireless services. ITU develops and manages the various international agreements regarding the use of the radio spectrum. Certain spectrum uses require more specific and detailed analysis and thus ITU discusses on such matters with member countries in greater depth before ratifying agreements.

Everything related to frequency spectrum must be done in accordance to international and national laws regarding the spectrum. That is why it is important to see the international regulatory body's frequency management whenever proposing national spectrum plans. The digital dividend that is formed complies with the ITU's regulation of spectral issues in order to minimize interference.

2.2 Digital Dividend and Analogue Switchover

It appears that the mobile telecommunications industry is seeking additional spectrum to accommodate the ever increasing growth in bandwidth demanding services such as video and interactive services. On the other hand, terrestrial Television broadcasting constitutes a large area of radio spectrum in the VHF and UHF bands. These spectrum have been used for many decades in many parts of the world for analogue TV transmission involving large networks of high power primary transmitters with their corresponding secondary transmitters emitting power towards roof-top, yagi antennas, or indoor antennas [7].

In fact, the terrestrial television broadcasting has been challenged by cable and satellite TV far greater than ever, and more recently by Asymmetric Digital Subscriber Line (ADSL) and internet television. However, terrestrial television broadcasting is still prevalent in developing countries like Ethiopia [2]. The World Radio Conference, WRC-07, has recommended analogue switch off to free up some usable frequency spectrum to be used by other wireless services. WRC-12 and WRC-15 further emphasize the need and show recommendations on how to actually implement the proposed plan to member states [8].

Digital television broadcasting constitutes less spectrum band than the analogue one. As a basis for comparison, an 8MHz bandwidth broadcasts a single analogue program whereas the same bandwidth could carry a multiplex of 20 digital programs of equivalent quality. Besides, most digital TV standards allow the use of Single Frequency Network (SFN) permitting reuse of the same spectrum for more

coverage areas. This increasingly enhances spectrum efficiency compared to the analogue networks.

From the viewers' perspective, the digital television offers better quality sound, interactive services, mobile reception, widescreen pictures, surround sound audios, multiple viewing angles, closed-captioning, electronic program guides, high definition picture and a wider range of channels than ever before [7].

As a result of digitization of television services more frequency spectrum will be made free. It is the *digital dividend* that becomes available after the re-location. This spectrum can be assigned for mobile services like the mobile broadband as the pressure on mobile services is currently getting enormous.

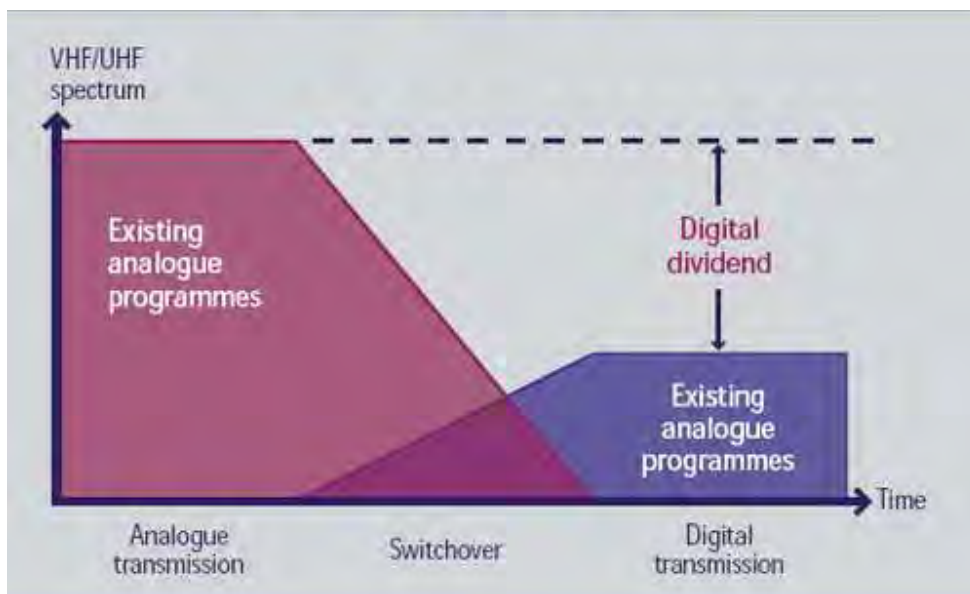


Fig. 2.1 The spectrum after the switchover of analogue to digital television transmission [9].

2.3 Digital Broadcast Standards and Modulation

The advent of Digital Versatile Disk (DVD) and its extended features have led to an expectation of higher picture quality from terrestrial digital television broadcasting. There are various standards for the digital television broadcast. ATSC is the most common used standard in the USA. However, most of the digital standards can be considered as variants of the broad standard known as Digital Video Broadcasting (DVB).

DVB-T (Terrestrial), DVB-H (Handheld) and DVB-HD (High Definition) are the most common variants. DVB-MHP (Multimedia Home Platform) is a relatively newer variant that involves interactive applications. DVB-C and DVB-S are the digital television standards for cable and satellite transmission respectively.

All variants in the DVB family offer different options in relation to modulation schemes, coding rate, guard intervals, etc. In addition to the different types of broadcast services these variants deliver, they form a basis in determining what kind of network planning would be used. This has a direct relation with the capacity and design and cost of implementation of any given standard. The standards also define the specification for channel coding, compression and modulation for terrestrial transmission.

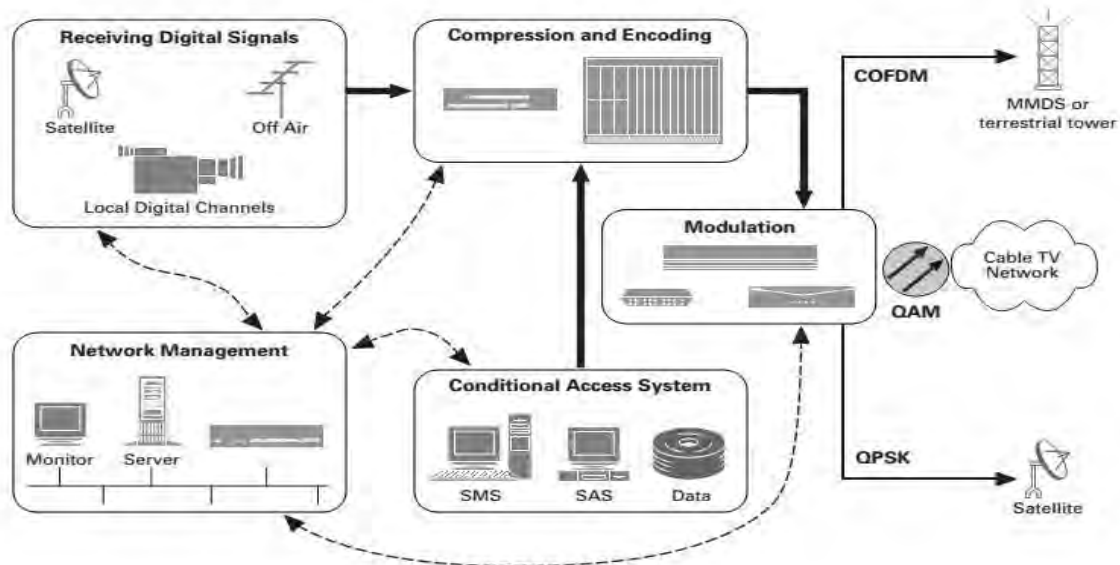


Fig. 2.2 Basic building block of a digital broadcasting system [10].

Moving Picture Experts Group-2 (MPEG-2) is the most successful video compression method that reduces the bit-rate required to represent video information to around 2% of its full value without visible loss of picture quality. All digital video standards make use of the MPEG-2 video compression technique.

After digital signal has been processed by the multiplexer, the content has to be propagated through the air. The video, audio, and data will be combined with the carrier signal in a process called modulation. The modulation technique used depends on the overall network architecture and the geography. The three most common types of modulation techniques for digital broadcast are Quadrature Amplitude Modulation (QAM), Quadrature Phase Shift Keying (QPSK), and Coded Orthogonal Frequency Division Multiplexing (COFDM). QAM can achieve a transfer rate of 40 Mbits/sec of MPEG-2 compressed data. QPSK is more immune to electromagnetic noise than QAM but is only capable of transmitting data at 10Mbits/sec. COFDM is a modulation scheme that divides a single digital signal

across 1,000 or more signal carriers simultaneously. The signals are sent at right angles to each other (hence, orthogonal) so they do not interfere with each other. COFDM is used predominately in Europe and is supported by the Digital Video Broadcasting (DVB) set of standards. COFDM operates well in a heavily built-up areas where digital transmissions can be deterred by buildings, bridges, and hills. COFDM can be implemented by either 2000(2K) or 8000(8K) carrier signals. DVB-T makes use an OFDM as it gives some level of protection against interfering signals and allows a 'guard interval' to protect echoes from buildings.

2.4 Proposed Digital Broadcast Deployment in Ethiopia

The Ethiopian Broadcast Agency has not indicated the specific parameters to be used in commencing its digital terrestrial television system. However, in its switch over plan from analogue to digital transmission, it has made it clear that DVB-T2 with modulation 256QAM 2/3 providing a net bit rate of 40.3 Mbps is the preferable technology due to several reasons mentioned in the roadmap [3].

A regional coverage area is characterized by regional services as part of the multiplex of all transmitters in the regional coverage area. For feeding the regional transmitters with the national and regional services, three basic network lay-outs can be considered.

1. **One main head-end only:** This approach allows all national and regional services to be transported to the main head-end and distributed to all transmitter sites from there.

In this scenario, the signals of the existing national public services (ETV1, ETV2, ETV3 and ETV4) are coded in the main head-end. All eleven regional

services are transported to the main head-end. Compression in MPEG4 for the case of DVB-T2 in the regional studios saves capacity in the transmission link.

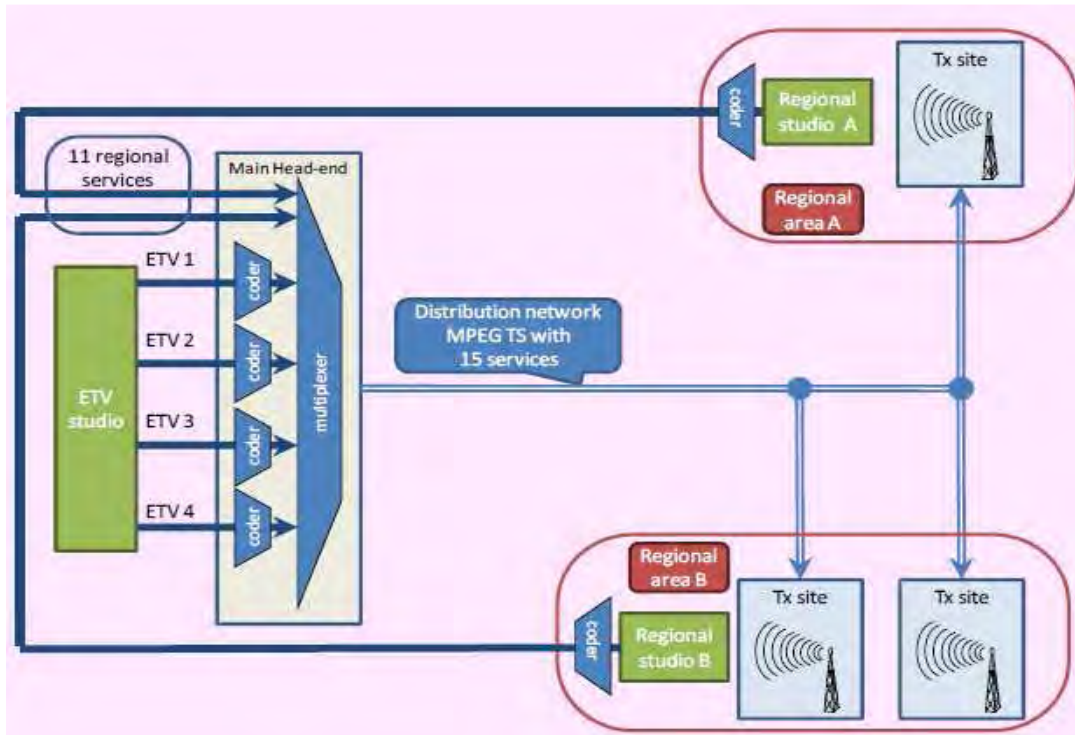


Fig. 2.3 Network lay out in one main head only [2].

A total of fifteen services can be multiplexed into one MPEG transport stream at the main head-end. The transport stream is distributed to all transmitter sites by means of:

- telecommunication satellite;
- optic fiber with additional microwave links from the points of presence of the optic fiber to the transmitter sites;
- DVB-S satellite used for distribution of the transport stream of the DTTB network.

2. Regional **head-end in each region**: National services and regional services are multiplexed at regional head-ends and distributed to the transmitter sites that are part of the regional coverage area.

In this approach, the signals of the national public services (ETV1, ETV2, ETV3 and ETV4) coded in the main head-end. From the main head-end one MPEG transport stream is distributed to the regional head-ends by means of:

- telecommunication satellite;
- optic fiber with additional microwave links from the points of presence of the optic fiber to the transmitter sites;
- DVB-S satellite used for distribution of the Transport Stream of the DTTB multiplex;
- DVB-S satellite (Arabsat package), as currently applied for analogue TV distribution.

For DVB-T2, the MPEG2 encoded signals will be re-coded to MPEG4 at the regional head-ends. Cascading of encoding processes could decrease picture quality. The service information contained in the DVB-S multiplex may not be appropriate for the DTTB network and may need to be re-inserted at the regional head-ends. It should also be noted that the Arabsat DBV-S service content of ETV is not always identical to the terrestrial content (e.g. football). With this way of distribution none of the transmitters in the DTTB network will be fed with the exclusive terrestrial content.

In each regional head-end the four national services and the regional encoded service (in MPEG2 in the case of DTMB and in MPEG4 in the case of DVB-T2)

are (re)multiplexed into a regional transport stream and distributed to the transmitter sites belonging to the region [2].

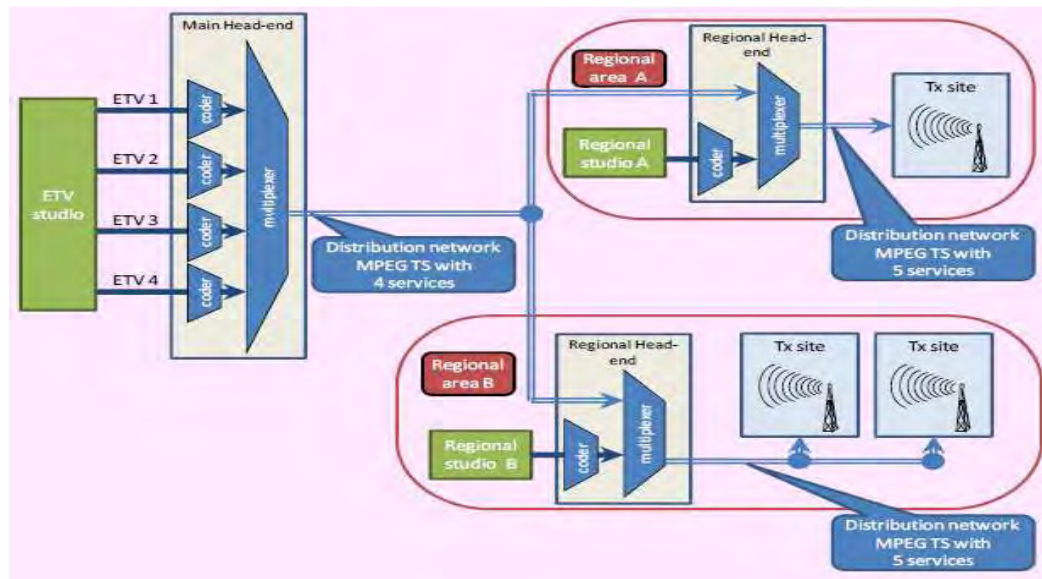


Fig. 2.4 Network lay out with regional head-ends [2].

3. **Combination of 1 and 2:** Some regional services are multiplexed at the main head-end and together with the national services distributed to all transmitter sites. Other regional services are coded and (re)multiplexed with national services at regional head-ends [2].

The transmission frequencies of DVB-T2 are usually similar to the analogue transmission frequencies. DVB-T2 differs only in the other technologies it uses to come up with better picture and audio quality not in its frequency band.

As it is discussed later in this chapter, there are four possible interference scenarios regarding DVB-T2 and LTE systems. The corresponding systematic study has also been discussed. In most cases DVB-T2 devices and the corresponding aerial antenna are designed to receive radio signals in the 800 MHz band. An LTE signal of 800 MHz obviously interferes and affects the DVB-T2 signal or even superimpose it. The

interference has a possible effect of sound and picture degradation on the DVB-T2 system, i.e., single pixel failures or sound disruptions, a frozen picture and in the worst case, a complete loss of signal.

2.5 Interference and Coexistence Analysis Methods

The limitation on valuable radio frequency spectrum has made important the sharing of radio bands between different radio services or similar radio services provided by different operators. It also happens that many wireless systems operate with frequencies adjacent to each other making the compatibility study between the systems necessary. These studies aim to analyzing the system criterion for coexistence of various wireless systems without significant negative impacts on each other. Different algorithms and methods can be used for the analysis as indicated in the upcoming section all leading to optimum results to ensuring coexistence of the systems under consideration.

In a scenario where LTE system is configured to operate in the same geographical region with a DTV system, interference between the two systems can occur. This section analyzes the interference scenario and looks for possible mitigation techniques that would work out to realize coexistence of the two systems given some criteria.

Interferences might arise from irradiations (interfering signal emissions) of LTE-base stations and LTE-end devices like modem or mobile phone. As end devices are mostly nearer to DVB-T2 receivers than the base stations, end devices are common interferers (downlink interference).



Fig.2.5 Example Picture of DVB-T interference [11].

2.5.1 Minimum Coupling Loss

A classical approach known as *Minimum Coupling Loss* (MCL) could be used to study interferences occurring between systems. The method is simple to use and does not require a computer for implementation. The primary drawback is that it is a worst case analysis and produces a spectrally inefficient result for scenarios of a statistical nature.

This method calculates the minimum isolation required between the interferer and victim system to ensure zero interference. The method assumes that the victim receiver is operating continually above 3 dB reference sensitivity. Interference must be limited to the noise floor to maintain the victim's protection ratio. A path loss formula of a particular propagation model will be chosen to determine the isolation that can be attained through a specified physical separation between two interfering radio systems. In this method the median path loss with no fading consideration is used. Besides, no statistical distribution of the interferers is to be taken.

Two interference mechanisms called *unwanted emissions* and *receiver blocking* are considered in the analysis by the MCL method.

According to Radio Regulations Article, RR Article 1, No. 1.146, unwanted emissions are emissions that consist of spurious emissions and out-of-band emissions. RR Article 1, No. 1.145 defines spurious emissions as emissions on a frequency, or frequencies, which are outside the necessary bandwidth and the level of which may be reduced without affecting the corresponding transmission of information. Spurious emissions include harmonic emissions, parasitic emissions, intermodulation products and frequency conversion products but exclude out-of-band emissions. In RR Article 1, No.1.144, out- of-band emissions are defined as emission on a frequency or frequencies immediately outside the necessary bandwidth which results from the modulation process, but excluding spurious emissions [12].

The receiver blocking is defined as the degradation of *receiver* sensitivity, usually by 3 dB, in the presence of a much stronger (*blocking*) signal. Sensitivity is measured through signal-to-noise ratio (SNR) at the output of the receiver. Different SNR values can be chosen according to the specific task. Blocking would therefore be the reduction in SNR caused by an interfering signal.

The unwanted emissions analysis equation is:

$$Isolation = P_{INT} + dB_{BW} + MC_{INT} + G_{VICT} + G_{INT} - (S_{VICT} - \frac{c}{I_{VICT}}) + f(dBc_{INT}, P_{INT}) \quad (2.1) \quad [12]$$

where:

- P_{INT} is the maximum transmit power of the interferer;
- dB_{BW} is the bandwidth conversion factor between interferer and victim;

- MC_{INT} is the multiple carrier margin to account for when the interferer is a base sit and has more than a single carrier being transmitted;
- G_{VICT} is the gain of the victim antenna (inc. cable loss);
- G_{INT} is the gain of the interferer antenna (inc. cable loss);
- S_{VICT} is the sensitivity of the victim;
- $\frac{c}{I_{VICT}}$ is the protection ratio of the victim;
- $f(dBc_{INT}, P_{INT})$ is a function defining the power of the wideband noise at the frequency;
- offset being considered relative to the interferer's carrier power.

The receiver blocking analysis equation is:

$$Isolation = P_{INT} + MC_{INT} + G_{VICT} + G_{INT} - f(B_{VICT}, S_{VICT}) \quad (2.2) \quad [12]$$

where:

- P_{INT} is the maximum transmit power of the interferer
- MC_{INT} is the multiple carrier margin to account for when the interferer is a base site and has more than a single carrier being transmitted
- G_{VICT} is the gain of the victim antenna (including cable loss)
- G_{INT} is the gain of the interferer antenna (including cable loss)
- $f(B_{VICT}, S_{VICT})$ is the blocking performance of the victim receiver at the frequency offset being considered.

The MCL method can be generalized as having the following characteristics and limitations:

- the result generated is isolation in dB, which may be converted into a physical separation if an appropriate path loss formula is chosen

- it is simple to use and does not require a computer for implementation
- it is a worst case analysis and produces a spectrally inefficient result
- the victim receiver is assumed to be operating 3 dB above reference sensitivity
- a single interferer transmitting at fixed (usually the maximum) power and using a single channel is considered

Therefore, the MCL approach is relatively straight forward, modeling only a single interferer-victim pair. It provides a spectrally inefficient result.

For the reasons explained above, the MCL method appears to be too rigid and difficult to implement in many cases, where operation of radio communications systems may not be described in static terms, e.g. random nature of operation of user terminals in the mobile systems. An alternative approach that alleviate most of the challenges is the Monte Carlo Method. With this model we are able to completely simulate almost all sorts of interference situations that can be thought of.

2.5.2 Monte Carlo Method

The Monte Carlo method handles analysis of complex statistical problems. The method is based on taking samples of a random process from the defined probability density function (pdf). This method is a statistical technique, which models a victim receiver amongst a population of interferers. It is capable of modeling highly complex systems including CDMA and LTE.

The most important characteristics of the Monte Carlo method that makes it preferable over the MCL method are:

- the result generated is a probability of interference;
- it is a statistical technique, which requires the use of a computer;

- it allows the user to model realistic scenarios and evaluate appropriate minimum frequency separations;
- an appropriate path loss model is required;
- the victim receiver has variable wanted signal strength;
- multiple interferers using multiple channels may be considered;
- the effect of features such as power control may be included.

The following table shows summarized features of the MCL and the Monte Carlo methods

MCL Method Features & Considerations	Monte Carlo Method Features & Considerations
Single Interferer using a single channel	Multiple interferes using multiple channels
A Deterministic Technique	A statistical Technique
Result is isolation distance	Result is probability of interference
Worst case analysis and spectrally inefficient	Used to model realistic scenarios and evaluate minimum frequency separations

Table 2.3 Comparison of the MCL and Monte Carlo Methods for interference analysis.

SEAMCAT is one of the software programs by which the Monte Carlo Method can be implemented. In this program, many events are generated and users can choose the number of simulation events and change input parameters. For this reason, the method is useful in simulating a random process in the area of wireless communications; the methodology is usually used to determine the compatibility between multiple systems operating in the adjacent or the same band. The results of the method have been agreed to the ITU-R and are described in ITU-R report [10].

Basically, there are four types of entities forming various scenarios regarding interference. They are the Victim Receiver, Interfering Transmitter, Wanted Transmitter and Wanted Receiver. The Victim Receiver (V_r) is the one subjected to an interference signal coming from Interfering Transmitter (I_t). The Victim Receiver gets a desired signal from the Wanted Transmitter (W_t).

The interferer might be from the same system as the victim or a different system or a mixture of both. The interferer has also a desired signal for its corresponding receiver called Wanted Receiver (W_r).

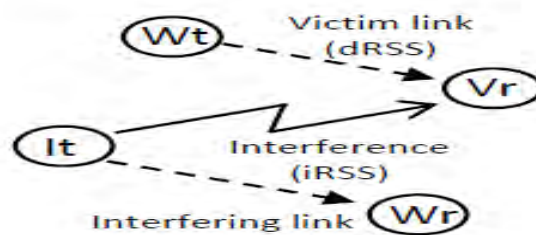


Fig. 2.6 Terminology as used in SEAMCAT [13].

W_t and V_r form the victim link whereas I_t and W_r form the interfering link as the I_t interferes the V_r . The signal strength by W_t on V_r is termed as desired received signal strength(dRSS) while by the I_t is interference received signal strength(iRSS).

The interference on the victim body might occur due to many sources of the same system or a different one.



Fig. 2.7 A typical victim and interferer scenario for a SEAMCAT simulation [14].

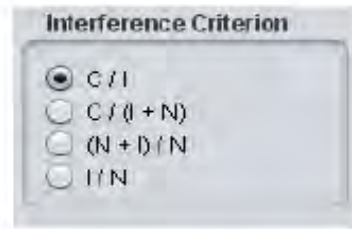
For DTV and LTE systems we have four cases:

- **Case 1:** DTV transmitter (W_t) transmitting to a DTV terminal (V_r) which is subjected to interfering signal coming from LTE BS (I_t). The LTE BS was intended to communicate with the MS (W_r) in downlink (DL). The DTV link is the victim link whereas the LTE Downlink is the interfering link.
- **Case 2:** DTV transmitter (I_t) interfering the LTE BS (V_r) as it transmits its signal to DTV terminals (W_r). In this case the MS (W_t) communicates with the LTE BS in Uplink(UL). That means the LTE Uplink is the victim link and the DTV link is the interfering link.
- **Case 3:** DTV transmitter (I_t) interfering the MS (V_r) while transmitting its signals to DTV terminals (W_r). The LTE BS (W_t) communicates with the MS in the downlink. In this case, the LTE downlink is the victim link whereas the DTV link is the interfering link.
- **Case 4:** LTE MS (I_t) interferes the DTV terminal (V_r) as the DTV transmitter (W_t) sends desired signal to DTV terminal and LTE BS (W_r) receives wanted signal from its MS. The LTE Uplink is the interfering link and the DTV is the victim link.

In the SEAMCAT simulation, each trial is made up of using different variables input by the user, and the protection criterion such as C/I or I/N is calculated in each trial.

The SEAMCAT simulation considers the following protection ratios:

C/I
 $C/(I+N)$
 $(N+I)/N$
 I/N



Where C=desired signal, I=interference and N=thermal noise

Fig. 2.8 Interference criteria for SEAMCAT simulation.

The ratios are related with each other as follows:

$$\left[\frac{N+I}{I}\right]_{\text{dB}} = \left[\frac{N+I}{N}\right]_{\text{dB}} - \left[\frac{I}{N}\right]_{\text{dB}} \quad \text{and} \quad \left[\frac{C}{N+I}\right]_{\text{dB}} = \left[\frac{C}{I}\right]_{\text{dB}} - \left[\frac{N+I}{I}\right]_{\text{dB}} \quad (2.3)$$

The two equations are proved in Appendix I.

Where $C/(I+N)$ is chosen as the protection criterion the impact of the interferer is negligible compared to the thermal noise, i.e. $C/(I+N) \approx C/N$, if $I/N \leq -20$ dB.

In the case where $I/N > 10 \dots 20$ dB, then $C/(I+N) \approx C/I$, i.e. the interferer is more dominant than the thermal noise.

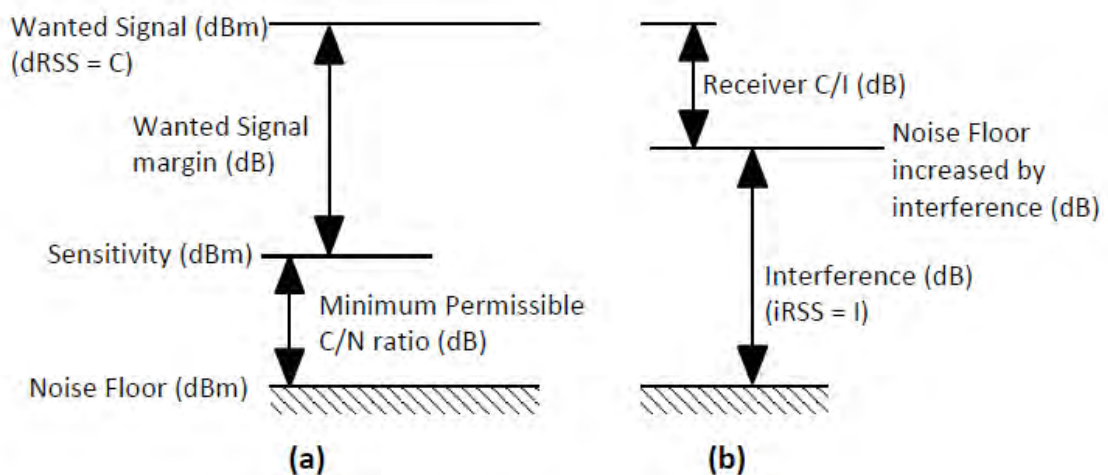


Fig. 2.9 Signal levels used to determine interference occurring [14].

Fig 2.9a shows the situation when there is no interference and the victim is receiving the desired signal with some margin. In this case the victim's Signal level is given by the sum of the Sensitivity and wanted signal margin.

While, Fig 2.9b illustrates what happens when interference occurs. The interference adds to the noise floor. The difference between the wanted signal strength and the interference signal, measured in dB, defines the Signal to Interference ratio. This ratio must be greater than the required C/I threshold if interference is to be avoided. The SEAMCAT simulation tool checks for this condition and records whether or not interference is occurring.

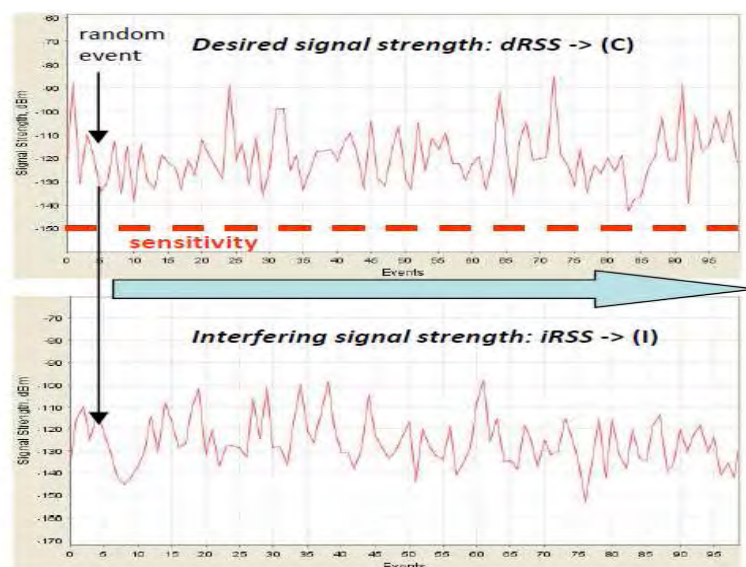


Fig. 2.10 Illustration of Desired and Interfering Signals as used in the interference criteria computation [14].

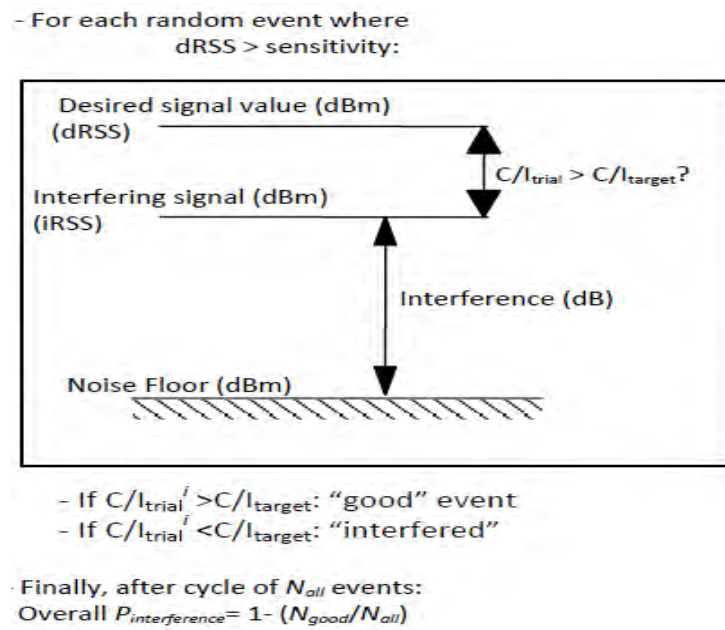


Fig. 2.11 Interference Criteria Computation [14].

The Monte Carlo technique in the SEAMCAT program works by taking several independent instants. For each instant, or simulation trial, a scenario is built up using a number of different random variables, i.e. where the interferer is located with respect to the victim, how strong the wanted signal strength is, which channels the victim and interferer are using etc. If a sufficient number of simulation trials (i.e., 20,000 snapshots) are taken then the probability of a certain event occurring can be calculated with a high level of accuracy.

In this way, the tool is able to quantify the probability of interference between radio systems and is able to help determine appropriate frequency planning rules or specify limits for transmitter/ receiver performance. In other words, SEAMCAT calculates the probability of interference (PI) of the victim receiver as follows:

$$P_I = 1 - P_{NI} \quad (2.4)$$

Here, P_I is the probability of interference in the victim receiver. The P_{NI} is the probability of non interference in victim receiver. When a $\frac{C}{I}$ criteria is considered, P_{NI} defined as:

$$P_{NI} = P\left(\frac{dRSS}{iRSS} > \frac{C}{I} \mid dRSS > \text{Sensitivity}\right) \quad (2.5)$$

where $dRSS$ is the desired received signal strength and $iRSS$ is the interfering received signal strength.

Using the conditional probability formula, $P(A|B) = \frac{P(A \cap B)}{P(B)}$, P_{NI} becomes

$$P_{NI} = \frac{P\left(\frac{dRSS}{iRSS} > \frac{C}{I} \cap dRSS > \text{Sensitivity}\right)}{P(dRSS > \text{Sensitivity})} \quad (2.6)$$

$$dRSS = P_{wt} + G_{wt} + G_{vr} - L_p \quad (2.7)$$

where P_{wt} is the power of the wanted transmitter (dBm), G_{wt} is the gain of the wanted transmitter antenna (dBi), G_{vr} is the gain of the victim receiver (dBi), L_p is the path loss.

For free space model the path loss is defined by :

$$L_p = 32.5 + 10 \log \left[\left(\frac{h_{tx} - h_{rx}}{1000} \right)^2 + d^2 \right] + 20 \log f \quad (2.8)$$

where d is given in Km and f is given in MHz and the antenna heights in m.

$$iRSS = P_{It} + G_{It} + G_{vr} - L_p \quad (2.9)$$

where P_{It} is the power of the interfering transmitter (dBm) and G_{It} is the gain of the interferer antenna (dBi).

iRSS is composed of two different source, the unwanted emission(I_{unwanted})and the receiver imperfection (I_{blocking}) as follows:

$$iRSS= I_{\text{unwanted}} +I_{\text{blocking}} \quad (2.10)$$

The nature of these two interference sources is well explained under the upcoming section of Interference Mechanism.

In such manner, the SEAMCAT can address virtually all radio interference scenarios in both co-channel (sharing) and adjacent frequency (compatibility) interference studies.

2.5.2.1 Interference Mechanisms

Several interference mechanisms such as unwanted emissions, receiver blocking, inter modulation products, co-channel and adjacent channel interference phenomena would be considered in the study of LTE and DTV systems interaction.

2.5.2.2 Unwanted emissions

These types of emissions consist of the spurious emissions and out-of-band emissions of the interfering transmitter that fall within the victim's receiver bandwidth.

The level of unwanted emissions is determined using the interferer's transmit mask, the selectivity of the victim receiver, interferer-victim frequency separation, antenna gains and propagation loss.

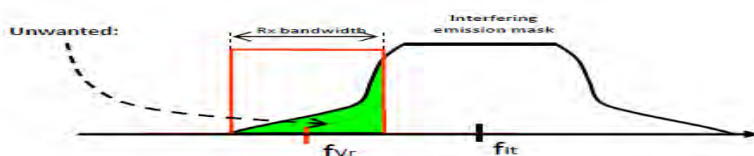


Fig 2.12 Interference due to the unwanted emissions (i.e. the unwanted emissions of I_i falling in the receiver bandwidth of V_r) [14].

In each trial of the Monte-Carlo Method the $I_{unwanted}$ is calculated at the victim receiver. The resulting interference power in the victim receiver after n number of trials is given as:

$$I_{unwanted}(\text{dBm}) = 10 \log \left(\sum_{i=1}^n 10^{\frac{I_{unwanted_i}}{10}} \right) \quad (2.11)$$

For a single i^{th} trial, the unwanted $I_{unwanted_i}$ is given as:

$$I_{unwanted_i} = iT_{emission}(f_{It}, f_{Vr}) + G_{IT} + G_{vr} - L_p \quad (2.12)$$

where $iT_{emission}(f_{It}, f_{Vr})$ is the emission leakage from the interfering transmitter operating at a frequency offset of f_{It} into the victim receiver operating frequency at f_{Vr} .

$iT_{emission}(f_{It}, f_{Vr})$ is a function of the operating frequency offset (MHz), the unwanted emission (dBm), and the reference bandwidth (MHz) as follows:

$$iT_{emission}(f_{It}, f_{Vr}) = P_{It} + emission_{unwanted}(f_{It}, f_{Vr}) \quad (2.13)$$

$$emission_{unwanted}(f_{It}, f_{Vr}) = 1 - 10 \left(\int_a^b P_{unwanted} \Delta f d\Delta f \right) \quad (2.14)$$

where $\Delta f = f_{It} - f_{Vr}$ is the difference between the frequency offsets of the interferer and the wanted transmitter $emission_{unwanted}(f_{It}, f_{Vr})$ is the unwanted emissions that fail into the victim receiver filter, and $p_{unwanted}(\text{dBm})$ is the unwanted power related to $emission_{unwanted}(f_{It}, f_{Vr})$ which has boundaries between $a = f_{Vr} - f_{It} - \left(\frac{b_{vr}}{2}\right)$ and $b = f_{Vr} + f_{It} - \left(\frac{b_{vr}}{2}\right)$, b_{vr} is the victim receiver bandwidth.

2.5.2.3 Receiver Blocking Power

The receiver blocking power is the power captured from the transmissions of the interferer due to selectivity imperfections of the victim's receiver. It is determined using the interferer's transmit power, victim receiver blocking performance, interferer - victim frequency separation, antenna gains and propagation loss.

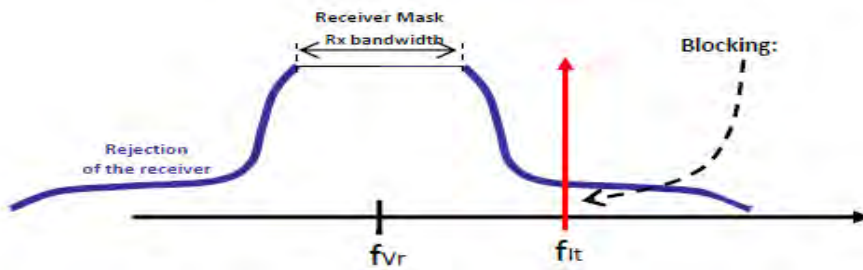


Fig. 2.13 The blocking of the victim receiver i.e. total emission power of I_t reduced by the blocking attenuation (selectivity) function of the V_r [14].

For each n number of trials, the interference due to victim receiver blocking is expressed as:

$$I_{\text{blocking}}(\text{dBm}) = 10 \log \left(\sum_{i=1}^n 10^{\frac{I_{\text{blocking},i}}{10}} \right) \quad (2.15)$$

For a single i th trial, the interference blocking is a function of frequency and is defined as:

$$I_{\text{blocking},i} = P_{It} + G_{It} + G_{vr} - L_p - \text{avr}(\Delta f) \quad (2.16)$$

where $\text{avr}(\Delta f)$ is the blocking attenuation of the victim receiver.

The blocking attenuation can be calculated using two modes: the sensitivity or the PR mode. Based on the receiver type, one of these modes is chosen to calculate the

receiver blocking attenuation. The PR mode is chosen for the broadcasting receiver, whereas the sensitivity mode is chosen to calculate the receiver blocking attenuation for the mobile receiver as shown in the tables. For the sensitivity mode, the block attenuation is given as.

$$avr(\Delta f) = I_{\max} + \frac{C}{N+1} + \text{sen}_{vr} \quad (2.17)$$

where I_{\max} (dBm) is the maximum allowed interference and sen_{vr} (dBm) is the sensitivity level of the victim receiver. In PR mode, we employ:

$$avr(\Delta f) = I - N \quad (2.18)$$

where I (dBm) is the level of the interference and N (dBm) is the noise floor level of the receiver. Both are functions of frequency difference Δf .

The combination of the unwanted emissions and the receiver blocking can also be studied simultaneously in SEAMCAT as depicted in the following figure.

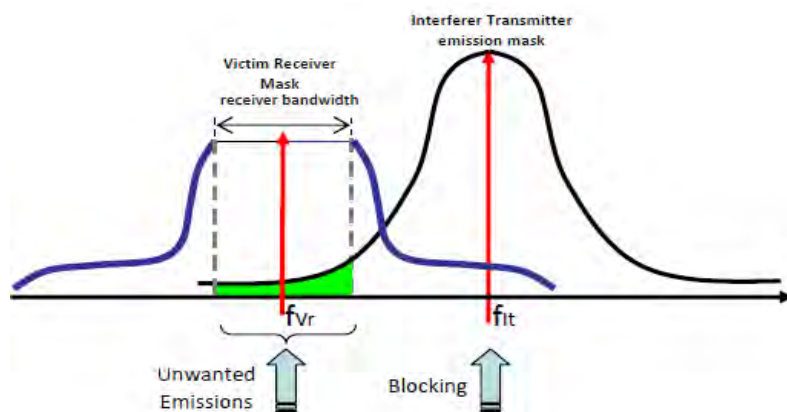


Fig. 2.14 The combination of unwanted emissions and the receiver blocking mechanism in SEAMCAT [14].

2.5.2.4 Intermodulation Interference

The inter modulation interference is the power of inter modulation products, reduced by the inter modulation attenuation function of the V_r . Inter modulation interference occurs as a result of two or more signals mix when they occupy the same transmission paths.

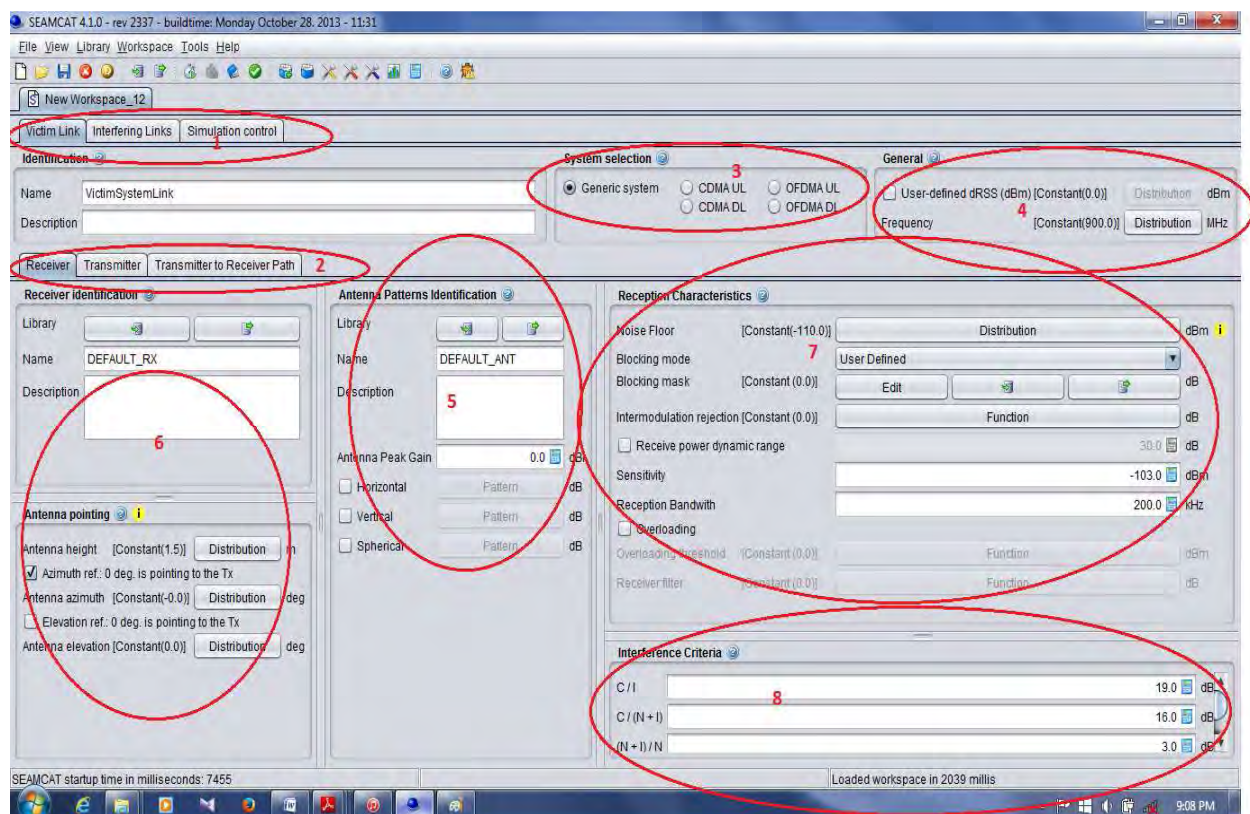


Fig. 2.15 SEAMCAT ver. 4.10 Interface.

In the interface the marked places where the user interact with have been explained as follows:

- 1-Links and Simulation control tabs
- 2-Entities of a link
- 3-The kind of system resembling the chosen entity
- 4-Operating frequency
- 5-Antenna Pattern(can be imported or defined by user)
- 6-Antenna Parameters
- 7-Parameters related to interference types
- 8-Protection ratios

Parameter	LTE-A BS		LTE-A UE	
	Rural	Urban	Rural	Urban
P _t (dBm)	48	24	23	
Operating Freq(MHz)	791-862			
BW(MHz)	5,20			
Height(m)	30	23.5	1.5	
Gain(dBi)	15		0	
Noise Figure(dB)	5		9	
Coverage Radius(Km)	4.3	0.5	-----	
Antenna Nature	Tri Sector Ref TR 36.942 V10		Omni Directional	
ACS(dB)	45		32	
Thermal Noise(dBm)	-102(5MHz) -95.98(20MHz)		-98(5MHz) -91.98(20MHz)	
Interference Threshold(dBm)	-108(5MHz) -101.98(20MHz)		-104(5MHz) -97.98(20MHz)	
Sensitivity(dBm)	-97(5MHz) -90.98(20MHz)		-93(5MHz) -86.98(20MHz)	
Propagation Model	Extended Hata			
Cell Layout	Wrap around 57 tri-sector cells uncoordinated		-----	
Users Per BS			20	50
Spectrum Emission Mask	TS 36.101v10(when Tx)		TS 36.104v10(when Tx)	
Receiver Blocking Attenuation Mode	Sensitivity Mode			

Table 2.3 LTE-A Parameters in rural and urban area deployment [5].

	DVB- Transmitter		DVB-Receiver	
	Rural	Urban	Rural	Urban
Pt(dBm)	74.6	63.6	-----	
Operating Freq(MHz)	782-862			
BW(MHz)	8			
Height(m)	150		10	
Gain(dBi)	0		14.15	
Noise Figure(dB)	-----		7	
Coverage Radius(Km)	51.76	17	-----	
Antenna Nature	Omni Directional		ITU-R BT.419-3	
Thermal Noise(dBm)	-98			
Sensitivity(dBm)			-78	-82
Propagation Model	Extended Hata			
Network Type	RN1	RN3	-----	
C/N(dB)	21	17	-----	
C/I(dB)	27	-30	23	-30
Reception Configuration	-----		RPC 1	
Spectrum Emission Mask	GE-06		-----	
Receiver Blocking Attenuation Mode	-----		PR	
Allowed Maximum Interfering Signal(dBm)	-----		-104	

Table 2.4 DVB-T Parameters in Urban and Rural area deployment [5].

Chapter Three: Propagation Analysis

3.1 Radio Wave Propagation

Propagation of radio waves determines how an electromagnetic signal moves from one point to another. It's the most fundamental aspect of wireless communication. We can categorize radio frequency propagation into two depending on the nature of the propagation: **Large scale propagation** and **Small scale propagation**.

Large Scale Propagation refers to the behavior of the radio frequency over large distances like 100λ or 1000λ , where λ is the wave length of the propagation. Whereas, **Small Scale Propagation** is about a radio channel elapsing over a small local area ranging $1-10 \lambda$ and lasting for a small time durations.

In Large Scale Propagation received power is directly related to the distance between Transmitter and Receiver and stationary with respect to time. But in Small Scale type of propagation power received by the receiver fluctuates rapidly based on position, speed, and direction of travel of the mobile.

An antenna is the device that helps wireless signals travel through the air. It has a role of converting an RF signal from guided media to an electromagnetic field of unguided (wireless) nature or vice versa. An isotropic antenna radiates electromagnetic energy equally in all directions, though this kind of antenna doesn't exist practically. All real antennas concentrate the energy of the wave in one or more directions.

The ratio of the energy densities by the real antenna and the ideal isotropic antenna yields the gain of the antenna.

$$g_t = \frac{\text{boresight energy}}{\text{isotropic energy}} \quad (3.1)$$

Effective Isotropic Radiated Power is the product of the antenna gain and the input energy.

EIRP=input power X antenna gain

$$\text{EIRP} = p_t \times g_t \quad (3.2)$$

The antenna gain or EIRP equation is only valid in the far field of antenna or a distance away of:

$$\text{dff} = \frac{2D^2}{\lambda} \quad (3.3)$$

where D is the largest physical dimension of the antenna[meters] and

λ is the wave length[meters]

In most cases the far field starts at 10λ . The area of the sphere formed taking d, distance between the transmitter and receiver, as its radius becomes:

$$A_{\text{sphere}} = 4\pi d^2 \quad (3.4)$$

Power density p_d in w/m² at the receiver becomes:

$$p_d = \frac{\text{EIRP}}{4\pi d^2} = \frac{p_t g_t}{4\pi d^2} \quad (3.5)$$

The actual received power depends on the ability of the receiver's antenna to catch the energy being radiated by the transmitter. As an antenna is physically larger, the more of the energy it actually catches. It's a matter of studying the geometry to determine the received power. How much power density intersects with the effective area of the received antenna. The effective area of an antenna is:

$$A_e = \frac{g_r \lambda^2}{4\pi} \quad (3.6)$$

where g_r is the gain of the receiver antenna. Putting all together:

$$p_{rec} = \frac{EIRP}{4\pi d^2} A_e = \frac{p_t g_t g_r \lambda^2}{(4\pi d)^2} \quad (3.7)$$

where P_{rec} is the received power. This is what we call the **Friis** Free Space Equation. It's the fundamental equation that describes how power falls off as distance increases for wireless signals. The Friis Space equation actually works for free space environments although many situations like satellite communications systems resemble the free space.

Therefore, the problem is dealing with situations involving mountains, the buildings, the earth, and the atmosphere. That takes us to the study of propagation models in which the free space model is greatly impacted by three phenomena:

- **Reflection** – Energy reflects off large (relative to λ) conductive objects.
- **Diffraction** – Bending of energy around objects.
- **Scattering** – Diffuse re-radiation of energy off rough (smaller than λ) objects.

The impact of the three phenomena is the basis for looking for various propagation models in the study of wireless communications.

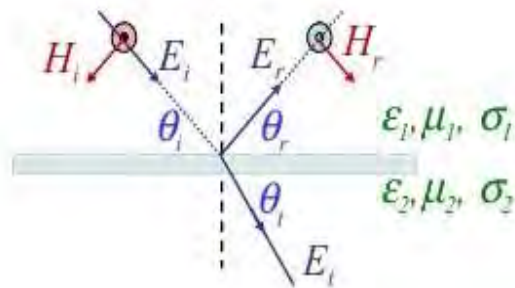
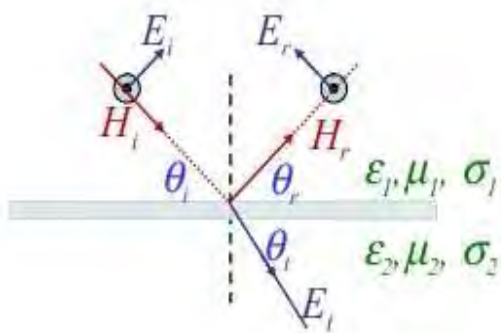
3.2 Propagation Mechanisms

As have been described in the above section, Reflection, Diffraction and Scattering, are the three basic propagations mechanisms that impact wireless communications.

3.2.1 Reflection

While a radio wave propagating in one medium hits another medium having a different electrical properties, the wave will either transmit through the medium or reflected back or in fact the reflection and transmission might occur equally at a time. If the wave hits a perfect dielectric material, the energy will be partly transmitted into the second medium and partly reflected back with no loss of energy in absorption. If the medium is a perfect conductor, then all the energy by the radio wave will be reflected back without loss of energy.

The Fresnel Coefficient (Γ) relates the reflected and the transmitted waves with the incident wave that hits the medium. It generally depends on the properties of the material like conductivity, relative permittivity etc, polarization, angle of incidence, and the frequency of the propagating wave.



Vertical Polarization: E-field in the plane to plane of incidence

Horizontal Polarization: E-field normal plane of incidence

E_i & H_i = Incident Electric and Magnetic Fields

E_r & H_r = Reflected Electric and Magnetic Fields

E_t = Transmitted (penetrating) Electric Field

Fig. 3.1 Electric Field in the plane of incidence and normal to the plane of incidence [15].

The Simple geometry of the dielectrics implies the following equations:

$$\Gamma_{\parallel} = \frac{E_r}{E_i} = \frac{\eta_2 \sin \theta_t - \eta_1 \sin \theta_i}{\eta_2 \sin \theta_t + \eta_1 \sin \theta_i} \quad (\text{E field in plane of incidence}) \quad (3.8)$$

$$\Gamma_{\perp} = \frac{E_r}{E_i} = \frac{\eta_2 \sin \theta_i - \eta_1 \sin \theta_t}{\eta_2 \sin \theta_i + \eta_1 \sin \theta_t} \quad (\text{E field not in plane of incidence}) \quad (3.9)$$

or

$$\Gamma_{\parallel} = \frac{-\epsilon_r \sin \theta_i + \sqrt{\epsilon_r - \cos^2 \theta_i}}{\epsilon_r \sin \theta_i + \sqrt{\epsilon_r - \cos^2 \theta_i}} \quad (3.10)$$

$$\Gamma_{\varepsilon} = \frac{\sin\theta_i - \sqrt{\varepsilon_r - \cos^2\theta_i}}{\sin\theta_i + \sqrt{\varepsilon_r - \cos^2\theta_i}} \quad (3.11)$$

Where ε_r is the relative permittivity of the second medium and η is the intrinsic impedance of the respective medium.

3.2.1.1 Reflection from a perfect conductors

Since a perfect conductor doesn't allow electromagnetic energy into it, a plane wave incident on the conductor reflects back all of the energy. Therefore, the angle of incidence equals the angle of reflection.

i.e., $\theta_i = \theta_r$, $E_i = E_r$ for E-field in the plane of incidence $E_i = -E_r$ for E-field not in plane of incidence.

3.2.1.2 Ground Reflection (2-Ray Model)

Ground reflection is the basis for modeling a useful propagation model that better estimates a physical propagation than the free space model. It involves direct path and ground reflected path between transmitter and receiver. The use of geometric optics helps to deduce a path loss formula for this model.

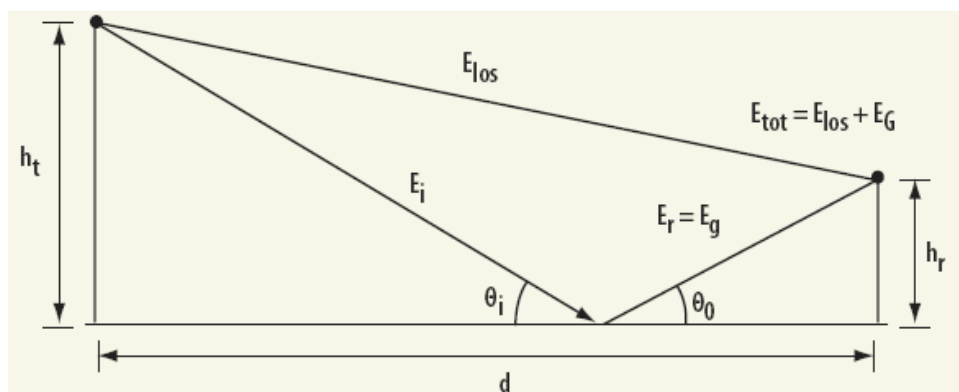


Fig. 3.2 Ground Reflection Model [16].

With h_t , height of transmitter and h_r , height of receiver and E_0 (V/m), the free space E-field at a reference distance d_0 , the free space propagating E-field at a distance $d > d_0$ is given by:

$$E(d,t) = \frac{E_0 d_0}{d} \cos(\omega_c (t - \frac{d}{c})) \quad \text{for } d > d_0 \quad (3.12)$$

Two propagating waves arrive at the receiver: the direct wave that travels a distance d' and the reflected wave that travels a distance d'' . The resultant E-field, E_T can be expressed as the sum of the E-field equations for distances d' and d'' .

$$E_T(d,t) = \frac{E_0 d_0}{d'} \cos(\omega_c (t - \frac{d'}{c})) + (-1) \frac{E_0 d_0}{d''} \cos(\omega_c (t - \frac{d''}{c})) \quad (3.13)$$

3.2.2 Diffraction

Radio signals propagate around the curved surface of the earth, beyond the horizon, and behind obstructions through its diffraction characteristics.

Diffraction is one of the most non-line of sight (NLOS) propagation mechanisms. Cellular systems rely on diffraction over roof tops and indoor systems rely on diffraction around wall edges and door openings for coverage.

The analysis of diffraction phenomenon is explained on the basis of Huygen's principle. The Huygen's principle states that all points on a wave front produces secondary wavelets, and such wavelets combine to produce a new wave front in the direction of propagation.

Therefore, diffraction is propagation of secondary wavelets into a shadowed region. The field strength of a diffracted wave in the shadowed region is the vector sum of

the electric field components of all the secondary wavelets in the region around the obstacle.

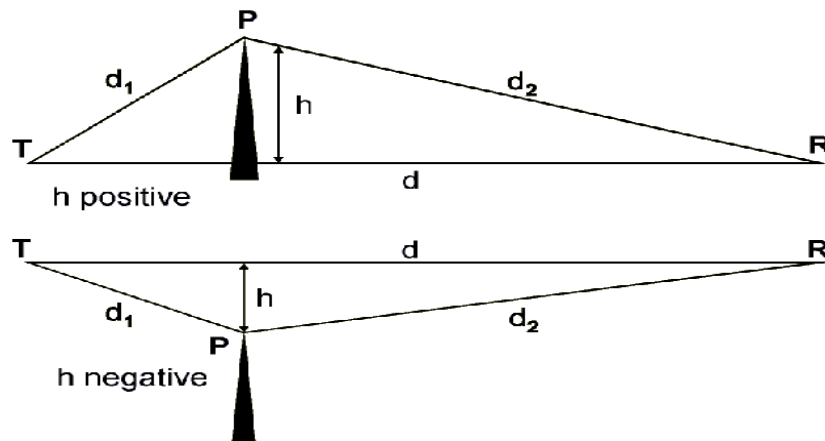


Fig. 3.3 Fresnel Zone Geometry [16].

Consider a transmitter and a receiver separated in free space as shown above, and an obstruction of effective height, h with an infinite width. The wave propagating over the top of the obstruction travels a longer distance than a direct line-of-sight path through the obstruction (if it existed).

The excess path length (Δ), which is the difference between the direct path and the diffracted path can be obtained from the geometry shown above assuming that $h \ll d_1, d_2$ and $h \gg \lambda$.

$$\Delta \approx \frac{h^2}{2} \frac{(d_1 + d_2)}{d_1 d_2} \quad (3.14)$$

The Corresponding phase difference is given by:

$$\phi = \frac{2\pi\Delta}{\lambda} \approx \frac{2\pi}{\lambda} \frac{h^2}{2} \frac{(d_1 + d_2)}{d_1 d_2} \quad (3.15)$$

3.2.3 Scattering

Some objects like trees and lamp posts tend to scatter energy in all directions when hit by electromagnetic waves. This feature gives a received signal a high opportunity to be higher than what's predicted by reflection and diffraction alone. Rough surfaces spread out(diffuse) radio waves in all directions due to scattering. Flat surfaces having larger dimensions than a wavelength can be considered as reflective surfaces. Surface roughness is characterized by Rayleigh criterion which defines a critical height(h_c) of surface protrusion.

For a given angle of incidence h_c is given by:

$$h_c = \frac{\lambda}{8 \sin \theta_i} \quad (3.16)$$

A surface is considered smooth if its minimum to maximum protuberance h is less than h_c , and is considered rough if the protuberance is greater than h_c . For rough surfaces, the flat surface reflection coefficient needs to be multiplied by a scattering loss factor, Q_s , to account for the diminished reflected field.

3.3 Characteristics of Propagation Models

Radio Propagation models characterize mathematical formulation of radio waves as a function of frequency, distance and other conditions. It's evident that antenna height of a mobile terminal is usually very small. Thus, obstacles and reflecting surfaces in the vicinity of the antenna have a substantial impact on the characteristics of the propagation path. Besides, there occurs a considerable change in the characteristics of the propagation as the mobile unit moves from time to time. All

these lead to the variation of the transmission path from direct line of sight to that severely obstructed by buildings, foliage and the terrain.

Generally, the wireless channel is modeled by taking into account several key parameters that vary significantly with the environment, rural versus urban, or flat versus mountainous. Three types of fading occurs as a result of the above mentioned characteristics: distance dependence, large-scale shadowing, small-scale fading

3.3.1 Distance Dependence

Distance dependence determines the path loss (measured in dB) associated with the distance covered.

$$L(d)=L_0+10\gamma\log\left(\frac{d}{d_0}\right) \quad (3.17)$$

where γ is the path loss exponent, which varies with terrain and environment, and L_0 is the pass loss at an arbitrary reference distance d_0 .

3.3.2 Large-Scale Shadowing

It causes variations over larger areas due to terrain, building, and foliage obstructions. It has a significant impact on link budget calculations.

Large-Scale fading measures the attenuation x measured in dB as a log-normal distribution $N(m,\sigma)$ with mean m and standard deviation σ .

The Probability density function of the attenuation is given by the usual Gaussian Formula:

$$p(x)=\frac{1}{\sigma\sqrt{2\pi}}\exp\left(-\frac{(x-m)^2}{2\sigma^2}\right) \quad (3.18)$$

3.3.3 Small-Scale fading

Moving scattering objects and the multipath that the signal takes cause small-scale fading. It produces great variation within a half wavelength. Rayleigh, Ricean, or similar fading distributions approximate the resulting fades in an acceptable range. Diversity, equalizing, channel coding and interleaving are some of the schemes used by radio systems to mitigate the impact of small-scale fading.

3.4 Classification of Propagation Models

Throughout the studies of radio waves, various propagation models have been developed. And they're broadly classified into three categories: Theoretical, Empirical and Deterministic models.

3.4.1 Theoretical Models

Theoretical assumptions serve as a basis for the propagation models under this category. They don't directly employ specific information about any given environment. The assumptions drawn might, however, be based on measurement of data or physical laws. Theoretical models are important for analytical studies of the communication systems that don't require any specific propagation information. Planning communication systems for a particular area makes use of better propagation models than this one.

3.4.2 Empirical Models

These type of models are based on measurement or observation of signal performance in real propagation environments. Non-line-of-sight (NLOS) and point-to-multipoint systems can be modeled through Empirical Analysis. The original data

taken for the developed models must be more or less comparable with the given environment where we want to adopt the models.

3.4.3 Deterministic Models

Deterministic models also known as physical models use the basic principles of radio waves instead of using measurement data outcomes. They usually require Digital Terrain Map that completely describes the 3-D topography of the propagation environment. A ray tracing model is a typical example for deterministic model as it shows the right traces of the path where the signal traverses across the terrain. Complex algorithms and software programs along with powerful computing devices are used by these models.

3.5 Comparison of Propagation Models

The explosive growth in mobile communications entails the need for having a propagation model that best fits a given scenario. This is important for determining base-station locations, obtaining suitable data rates, and estimating their coverage without necessarily conducting a series of propagation measurements as this might be time consuming and expensive.

3.5.1 Free Space Loss Model

Electromagnetic field propagation suffers fading due to various effects as it travels through wireless channels. However, this effect is reasonably low in some cases like that of the satellite communication. There is a direct line-of-sight communication between the transmitter and the receiver. Free space model determines the received power strength decaying as inversely proportional with the distance.

Friis Free Space equation is the basis for free space loss model.

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2} \quad (3.19)$$

where P_t is the transmitted power, P_r is the received power, G_t is the transmitter antenna gain, G_r is the receiver antenna gain and d is the transmitter-receiver distance.

The Friis equation in terms of $P_r(d_0)$, received power at some close-in (reference) distance from the transmitter, is given by:

$$P_r(d) = P_r(d_0) \left(\frac{d_0}{d}\right)^2 \quad d > d_0 \quad (3.20)$$

$$\text{Generally, } P_r \propto d^{-\gamma} \quad (3.21)$$

where γ is the path loss exponent. The following table shows typical path loss exponents.

Environment	Path loss exponent, γ
Free Space	2
Urban Area	2.7 to 3.5
Suburban Area	3 to 5
Indoor (line-of-sight)	1.6 to 1.8

Table 3.1 Typical Path loss exponents [17].

Suppose G_t is the gain of a transmitter antenna whose power is P_t . The radiated power at a distance d is given by:

$$Q = \frac{P_t G_t}{4\pi d^2} \text{ watts/m}^2 \quad (3.22)$$

The effective area of the receive antenna located at a distance d having a gain of G_r is given by:

$$A = G_r \frac{\lambda^2}{4\pi} \quad (3.23)$$

The received power will be given as:

$$p_r = \rho A = p_t G_t G_r \left(\frac{\lambda}{4\pi d}\right)^2 \quad (3.24)$$

The path loss, L_p is given by:

$$L_p = \frac{p_t G_t G_r}{p_r} \quad (3.25)$$

$$L_p = \left(\frac{4\pi d}{\lambda}\right)^2 \quad (3.26)$$

The free space formula in dB, is given by:

$$L_p = \log\left(\frac{4\pi d}{\lambda}\right)^2 \quad (3.27)$$

$$L_p(\text{dB}) = 32.5 + 20 \log f + 20 \log d \quad (3.28)$$

where the frequency, f is measured in MHz and the distance d , is in Km.

3.5.2 Irregular Terrain Models

Propagation models make use of Point-to-Area and Point-to-Point methods. Point-to-Area methods are used for larger areas and general estimations. The result in this method is estimated through use of general propagation rules, earlier statistical measurements and approximate terrain descriptions.

On the other hand, Point-to-Point method requires greater number of input parameters and it uses advanced evaluation of geographical and climate phenomena

like diffraction, scatter, rain and vapor attenuation. It entails input from DEM/DTM maps and it's usually employed for detailed radio planning. There are several propagation models formulated using either of the methods described. Several researches have been conducted to test the accuracy of the propagation models and compare each other to come up with the best model for a specific scenario.

3.5.2.1 ITM model

This model is also known as Longley-Rice Method. It's a radio signal propagation model for predicting the attenuation of radio waves in the telecommunication link operating in the frequency range of 20 MHz-20GHz [17-19].

It considers the terrain elevation and landscape irregularities. Designing of television broadcasting in the USA was made by this model in 1960s and 1970s. Then it was extensively applied for preparing channel allocations for VHF/UHF bands. The ITM model has two modes depending on the requirement of the desired radio planning, i.e., a mode for predictions over an area and a mode for point-to-point link predictions.

This model, like most other propagation models, requires the input of certain general parameters essential for propagation calculations.

Operating frequency, length of the path, polarization of antenna, heights of the antennas, the refractivity of the atmosphere, the effective earth curvature, the conductivity of the soil, the relative permittivity or dielectric constant of the ground and the climatic conditions are the most prominent parameters needed in the calculation of the model. The availability of values for these parameters suffices empirical computations of the free space loss, the ground reflection coefficient, the

Fresnel parameters of knife edge diffraction and hence the total electric field strength or the attenuation of the desired/interfering radio signal. Therefore, it can be said that the ITM model encompasses wide operating frequency range (VHF,UHF, and SHF) and wide series of parameters allowing detailed parameterization. The required parameters can be categorized as shown in the following table:

System Parameters	Terrain Parameters	Deployment Parameters	Statistical Parameters	ITM Limitations
Frequency	Irregular Terrain Parameters	Sitting criteria	Percentage of localization	Frequency: 20 MHz-20 GHz
Height of antenna	Conductivity of ground		Percentage of time	Distance: 1-2000 km
Distance	Relative permittivity		Confidence level	Height of antenna: 0.5-3000 m
Polarization	Surface refractivity		Mode of variability	
	Radio climate		Signal standard deviation	

Table 3.2 ITM parameters [18].

Seven radio climate zones are considered in the ITM propagation model. The following table illustrates the climate codes used in the implementation of the model. The codes used in determining the climate regions have great application in the Monte Carlo Simulation method that we will detail discuss about in the upcoming sections.

Code	Radio Climate region
1	Equatorial (Congo)
2	Continental Subtropical(Sudan)
3	Maritime Subtropical(West coast of Africa)
4	Desert(Sahara)
5	Continental Temperate
6	Maritime Temperate , over land(UK and Continental west coasts)
7	Maritime Temperate, over Sea

Table 3.3 Radio Climate code used in ITM model [20].

Landscape	Irregularity Parameter dh (m)
Flat Terrain	0
Plains	30
Hills	90
Mountains	200
Rugged Mountains	500

Table 3.4 Irregularity parameter in meters for various landscapes [20].

Ground Type	Conductivity of Ground (S/m)	Relative Permittivity,
Average Ground	0.005	15
Poor Ground	0.001	4
Good Ground	0.02	25
Fresh Water	0.01	81
Sea Water	5	81

Table 3.5 Conductivity and Relative permittivity of ground types [20].

The **radio refractivity** is an important parameter in determining the quality of VHF, UHF and SHF signals. Surface (ground level) and elevated refractivity data help determine the prediction of propagation effects. In particular, surface refractivity is useful for this type of analysis. Local coverage and statistics of refractivity provide the most useful indication of refractivity-related effects required for prediction methods [20].

The refractivity, N is related to the refractive index, n of air as:

$$N = (n - 1) \times 10^6 = 77.6 \frac{p}{T} + 3.73 \times 10^5 \frac{e}{T^2} \quad (3.29) [21]$$

where p = atmospheric pressure (hPa), e =water vapor pressure(hPa) and T =absolute temperature (K). The water vapor pressure e is calculated from the relative humidity, and saturated water vapor, using the expression:

$$e=H \times \frac{6.1121 \exp\left(\frac{17.502t}{t+240.97}\right)}{100} \quad (3.30) [21]$$

Where:

H=relative humidity (%), t=temperature in degree Celsius (°C)

The effective earth radius factor k can be used to characterize refractive conditions as normal refraction or standard atmospheric, sub-refraction, super-refraction and ducting respectively.

Thus k can be expressed in terms of refractive gradient, $\frac{dN}{dh}$

$$K \approx \frac{1}{1 + \left(\frac{dN}{dh}\right)/157} \quad (3.31)$$

Near the earth's surface, $\frac{dN}{dh}$ is about -39N/Km which gives an effective earth radius factor, $k=4/3$.

This is known as normal refraction or standard atmosphere. In this case, radio signals travel on a straight line path along the earth's surface and go out to space unobstructed.

If $\frac{4}{3} > k > 0$, sub-refraction occurs, meaning that radio waves propagate abnormally away from the earth's surface.

When $\infty > k > \frac{4}{3}$, super-refraction occurs and radio waves propagate abnormally towards the earth's surface thus extending the radio horizon.

If $-\infty < K < 0$, ducting occurs and the waves bend downwards with a curvature greater than that of the earth.

We can conclude that surface refractivity depends on climate zone. Sitting criteria is a qualitative description with terminals sites chosen to improve communications. ITM model defines four modes of variability: Single message mode, Individual mode, Mobile mode, and Broadcast mode. Selected mode determines the meaning of the reliability and confidence values used in the model.

ITM model describes three types of variability which are time, location and situation. These three “dimensions of variability” were developed to contribute for the category variations in measured median signal levels.

Time Variability contributes for variations of hourly median values of attenuation due to, for example, slow changes in atmospheric refraction or in the intensity of atmospheric turbulence.

The field strength value obtained through computation is an hourly median value. It's expected that the actual field strength at the receiver is above that value during half of each hour and below that value for half of each hour.

The effects of such changes over time is described by time variability. It's expressed as a percentage from 0.1% to 99.9%.

The value determines the fraction of time during which actual received field strength is expected to be equal to or higher than the hourly median field computed by the program.

This allows to determine how to relate time variability with atmospheric and other effects on the field strength. As higher percentage reliability values are entered, the variability resulting from these factors reduce effectively. That is the resulting field strength predicted by the program will be lower but with increased reliability the

actual field that could be measured would equal or exceed the computed value at any given time.

Location variability contributes for variations in long-term statistics that occur from path to path due to, for example, differences in the terrain profiles or environmental differences between the paths. The location variability for the calculation is expressed as a percentage from 0.1% to 99.9%. This value gives the fraction of locations where actual received field strength is expected to be equal to or higher than the median field computed by the program. This variable allows you to specify how you want to deal with the location variability. Entering higher percentage reliability values effectively reduces the variability resulting from these factors. The resulting field strength predicted by the program will be lower, but with increased reliability that the actual field that could be measured would equal or exceed the computed value at any given time.

Situation variability contributes for variations between systems with the same system parameters and environmental conditions, including differences in the ability of individuals to accurately take field strength readings. Variables whose effects we do not recognize are commonly known as situation variables.

The effects of these differences produce the changes in observed statistics". Situation variability describes the effects of the changing conditions resulting from such variables. The situation variability for the calculation is expressed as a percentage from 0.1% to 99.9%. This value gives the fraction of "identical" paths on which actual received field strength is expected to be equal to or higher than the field computed by the program. Entering higher percentage confidence values effectively reduces the variability resulting from these factors. The resulting field strength predicted by the

program will be lower, but with increased confidence that the actual field that could be measured would equal or exceed the computed value.

Reliability refers to a measure of the variability that a radio system will observe during its use. Confidence refers to the variability that remains after specifying reliability, measurable in the aggregate of a large number of radio systems.

3.5.2.2 The ITU P 452 Model

This model is basically the summation of line-of-sight loss model, clutter model loss and the sub path diffraction loss model.

Path Type	Model Description
Line-of-sight	<p>The loss prediction is the sum of the losses given by the line-of-sight and clutter-loss models.</p> $L_b(p) = L_{bo}(p) + A_{ht} + A_{hr} \quad (3.32)$ <p>Where:</p> <p>$L_{bo}(p)$: predicted basic transmission loss not exceeded for p% of time given by the line-of-sight model</p>
Line-of-sight with sub-path diffraction	<p>The loss prediction in this type is computed by summing the losses given by the line-of-sight and diffraction (sub-path) models and clutter models.</p> $L_b(p) = L_{bo}(p) + L_{ds}(p) + A_{ht} + A_{hr} \quad (3.33)$ <p>Where:</p> <p>$L_{ds}(p)$ is prediction for p% of time given by the sub-path diffraction loss element of the diffraction model.</p>

Table 3.6 General ITU P452 Propagation losses [22].

ITU P452 Line-of-sight propagation

Predicted basic transmission loss not exceeded for p% of time due to the line-of-sight propagation may be expressed by:

$$L_{bo}(p) = 92.5 + 20 \log f + 20 \log d + E_s(p) + A_g \quad (3.34)$$

Where:

$E_s(p)$ is correction for multipath and focusing effects

$$E_s(p) = 2.6 \left((1 - e^{-\frac{d}{10}}) \log\left(\frac{p}{50}\right) \right) \text{ dB} \quad (3.35)$$

$$A_g = [\gamma_o + \gamma_w(\rho)] \times d \quad \text{dB} \quad (3.36)$$

Where: $\gamma_o, \gamma_w(p)$ are specific attenuation due to dry air and water vapor, respectively and ρ is water vapor density.

Attenuation due to atmosphere

According to Recommendation ITU-R P676

Attenuation due to water:

$$\gamma_w(\rho, f) = \left[0.05 + 0.0021\rho + \frac{3.6}{(f-22.2)^2 + 8.5} + \frac{10.6}{(f-183.3)^2 + 9} + \frac{8.9}{(f-325.4)^2 + 26.3} \right] f^2 \rho 10^{-4} \quad (3.37)$$

for $f < 350 \text{GHz}$

Attenuation due to oxygen:

$$\gamma_w(f) = \left[7.19 \times 10^{-3} + \frac{6.09}{f^2 + 0.227} + \frac{4.81}{(f-57)^2 + 1.5} \right] f^2 \rho 10^{-3}; \text{ for } f \leq 57 \text{GHz} \quad (3.38)$$

The water vapor density ρ is a variable and it's set to 3g/m^3 .

Clutter Loss Calculation

The additional loss due to protection from local clutter is given by the expression:

$$A_h = 10.25 X e^{-d_k} \left\{ 1 - \tanh \left[6 \left(\frac{h}{h_a} - 0.625 \right) \right] \right\} - 0.33 \text{ dB} \quad (3.39)$$

Where:

d_k : distance (km) from nominal clutter point to the antenna

h : antenna height (m) above local ground level

h_a : nominal clutter height (m) above local ground level

Clutter(Ground-Cover) Category	Nominal Height, h_c (m)	Nominal Distance, d_c (Km)
Category 1 High Crop Fields Park Land Irregularly Spaced Sparse Trees Orchard(Regularly Spaced) Sparse Houses	4	0.1
Category 2 Village Center	5	0.07
Category 3 Deciduous trees (irregularly spaced) Deciduous trees (regularly spaced) Mixed tree forest	15	0.05
Category 4 Coniferous trees (irregularly spaced) Coniferous trees (regularly spaced)	20	0.05
Category 5 Tropical rain forest	20	0.03
Category 6 Suburban	9	0.025
Category 7 Dense Suburban	12	0.02
Category 8 Urban	20	0.02
Category 9 Dense Urban	25	0.02
Category 10 Industrial Zone	20	0.05

Table 3.7 Nominal Clutter Heights and Distances [22].

Sub Path Diffraction Model

The diffraction loss (A) in terms of the first Fresnel zone radius, R_1 is given as follows:

$$A = \left[1 - \frac{5h}{3R_1}\right] X A_h \quad (3.40)$$

Where h is path clearance and A_h is the diffraction loss at the horizon

$$h = d_2 \left\{ \frac{h_1 - \frac{d_1^2}{2a_e}}{d} \right\} + d_1 \left\{ \frac{h_2 - \frac{d_2^2}{2a_e}}{d} \right\} \quad (3.41)$$

Where:

$$d_1 = \frac{d}{2} (1 + b) \quad (3.42)$$

$$d_2 = d - d_1 \quad (3.43)$$

$$b = 2\sqrt{\frac{m+1}{3m}} \cos\left\{\frac{\pi}{3} + \frac{1}{3} \cos^{-1} \frac{3c}{2} \left(\sqrt{\frac{3m}{(m+1)^3}}\right)\right\} \quad (3.44)$$

$$c = \frac{|h_1 - h_2|}{h_1 - h_2} \quad (3.45)$$

$$m = \frac{d^2}{4a_e (h_1 + h_2)} \quad (3.46)$$

For diffraction loss at horizon, the path length d (Km) is given by:

$$d = \sqrt{2a_e h_1} + \sqrt{2a_e h_2} \quad (3.47)$$

Where h_1 and h_2 are transmitter and receiver heights, a_e is the effective radius of the earth and it's considered as 8500 Km.

3.5.3 City Models

City Models are empirical mathematical formulation that characterize radio wave propagation as a function of frequency, distance and other parameters in cities. They consider areas where direct line-of-sight path between transmitter and receiver is highly deterred by the presence of high rise buildings causing severe diffraction losses. City Models are highly applicable in forming proper mobile radio systems planning, interference estimations, frequency assignments, and cell parameterization for network planning processes.

3.5.3.1 Okumara Model

It's a city model based on measured data with no analytical explanation. It's the simplest and best in terms of path loss accuracy in cluttered mobile environment. It has a disadvantage of having a slow response to rapid terrain changes. Common standard deviations between predicted and measured path loss in this model lies between 10dB-14dB. Okumara Model is useful for frequencies ranging between 150MHz-1920MHz, although it can be extrapolated to 3GHz frequency. It's valid for coverage distances between 1Km-100Km. Base station heights 30m-1000m can be analyzed through this model [23].

Path Estimation

The Median value of propagation path loss is equated in Okumara model as follows:

$$l_{50}(dB) = l_f + A_{mu}(f, d) - G(h_{te}) - G(h_{re}) - G_{Area} \quad (3.48)$$

where:

- l_{50} is 50% value of propagation path loss (median);
- l_f is Free space propagation path loss;
- $A_{mu}(f, d)$ is the median attenuation relative to free space;
- $G(h_{te})$ and $G(h_{re})$ are base station antenna height and mobile station antenna height gain factors, respectively;
- G_{Area} is gain due to environment.

The antenna gain varies at a rate of 20dB per decade or 10dB per decade.

The Okumara model can further be corrected for terrain undulation height ,isolated ridge height, average terrain slope and mixed land/sea parameters.

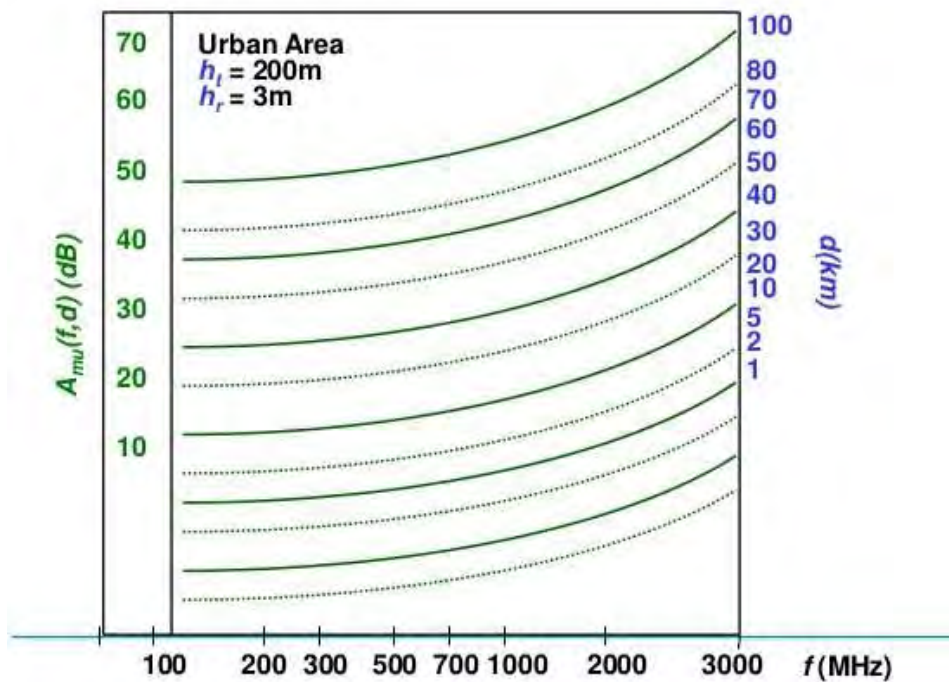


Fig. 3.4 Curves plotted for Median Attenuation Relative to Free Space, $A_{mu}(f,d)$ as a function of frequency of propagation and coverage distance [23].

3.5.3.2 Hata Model

Hata's Model is empirical mathematical formulation of the relationships described in the Okumura model. It's limited to certain ranges of input parameters and is only over quasi-smooth terrain.

The applicable frequency range is between 150 MHz and 1500 MHz, Base Station Antenna Height between 30m and 200m, Mobile Station Antenna Height between 1m and 10m and coverage radius 1Km and 20Km [24-26].

$$L(\text{dB}) = A + B \log d \quad \text{for Urban Areas}$$

$$L(\text{dB}) = A + B \log d - C \quad \text{for Suburban Areas} \quad (3.49)$$

$$L(\text{dB}) = A + B \log d - D \quad \text{for Open Areas}$$

Where:

- $A = 69.55 + 26.161 \log f - 13.82 \log h_b - a(h_m)$
- $B = 44.9 - 6.55 \log h_b$
- $C = 5.4 + 2[\log(\frac{f}{28})]^2$
- $D = 40.94 + 4.78[\log f]^2 - 18.33 \log f$

Where, $a(h_m) =$

$$\left\{ \begin{array}{ll} [1.1 \log(f) - 0.7] h_m - [1.56 \log(f) - 0.8]; & \text{for medium or small cities} \\ 8.29 [\log(1.54 h_m)]^2 - 1.1; & \text{for large city and } f \leq 200 \text{ MHz} \\ 3.2 [\log(11.75 h_m)]^2 - 4.97; & \text{for large city and } f \geq 400 \text{ MHz} \end{array} \right.$$

3.5.3.3 COST-231 Hata Model

The Cost231-Hata model extension of Hata's model for use in the 1500-2000 MHz frequency range. The model works very well for frequency ranging from 1500 MHz to 2000 MHz, Base Station Antenna Height 30m to 200m, Mobile Station 1m to 10 m and Transmission radius 1Km to 20 Km.

The path loss according to COST-231 Hata Model is expressed as follows:

$$L(\text{dB}) = A + B \log(d) + C \quad (3.50)$$

Where:

$$A = 46.3 + 33.9 \log f - 13.28 \log h_b - a(h_r)$$

$$B = 44.9 - 6.55 \log h_b$$

$$C = 0 \text{ dB ;} \quad \text{for medium city and suburban areas}$$

$$C = 3 \text{ dB ;} \quad \text{for metropolitan areas}$$

$$a(h_r) = 3.2[\log(11.75h_r)]^2 - 4.97; \quad \text{for } f \geq 400\text{MHz} \quad (3.51)$$

$$a(h_r) = [1.1 \log f - 0.7]h_r - [1.56 \log f - 0.8] \quad (3.52)$$

Where h_r is the receiving antenna height above the ground.

For sites having partly dense urban, partly light dense urban and partly open with marginal coastal zones and sites having partly urban, partly light dense urban and partly industrial zone, path loss is calculated using (3.67) and (3.69) with C value 3 dB whereas sites with partly urban, partly open, partly low density vegetation, path loss is calculated using (3.67) and (3.69) with C value 0 dB. [26-28]

3.5.3.4 ECC-33 Model

Electronic Communication Committee (ECC) recently developed, ECC-33 model through the ITU-R Recommendation P.529 as the extension of the Okumara model for frequencies reaching to 3.5GHz. The path loss in this model is given by:

$$P_l(\text{dB})=A_{fs}+A_{bm}-G_b-G_r \quad (3.53)$$

Where,

- A_{fs} is the free space attenuation in dB
- A_{bm} is the basic median path loss in dB
- G_b is transmitter antenna height gain factor
- G_r is the receiver antenna height gain factor

These factors can be separately computed as follows:

$$A_{fs} = 92.4 + 20 \log d + 20 \log f \quad (3.54)$$

$$A_{bm} = 20.41 + 9.83 \log d + 7.894 \log f + 9.56[\log f]^2 \quad (3.55)$$

$$G_t = \log(h_b/200)[13.98 + 5.8(\log d)^2] \quad (3.56)$$

$$G_r = \begin{cases} [42.57 + 13.7 \log f][\log h_m - 0.585], & \text{for medium cities} \\ 0.759h_m - 1.892, & \text{for large cities} \end{cases} \quad (3.57)$$

Where h_b and h_m are base station and mobile antenna heights respectively. Moreover, d is the distance between the receiver and the transmitter [29].

3.5.3.5 Erickson Model

It's Erickson's implementation of Hata Model. The path loss according to this model is computed as follows:

$$P_L = a_0 + a_1 \log d + a_2 \log h_b + a_3 \log h_b \log d - 3.2 (\log(11.75h_r))^2 + g(f) \quad (3.58)$$

$$\text{where, } g(f) = 44.49 \log f - 4.78(\log f)^2 \quad (3.59)$$

The parameters a_0, a_1, a_2 and a_3 are constants with default values 36.2, 30.2, 12, and 0.4 respectively. The following table illustrates the values commonly used for these coefficients in the areas specified.

Environment	a_0	a_1	a_2	a_3
Urban	36.2	30.2	12.0	0.1
Suburban	43.20	68.93	12.0	0.1
Rural	45.95	100.6	12.0	0.1

Table 3.8 Common values of the coefficients in the Erickson model [30].

3.5.3.6 ITU-R P.1546-5 Model

ITU has developed this model as a new recommendation for terrestrial services in the range 30MHz to 3000MHz. This recommendation is for effective transmitting antenna height less than 3000m serving tropospheric radio circuits over land paths, sea paths or mixed land-sea paths up to 1000Km length. The foundation of this method is Interpolation/Extrapolation methods from empirically derived field-strength curves as functions of distance, antenna height, frequency and percentage time.

This model provides a set of curves of field strength as a function of frequency (100MHz, 600 MHz, and 2GHz), distance(1 Km to 1000 Km), transmitting height(10 m

to 1200 m), location variability(1% to 99%), and path type(land, cold sea, warm sea, and mixed paths) provided that the height of the receiving antenna is equal to the representative height of ground cover.

Correction factors in this recommendation include correction for transmitting height, interpolation of field strength as a function of distance and frequency, correction for receiving antenna height, correction for cluttered transmitter, terrain clearance angle correction, correction due to tropospheric scattering, etc [17-18].

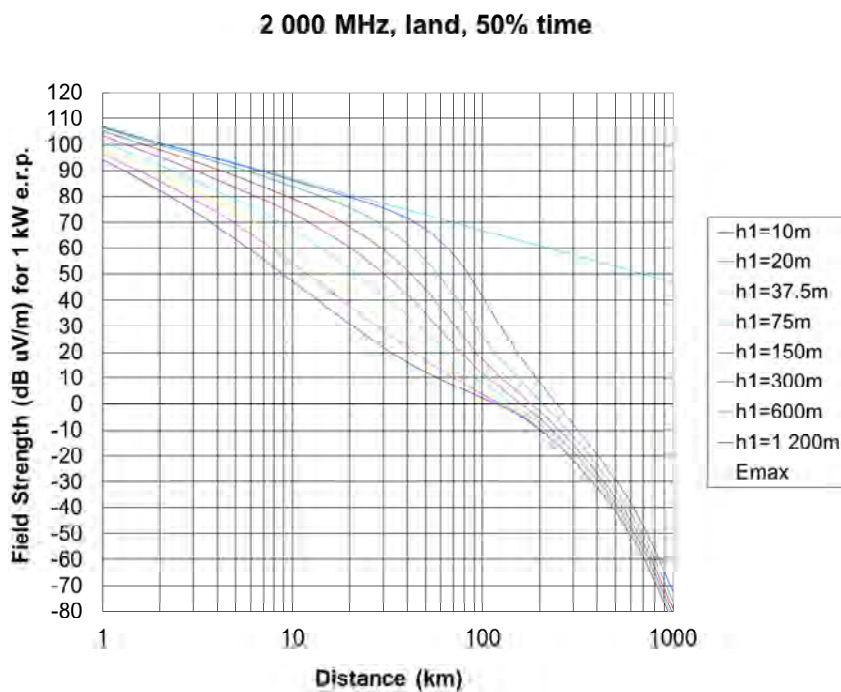


Fig. 3.5 Field strength prediction curve of ITU-R P.1546-5 Model for land propagation and field strengths exceeding 50% of the time at 2000 MHz [19].

Chapter Four: Results and Discussion

4.1 Coexistence Requirements

From the studies conducted in this research, it can be shown that LTE broadband and DVB broadcast coexist under certain fulfilled conditions. The most prominent factors to be considered in mitigating their interference are the separation in distance and in frequency between the two systems, as thoroughly discussed in the interference situations in Chapter Two.

The SEAMCAT simulation program plays a great role in plotting the coexistence scenarios using various propagation models adopted for LTE broadband services. In fact, the SEAMCAT tool has limited in-built programs for the most common propagation models. Official version of SEAMCAT (version 4.1.0) lacks ability of using DEM (Digital Elevation Map)/DTM (Digital Terrain Map) that would model the geographical and climatic conditions of a certain region. That means all types of analysis carried out by SEAMCAT involves only a flat terrain. The inadequacy of this program in this regard has been compensated by its expandability to allow a user programmed plug-in to model a desired region where electromagnetic analysis will be studied.

It is known that properties of radio propagation in a terrestrial environment are difficult to predict. The problem is particularly worse for radio waves at VHF, UHF, and SHF that travel through buildings, trees, clutter of hills and the steadily varying atmosphere. Therefore, design of radio equipment and radio systems may not

require knowledge of precise characteristics of the propagation channel nor how the operation is affected.

Instead, the designing must be content with propagation models that more or less resemble a certain area under consideration. All propagation models, in fact, study electromagnetic energy interaction with the physical world at various levels. In view of this, a Java program can be written for any propagation model and embedded in the tool.

The JAVA plug-in addresses the issue of irregular terrain scenario where wireless systems work. The actual received signal strength prediction on the victim receiver depends on the precise propagation model used for a chosen region that best describes the type of system used and the feature of terrain.

Propagation models make use of Point-to-Area and Point-to-Point methods. Point-to-Area methods are used for larger areas and general estimations. The result in this method is estimated through use of general propagation rules, earlier statistical measurements and approximate terrain descriptions. On the other hand, Point-to-Point method requires greater number of input parameters and it uses advanced evaluation of geographical and climate phenomena like diffraction scatter, rain and vapor attenuation. It entails input from DEM/DTM maps and it's usually employed for detailed radio planning.

There are several propagation models formulated using either of the methods described above. Some of them are built in the propagation model option of the SEAMCAT program and some are allowed to be integrated into the program through JAVA plug-ins. In this study, the parameters obtained from "low level

design of eUTRAN (LTE) documentation for Addis Ababa" by HUAWEI TECHNOLOGIES CO., LTD and the Ethio Telecom are also illustrated as a reference for a more practical analysis [13].

The suitable antenna heights in making the best balance among coverage, capacity and performance are shown in the table below.

Scenario	Dense urban	Urban
Antenna Height (m)	25-30	30-35

Table 4.1 Antenna Height Design [31].

The Link Budget is a crucial step in cellular design as it helps to get the maximum cell radius for meeting a defined coverage and quality requirement. It includes information on frequency, cable loss, softer handover, power etc.

Morphology	Dense Urban		Urban	
Duplex Mode	FDD		FDD	
System Bandwidth (MHz)	20		20	
Max Total Tx Power (dBm)	23	46	23	46
Subcarrier Power (dBm)	6.19	15.21	6.19	15.21
Tx Antenna Gain (dBi)	0	18	0	18
Tx Cable Loss (dB)	0	0.5	0	0.5
Tx Body loss (dB)	0	0	0	0
EIRP per Subcarrier (dBm)	6.19	32.71	6.19	32.71
SINR (dB)	-2.21	-3.42	0.51	-2.84
Rx Noise Figure (dB)	2.3	7	2.3	7
Receiver Sensitivity (dBm)	-132.15	-128.66	-129.43	-128.08
Rx Antenna Gain (dBi)	18	0	18	0
Rx Cable Loss (dB)	0.5	0	0.5	0
Target Load	50.00%	100.00%	50.00%	100.00%
Interference Margin (dB)	0.94	5.41	1.97	5.99
Penetration Loss (dB)	19	19	15	15
Area Coverage Probability	95.00%	95.00%	95.00%	95.00%
Path Loss (dB)	126.42	127.48	128.11	131.76
Propagation Model	Cost231-Hata		Cost231-Hata	
eNodeB/UE Antenna Height (m)	25	1.5	30	1.5
Frequency (MHz)	1800	1800	1800	1800
Cell Radius (km)	0.41	0.44	0.59	0.75

Table 4.2 LTE Link Budget as used by the Low Level Design (LLD) mobile network design in Addis Ababa [31].

The LTE frequency bandwidth is 20MHz, and the Uplink is from 1727.5MHz to 1747.5MHz, the Downlink is from 1822.5MHz to 1842.5MHz.

Operator	Bandwidth	1800M			
		Uplink		Downlink	
Ethio Telecom	1800	1710~1747.5		1805~1842.5	
	GSM	1710-1727.5		1805-1822.5	
	LTE bandwidth		1727.5-1747.5		1822.5-1842.5

Table 4.3 LTE Frequency Planning [31].

Since the Ethio Telecom has planned the operating frequency to be far away from television transmission frequencies, as there is no frequency spectrum scarcity in the country, it's difficult to have a clear picture of the interference that would exist between the two systems. As described in the objective section of this study, the situation involves scenarios where more telecom operators and broadcasters come into play and realize proper frequency planning beforehand.

For this reason, we will be dealing with a more general parameters used for LTE planning as shown below and treat them using various propagation models.

Parameter	Description
Bandwidth	7 MHz, 8 MHz
Frequency	758 to 830 MHz 830 to 862 MHz
Transmitting Mode	8k, 16k, 32k normal (channel 7 MHz),
Guard Interval	1/4, 1/8, 1/16, 1/32, 1/128, 19/128, 19/256
Code Ratio (PLP)	3/5, 2/3, 3/4, 4/5, 5/6
Constellation (PLP)	64 QAM, 256 QAM both with and
Pilot Pattern	PP2, PP3, PP4, PP5, PP6, PP7
Length of the FEC framework	64800 (long)

Table 4.4 Common Parameters for DVB-T2 Broadcast [4,5,7].

Consequently, the following parameter on the DVB-T2 technology can be employed in analyzing the coexistence scenario with the LTE system.

Parameter	DVB-T2(BS)		DVB-T2(SS)	
	Rural	Urban	Rural	Urban
Transmitted Power(dBm)	91.56	85.15	-----	
Bandwidth(MHZ)	8			
Height(m)	350	300	10	
Antenna Pattern			DVB-T ITU-R BT.419	
Gain(dBi)	0		14.15	
Noise Figure(dB)	-----		7	
Coverage Radius(Km)	80.5	70.53	-----	
Sensitivity(dBm)	-----		-78	-82
Thermal Noise(dBm)	-----		-98	
Propagation Model	Extended Hata Model			
Network Type	RN1	RN3	-----	
C/N(dB)	21	17	-----	
C/I(dB)	27	-30	-----	

Table 4.5 Typical deployment parameters of DVB-T2 [4,5,7].

Parameter	Unit	LTE	
		MS	BS
Antenna input Power	dBm/channel	23	58
Operating Frequency	MHz	791-862	
Receiver bandwidth	MHz	4.5,	4.5, 9, 13.5 and 18
Channel bandwidth	MHz	5, 10,	5, 10, 15 and 20
Reference System noise figure (taken from values quoted in standards)	dB	9	5
Reference Noise level (taken from values quoted in standards)	dBm/channel	-98 in 5	-102 in 5 MHz -99 in 10 MHz
Reference Receiver Sensitivity (taken from values quoted in standards)	dBm/channel	-100 in 5 MHz	-101.5
Interference criterion I (C/(N+I))	dB	-3	
Interference criterion II (I/N)	dB	-6	
Maximum antenna gain	dBi	0	15
Antenna height	m	1.5	20 to 30
Antenna Pattern			ITU-R F.1336,K=0.7

Table 4.6 Typical deployment parameters of LTE [4,5,7].

4.2 Interference Scenarios

With the typically used implementing parameters of the LTE-broadband and DVB-T2 broadcast systems, all the possible interference scenarios that might appear between them can be described as indicated in Chapter II. The cases studied make use of the Extended Hata and the Longley-Rice Terrain Propagation Model with good approximation of terrain parameters for Addis Ababa city.

The Java program used for this model has been built in the SEAMCAT software and the required input parameters in the model are shown below as they appear in the software interface. The source code of the Java plug-in used in this study is available over the internet [32]. As indicated in Chapter III, the radio climate region, irregularity parameter, conductivity, relative permittivity and other terrain parameters must be at least approximately determined for the region where the deployment of these systems is supposed to take effect.

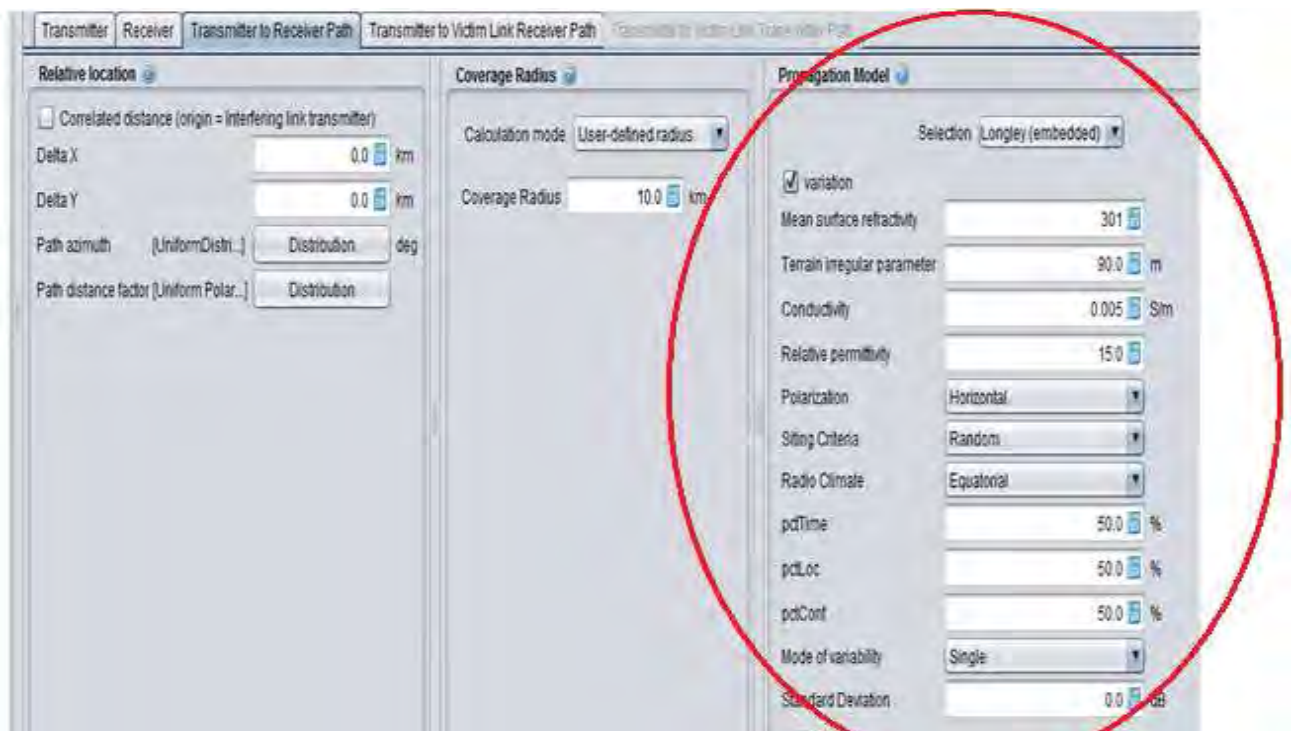


Fig. 4.1 Longley Rice propagation Parameters.

For the Addis Ababa city that has been dealt in this analysis, we have the following figures.

Parameter	Value
Radio Climate	Equatorial
Mean Surface Refractivity	301
Terrain Irregular Parameter	90
Soil Conductivity	0.005(S/m)
Relative Permittivity	15

Table 4.7 Common Terrain Parameters for Addis Ababa City [33,34].

Entering all the necessary parameters in the SEAMCAT simulation tool and allowing the program to generate a number of signals, the interference scenario produces the desired outline showing the minimum distances that must be maintained between the two system elements to avoid interference. OFDMA access method parameters

are entered for the LTE transmitter and receiver in each of the cases. And the first section of the outline for all the four cases indicates the simulations made using extended Hata propagation model, whereas the second section is for the Longly-Rice terrain model.

Case I The LTE BS interfering the DVB terminal (DVB SS) as the LTE BS communicates with its corresponding MS and the DVB transmitter's signal is received by the DVB terminal.

In this case, the LTE BS-LTE MS forms the interfering link whereas the DVB BS-DVB SS forms the victim link. The simulation is made by entering the distance between the LTE-BS and DVB-BS to be 5Km from each reference axis. The simulation outline also shows the dRSS, iRSS unwanted and iRSS blocking pdfs that might arise from the given input parameters tested with 20,000 randomly generated events.

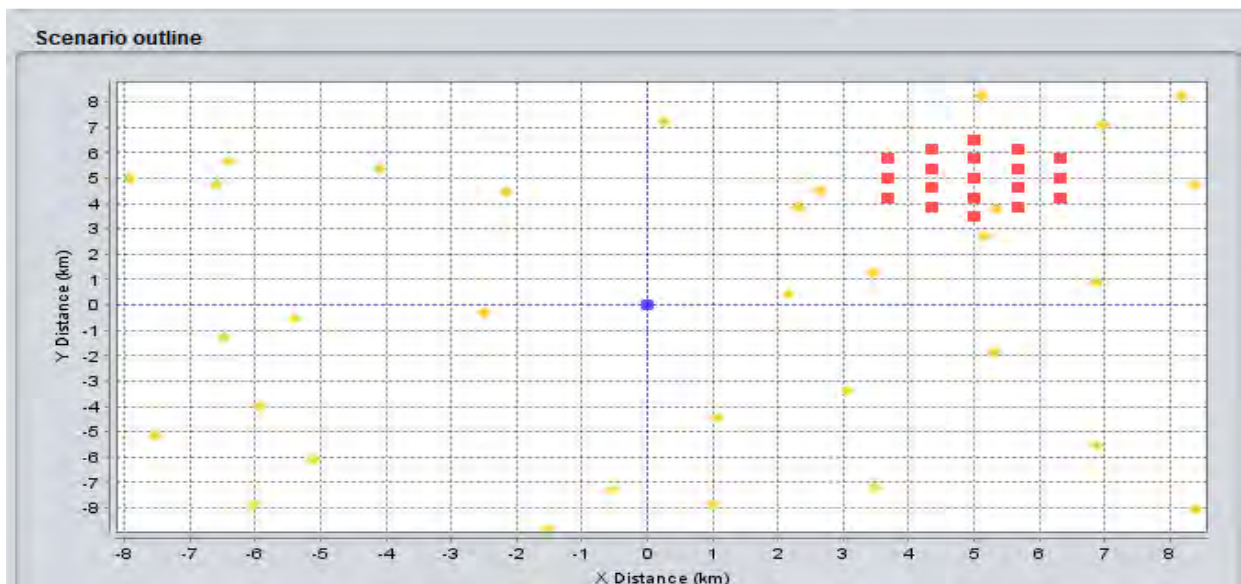


Fig. 4.2 Simulation of Case I.

In this case the red dots represent the LTE-BS transmitters, with the reference position of DVB-transmitter, represented by the blue dot. The yellow dots represent the DVB-receivers.

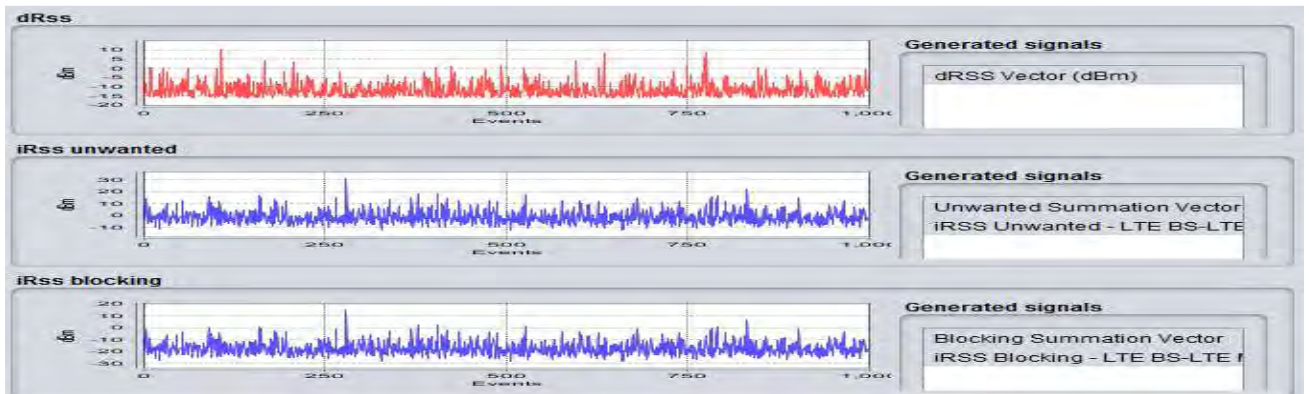


Fig. 4.3 dRSS, iRSS unwanted and iRSS blocking for the given input parameters.

- **Case II** The LTE MS interfering the DVB SS as it transmits towards its corresponding BS in uplink mode. In this case, the victim link is formed by DVB BS-DVB SS with DVB SS as a victim receiver and DVB-BS as a wanted transmitter whereas the interfering link is LTE MS-LTE BS having LTE MS as an interfering transmitter and LTE BS as wanted receiver.

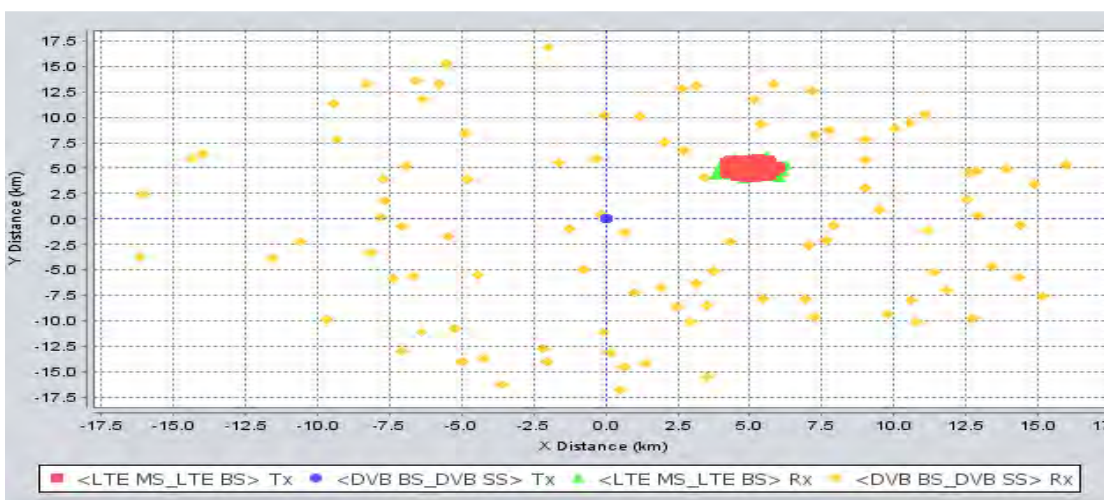


Fig. 4.4 Simulation outline showing the scenario of Case II for Generic Systems.

Note that the red dots in the outline indicate the LTE MS (the interferer) and the green dots the LTE BS (the desired receiver) , the blue reference dot of the DVB BS(desired transmitter) and the yellow dots of the DVB SS(victim receiver). The assumption is that the DVB transmitter covers an area of 17Km radius and each LTE BS spans 0.44 Km radius. The MS are considered as generic wireless system in the simulation as the complexities required by OFDMA BS are not applicable for them. It's assumed also that the LTE BS is at least 5Km away from both axes of the DVB-BS position.

- **Case III** The DVB BS interfering the LTE BS. In this case DVB BS-DVB SS forms an interfering link whereas LTE BS-LTE MS becomes a victim link. This means, DVB BS is an interferer, DVB SS a wanted receiver, LTE BS a victim receiver as it receives desired signal from LTE MS in uplink which makes the LTE MS the desired transmitter.

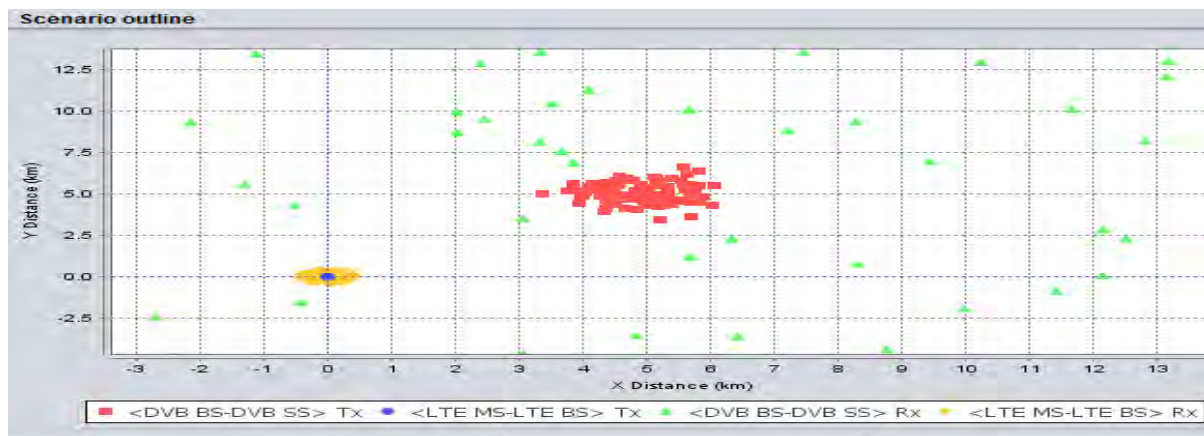


Fig. 4.5 Simulation outline showing the scenario of Case III.

In the outline the red dots show the DVB BS(interfering transmitters) along with the green DVB SS(desired receivers) and the blue reference LTE MS(wanted transmitter)

and its corresponding yellow LTE BS(victim receivers). Again 5Km distance from each axis of the LTE-BS is spanned for the DVB-BS to settle.

- **Case IV** DVB BS interfering LTE MS as it broadcasts to corresponding DVB terminals (DVB SS) downlink. In this case the DVB BS-DVB SS forms the interfering link whereas LTE BS-LTE MS becomes the victim link. That means, we have DVB BS as an interfering transmitter with its corresponding desired receiver DVB SS. The LTE MS a victim receiver with a desired transmitter LTE BS in downlink.

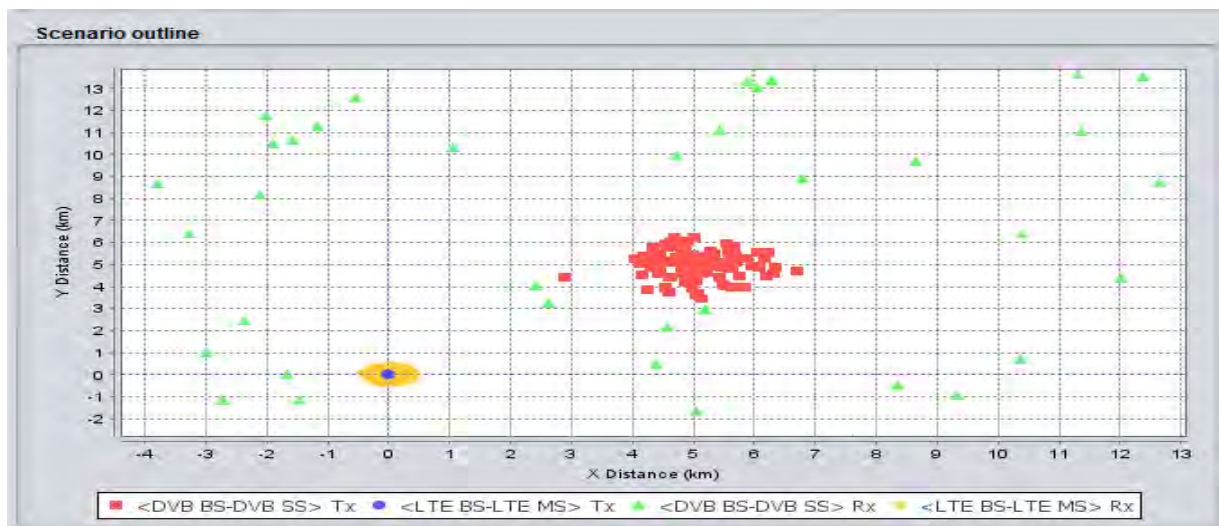


Fig. 4.6 Simulation outline showing the scenario of Case IV.

The outline indicates the red DVB BS(interfering transmitter) interfering the yellow LTE MS (victim receivers), green DVB SS (wanted receiver) and the blue reference LTE BS (wanted transmitter). Coverage radius for LTE BS is 0.44 Km and DVB BS is 5Km away from LTE BS on both axes. The software gives several information about each dot as we move the cursor towards it.

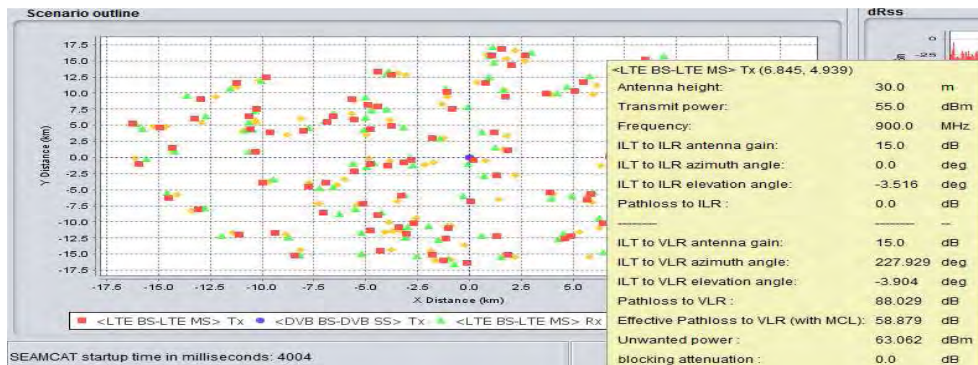


Fig. 4.7 Information about the dot representing a component in the scenario.

The following scenarios show the above cases made using Longley-Rice propagation model with terrain parameters for Addis Ababa City. With all other parameters kept similar, the scenarios for this kind of terrain based propagation model change interference situations as it's all illustrated in the section that deals about Mitigation Techniques.

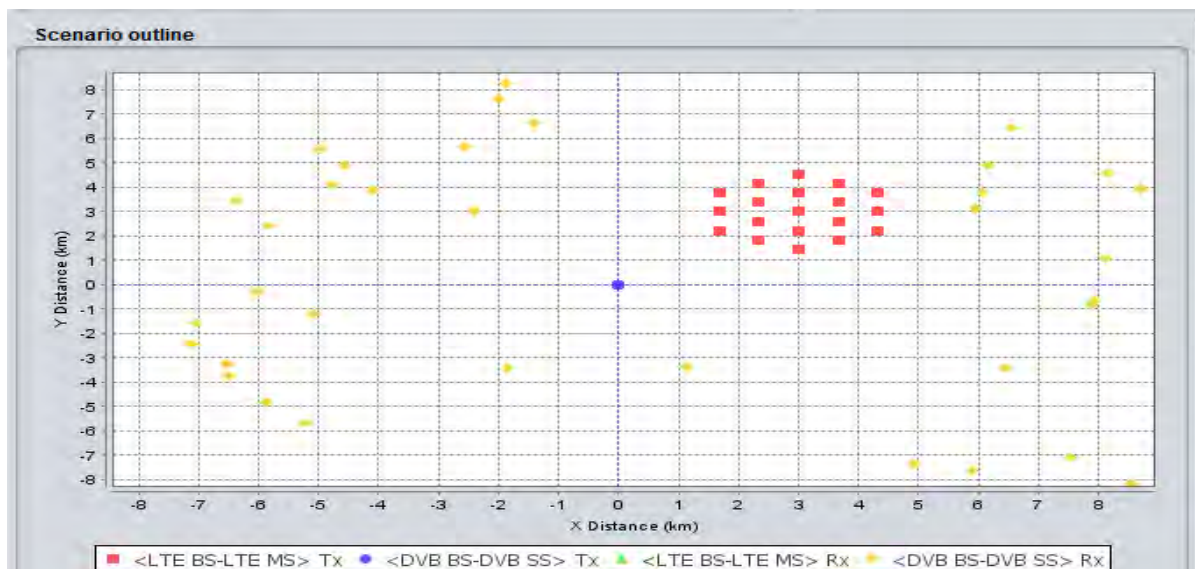


Fig 4.8 Simulation outline for Case I using Longley-Rice Terrain Propagation Model.

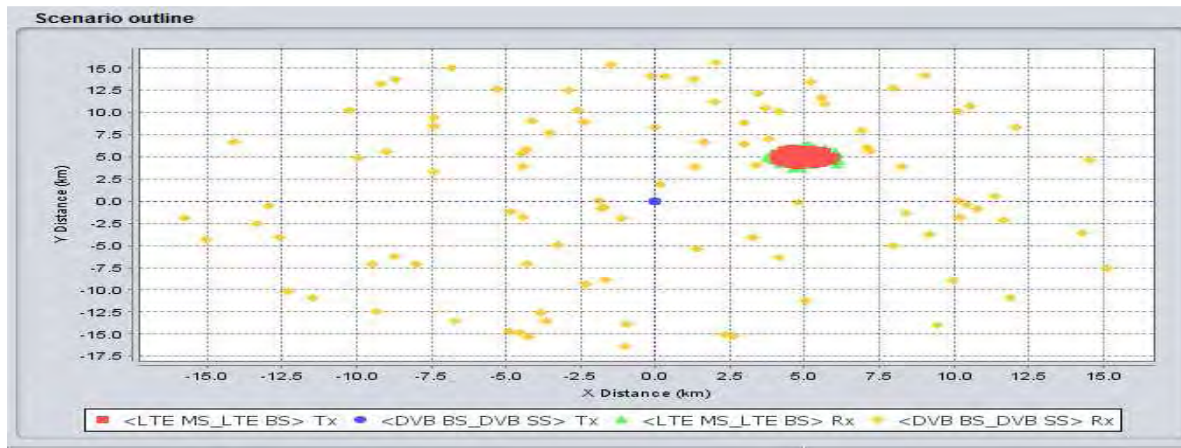


Fig 4.9 Simulation outline for Case II using Longley-Rice Terrain Propagation Model.

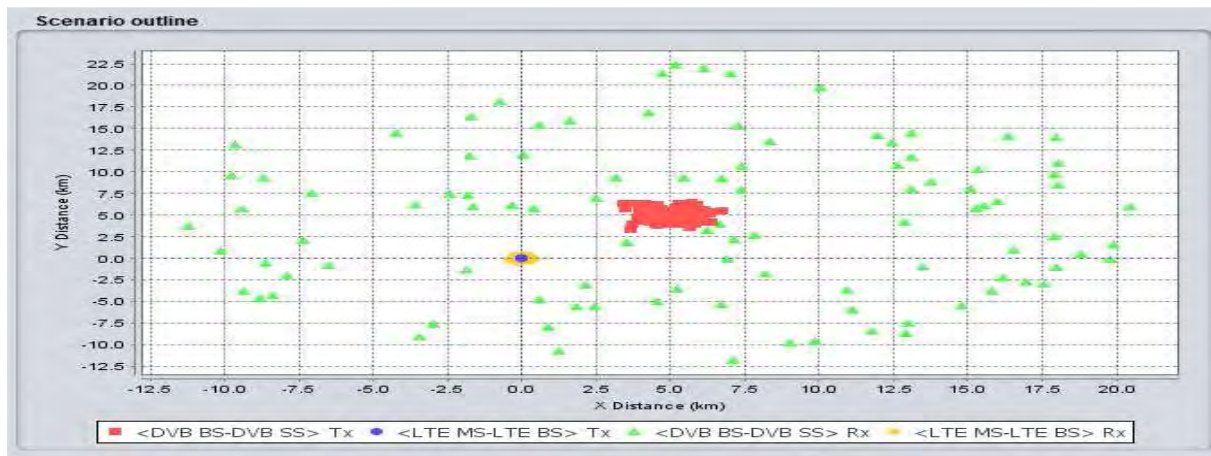


Fig 4.10 Simulation outline for Case III using Longley-Rice Terrain Propagation Model.

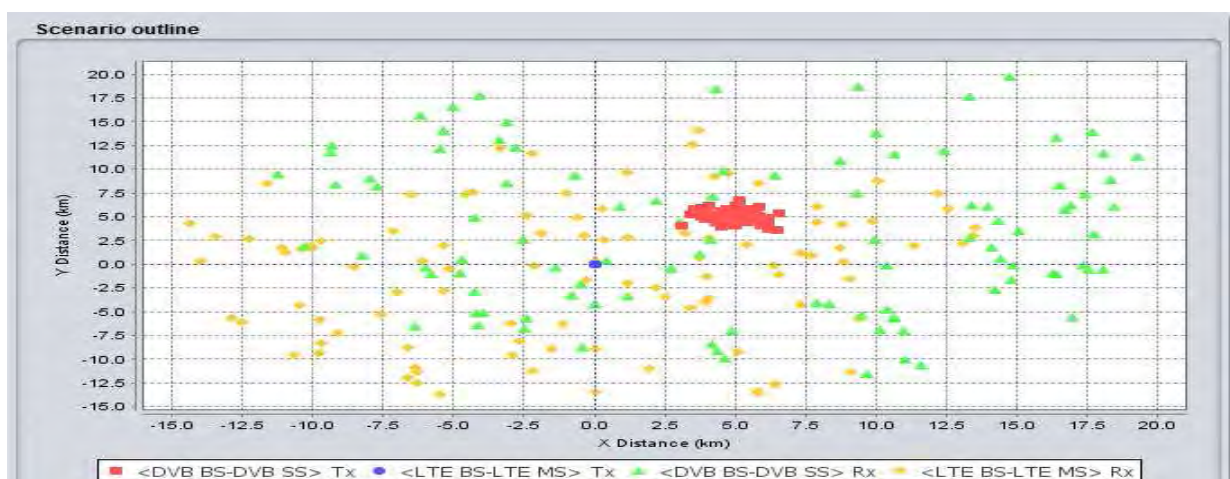


Fig 4.11 Simulation outline for Case IV using Longley-Rice Terrain Propagation Model.

The Simulation Reports for all cases are drawn by the program and the Report for Case I is shown in Appendix II as an example.

4.3 Interference Mitigation Techniques

Radio compatibility between systems can be achieved by studying the difference between desired and interfering signal levels that the victim receiver incurs. This study helps to draw a separation among the victim and interfering systems or services in geographical space or frequency domains. It has also been tried to see the effect of applying a cognitive radio access technique to mitigate the interference occurrence without using protection guard and hence the spectrum can be used more efficiently. As described in Chapter II, the most prominent interference mechanisms for analyzing situations in adjacent bands are the unwanted emissions from the transmitters together with the blocking and inter modulation levels subjected to the victim receiver.

The statistical Monte Carlo methodology implemented through the SEAMCAT program derives both the minimum separation distance(guard distance) and frequency distance(guard band) that must be maintained to realize operational compatibility between DVB-T2 broadcast and LTE-wireless broadband systems.

By varying the relative distance of the victim link from the interfering link on "Transmitter to Victim Link Path" tab of the "interfering link" section of the SEAMCAT interface, the level of those determining parameters would be evaluated.

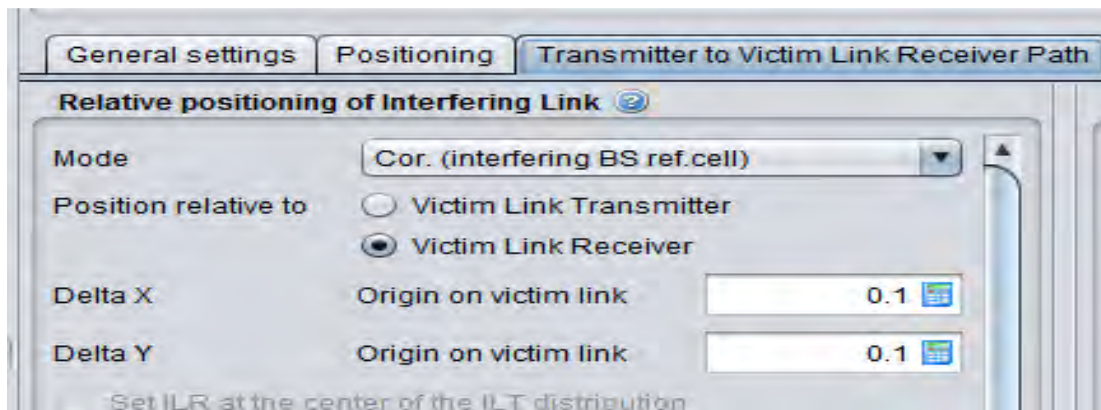
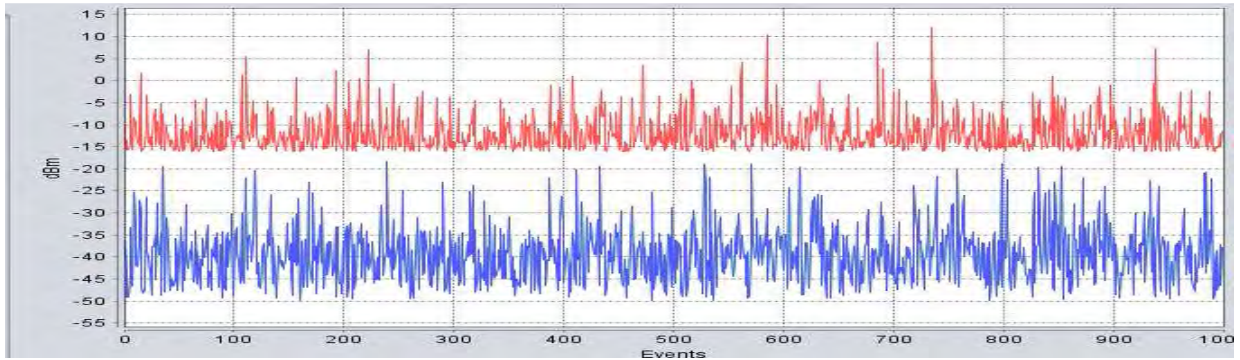


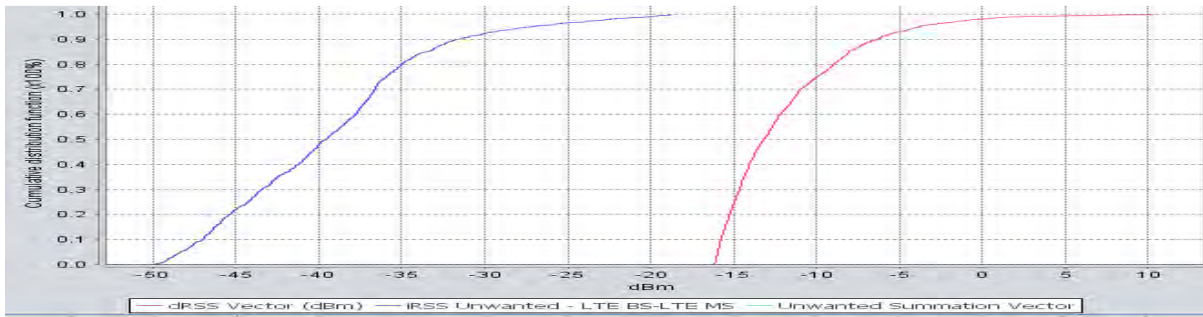
Fig. 4.12 Relative position of interfering transmitter with respect of the victim receiver.

The simulations, therefore, examine the probability of interference for various separation distances given a specific frequency and power limitation. SEAMCAT checks if the calculated SIR ratio received by the victim receiver to be greater than C/I_{target} , which is set as the minimum allowable threshold. The allowable threshold is expressed in the simulation in one of four criteria, C/I , $C/(I+N)$, $(N+I)/N$ and I/N .

To achieve the threshold, we consider different distances for different powers by changing the distance between the interfering transmitter and the victim receiver for the various cases discussed above. In each case shown above, the desired Signal Strength($dRSS$) and interfering Receiver Signal Strength($iRSS$) received by the victim receiver are drawn by the simulation. The results show how varying protection distance, defined either by a physical distance or guard band, affects the levels of the two kinds of signals that the victim receiver acquires. The probability of interference by interfering transmitter can also be shown along with this parameters from the translation mode of the simulation.



A



B

Fig. 4.13 A dRSS in dBm and iRSS in dBm for a Victim receiver in Case I.

B Cumulative probability of dRSS and iRSS at 3Km guard distance between interfering transmitter and wanted transmitter for Case I.

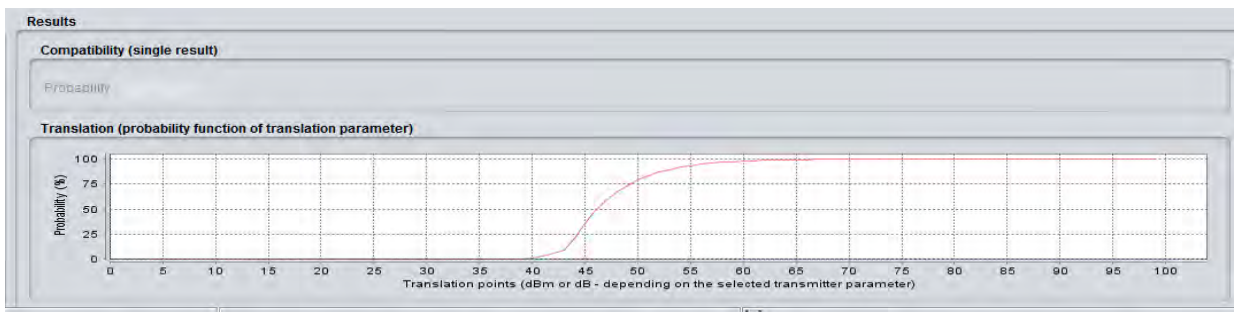


Fig. 4.14 Probability function of the interfering transmitter at a 0.1Km guard distance from each axes of the victim link receiver for Case I.

The Probability function drawn in the translation mode clearly shows the variation of the interference probability as guard distance and guard bands change.

For **case I**, the LTE transmitter uses a center of frequency of 826MHz with reception bandwidth of 10MHz. And the DVB transmitter transmits with a frequency of 822MHz with 8Mz bandwidth forming an overlap with the LTE system. The two systems are separated by a minimum distance of 0.1Km measured from each axes of the victim receiver to the interfering transmitter.

Maintaining the distance between them and varying the guard band by reducing the bandwidth of the LTE to 5MHz and DVB to 2MHz, the following probability function of interfering transmitter arises. This forms a 0.5 MHz guard band between the two systems.

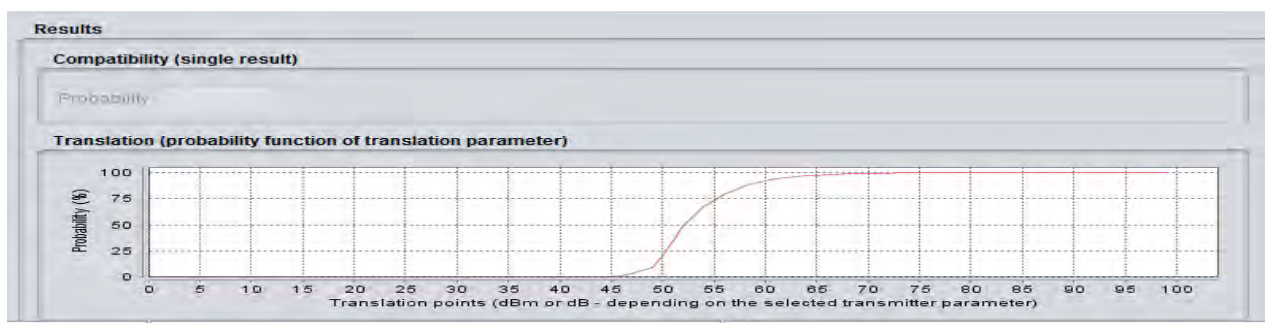


Fig. 4.15 Probability function of the interfering transmitter at a 0.1 Km guard distance from each axes with 0.5 MHz guard band for Case I.

Figure 4.15 shows how the interference probability reduces by increasing the guard band. On the other hand, keeping the frequency parameters and increasing the guard distance is evidenced by the probability function outline to reduce the interference effect.

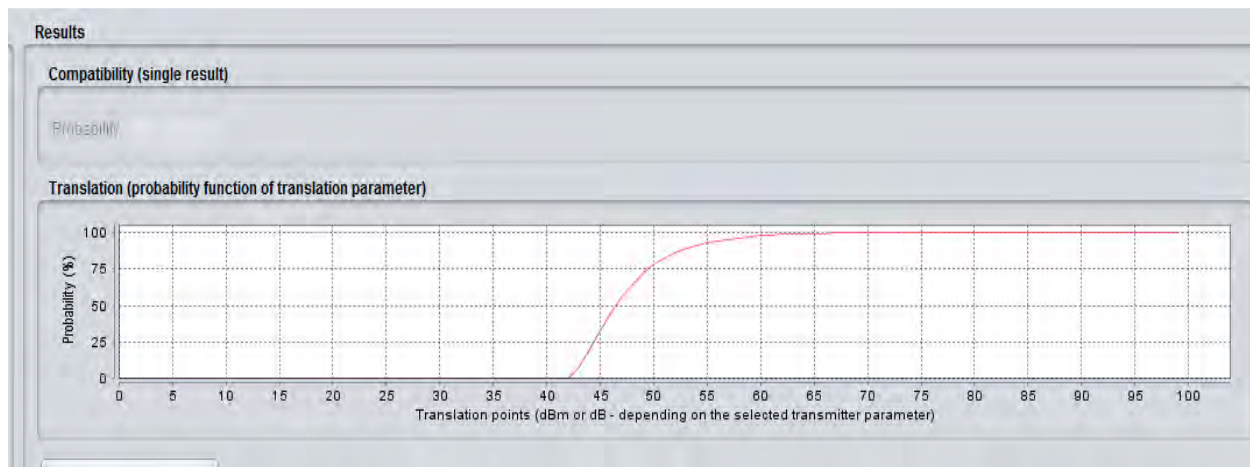


Fig. 4.16 Probability function of the interfering transmitter at a 0.4 Km guard distance from each axes with the original overlapping bandwidth settings for the two systems in Case I.

The same analysis drawn for all the cases using different propagation models help determine the separation geographical distances and guard bands for realizing compatibility and coexistence of the two wireless systems.

The other interference mitigation technique involves spectrum sensing by using what is called Cognitive Radio(CR) access method. The main idea in spectrum sensing is that the performance of one radio system in a given band can be optimized by letting it detect the existence or absence of another radio system in that band and use the free spectrum for itself. If we take Case I where the LTE-BS transmitter interferes the DVB-SS receiver, the CR access method enables the LTE system to detect the underutilized spectrum bands of the DVB system. Cooperative and non-cooperative methods are the two ways by which spectrum system can efficiently be used by a radio system.

Cooperative CR requires the two radio systems to exchange information during the time of spectrum usage necessitating the development of a protocol for the communication. On the other hand, the non-cooperative sensing scheme enables a

radio system to sense the environment and decide by itself without establishing any sort of communication with other spectrum users [35,36].

In this modeling for Case I, the interfering transmitter(LTE-BS) detects a sensing signal from the wanted transmitter(DVB-BS) and checks if the level of the sensing signal is less than the threshold set by its system. If it's so, the LTE-BS can send the signal to its desired receiver(LTE-UE) otherwise, it will stay idle. It can be said that CR is a way to find unused and underutilized spectrum band and make a decision to use the spectrum.

All the applicable calculations and algorithms are used by the SEAMCAT analysis tool. However, we are only required to enable the 'CR' checkbox for the systems to tell the program that the systems use the access method. In doing so, the program evaluated the interference probabilities when CR is used. It can be seen that the probability of interference declines considerably by applying this technique to the considered radio systems.

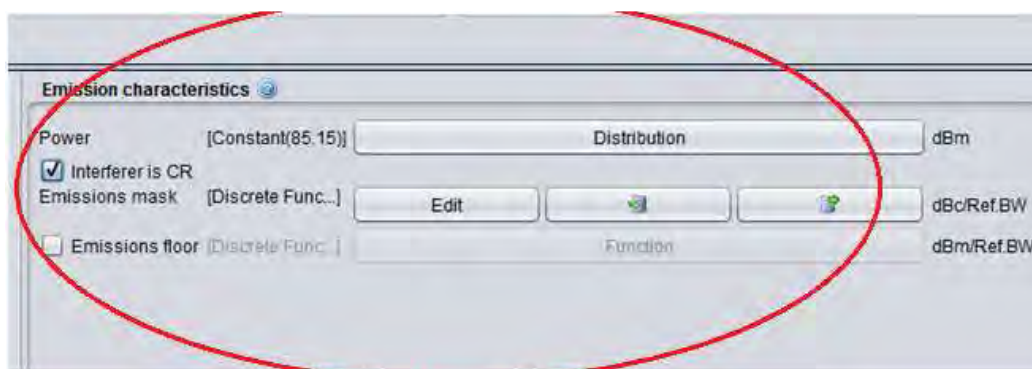


Fig. 4.17 CR access method enabling check box on SEAMCAT program.

The following outline shows the interference probability caused by the LTE-BS transmitter on DVB-SS receiver when CR access method is used. The victim and the interferer are 0.4Km apart from both axes and the overlapping frequency bands are

used as shown in Case I. From the outline, the interference can be seen as extremely unlikely as a result of cognitive radio spectrum sensing applied on the LTE-BS.

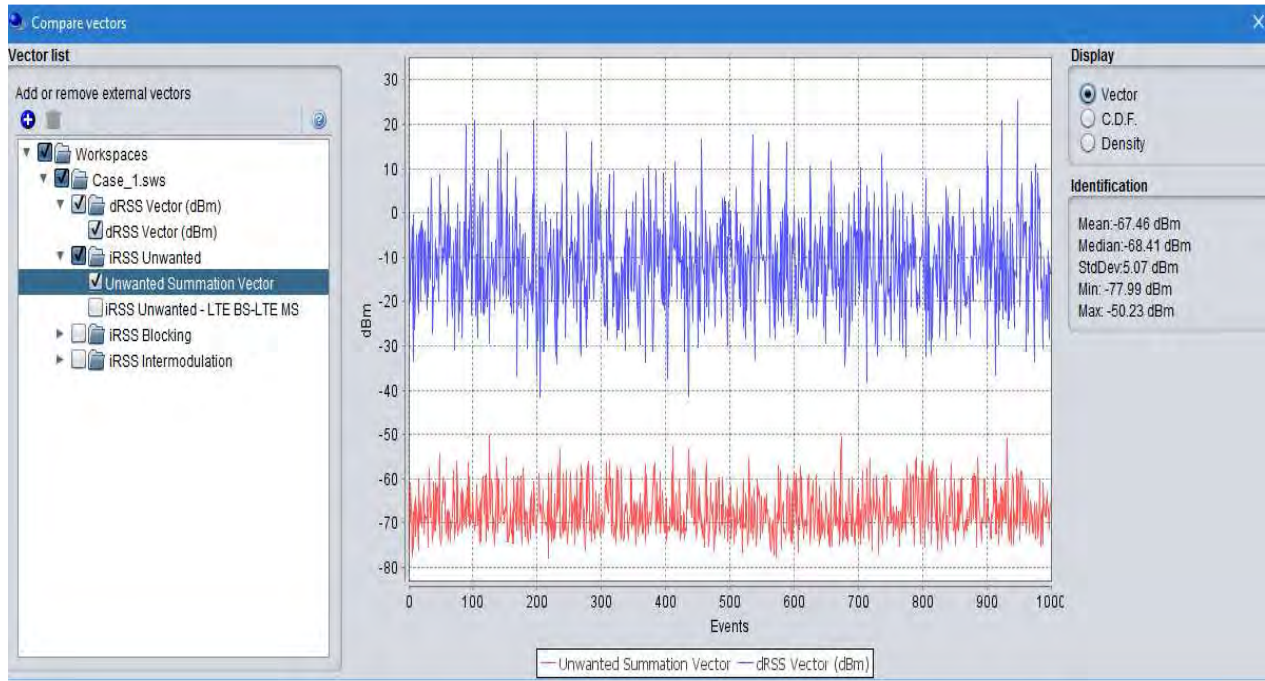


Fig. 4.18 dRSS and iRSS on the victim receiver for Case I with CR used at the interferer, LTE-BS.

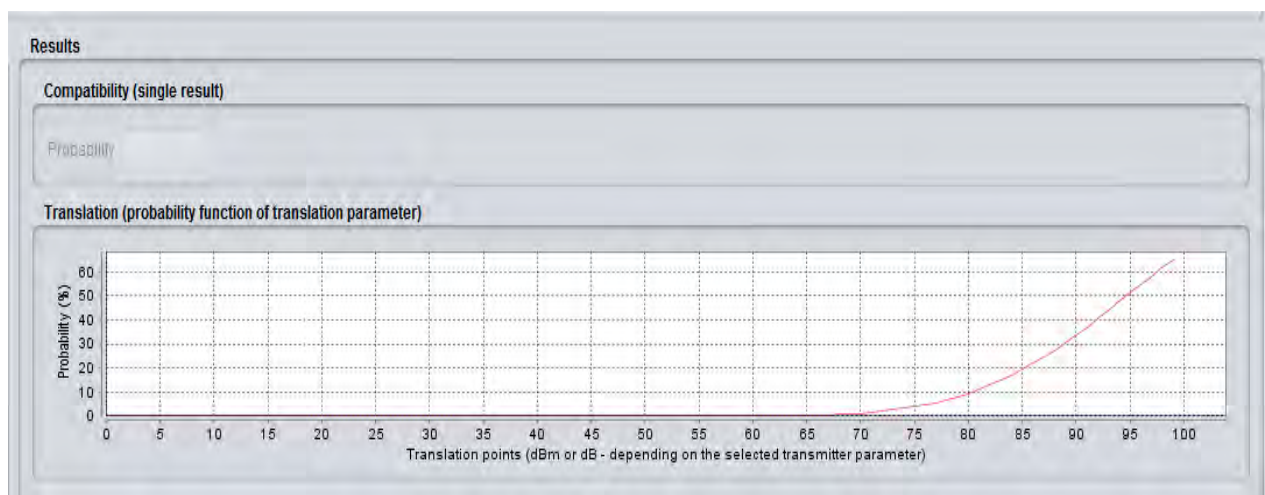


Fig. 4.19 Probability of interference by the LTE-BS for Case I with CR used.

4.4 Proposed National Frequency Plan for Telecom and Broadcast services

Currently MCIT, a government body responsible for spectrum issues, uses the frequency spectrum map shown in Figure 4.22 for various wireless systems to operate in. The Map was prepared in 2001 in agreement with international spectrum laws and the country's telecommunication proclamation. It is understood that ITU is working closely with the ministry to facilitate the Analogue to Digital transition so that a convenient digital dividend will be produced. The challenge in digital transition is the highly dispersed bands occupied by analogue radio services. In fact, the interest of this study is wireless broadband and broadcast services that can operate in the 700 MHz and above region. The plan of creating a digital dividend requires making free all the bands that have been occupied by the present analogue broadcasting services. After a feasible digital dividend has been created, it's possible to section bands for different radio services.

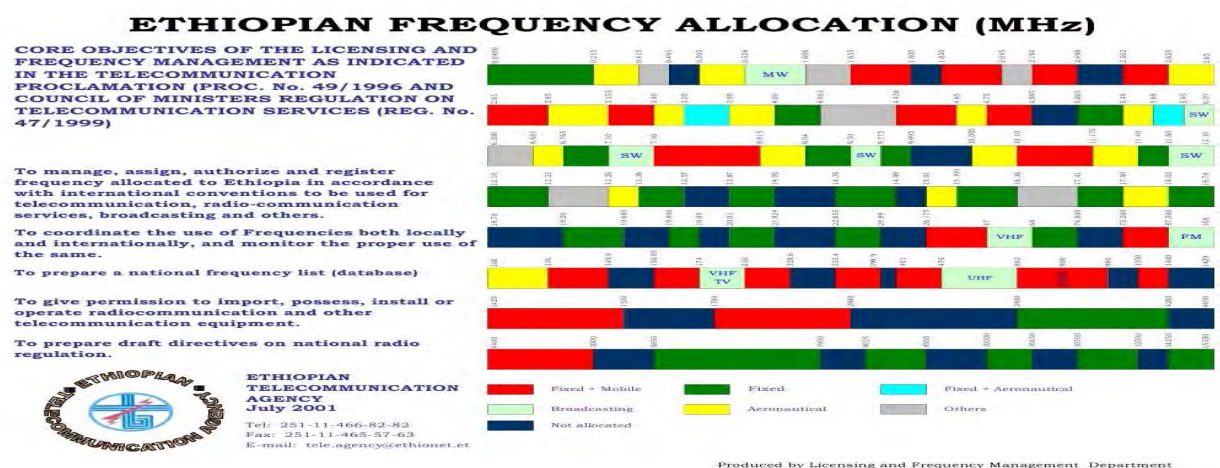


Fig.4.20 Frequency Spectrum Map of Ethiopia ratified by the then Ethiopian Telecommunication.

The area that interests this study is the region between 470MHz-1429 MHz. It is shown that the band 470-862 MHz allocated for the currently existing UHF TV broadcast.

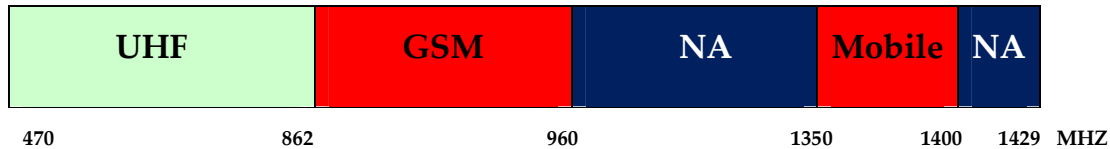


Fig. 4.21 Bands of interest for Mobile Broadband and Digital Television.

The 'NA' refers to 'Not Allocated' band and GSM refers to the band allocated for the first 2nd Generation circuit switched digital cellular phones in Addis Ababa by the time this spectrum table was developed. The 'Mobile' refers to the band allocated to be given for future mobile phone deployments again by the time this table was developed. The first thing to do is to merge these dispersed regions into one. As there are wasted regions in 'NA', 'UHF' and 'Mobile' bands.

As discussed in Chapters One and Two, one of the advantages of having a digital broadcast television channels is its efficiency in the spectrum. For instance, an 8MHz bandwidth used for terrestrial digital television transmission supports 20 digital TV channels, which is a big efficiency compared to one channel supported by analogue terrestrial TV of the same bandwidth.

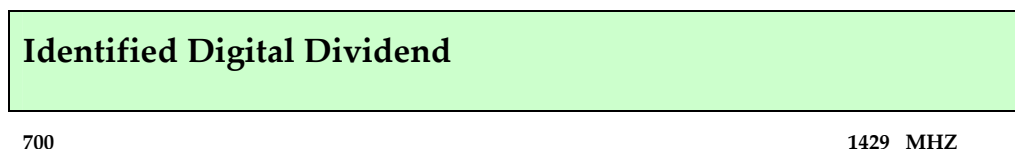


Fig. 4.22 Proposed Digital Dividend for Ethiopia wireless system platforms.

This region is identified as a digital dividend because the current technologies related to Digital TV broadcast and LTE broadband make use of frequencies found in this region.

It can be sectioned into two regions for the two systems separated by a 5MHz guard band. The LTE-Broadband can further be planned for accommodating more service providers and ensuring compatibility among their handover technologies.

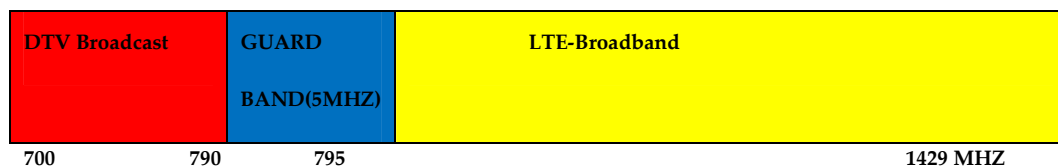


Fig. 4.23 Proposed DTV and LTE Bands.

Using TDD and FDD duplexing techniques respectively for OFDMA type modulation LTE system, the following band plans can be proposed for a single LTE wireless system.

790-795 MHz Guard Band	795-	800-	805-	810-	815-	820-	825-	830-	835-	840-	845-	850-	855-	860-
	800	805	810	815	820	825	830	835	840	845	850	855	860	865
14 blocks of 5MHz(70MHz),Unpaired														

Fig. 4.24 TDD duplexing implementation.

790-791 MHz	791-	796-	801-	806-	811-	816-	821-832	832-	837-	842-	847-	852-	857-	862-
	796	801	806	811	816	821		837	842	847	852	857	862	867
Guard Band	Downlink						Duplex Gap	Uplink						
1MHz	6Blocks of 5MHz(30MHz)						11MHz	6Blocks of 5MHz(30MHz)						

Fig. 4.25 FDD duplexing implementation.

Chapter Five: Conclusion and Recommendation

5.1 Conclusion

Wireless communication systems are increasing at a tremendous rate from time to time in response to sophisticated software applications that require high bandwidth for their data transfer. Frequency spectrum is one of the most important resources that face strain as a result of the progress in this area. For this reason, there needs to be a proper planning of this scarce resource so that different wireless systems operate orderly and without affecting each other.

It is believed that the digital dividend is the best solution to manage the problem that might arise in frequency spectrum scarcity. This study attempts to show how a digital dividend can be realized for wireless systems in Ethiopia. It also shows the mitigation methods for possible interferences between digital television and mobile broadband systems.

The thesis indicates what will happen in the country when more telecom operators begin providing services and more terrestrial television channels air in the future. Radio planners do the work of studying the spectrum nature of the medium in relation to the standards of the equipments they use for implementing their system.

In this thesis, the coexistence between the two major systems, digital terrestrial television and wireless broadband has been studied for the case of Ethiopia. In

regards to the coexistence study, the frequency plan has been suggested. The mitigation techniques used have been compared each other.

The separation in geographical distance versus the guard band between the two systems gives a good insight in proper planning of the spectrum. Moreover, the application of frequency sensing on the wireless systems help to bypass the restrictions laid on separation distances and guard band and gives more efficiency in utilizing the frequency spectrum. This method, if used together with the two mitigation methods, decreases interference and enables to use the available spectrum more efficiently.

The Monte Carlo statistical approach performs an interference analysis by using the stochastic nature of wireless signals. This study makes use of the SEAMCAT software that generates many signal samples and evaluates them based on the Monte Carlo approach.

The results in this study give a valuable indication on applicability of the freed spectrum as a result of digital dividend and show the required guard band. The acquired compatibility results can be used by National Regulatory Authorities, telecom operators when planning mobile services.

5.2 Recommendations

Radio planners make a detailed analysis about their spectrum requirements. Spectrum sensing using cognitive radio access method can be studied in detail to further improve efficient utilization of the spectrum.

Antenna patterns, antenna discrimination, spatial LTE planning in relation to DVB system, down tilting of antenna are some of the things which can be adjusted and varied to come up with best interference free scenarios.

What is done in this network shows only two propagation models called Extended Hata and Longley-Rice Terrain model for the City of Addis Ababa. The SEAMCAT program integrates a terrain model written using a Java program. The SEAMCAT programmers will come up with the software's capability of supporting Digital Terrain Map in the future. Therefore, the study can be expanded for other towns and cities of the country. Moreover, the interference between wireless broadband and unlicensed indoor wireless devices like wireless microphone, Bluetooth devices etc can be analyzed.

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Appendix I

$$\left[\frac{N+I}{I}\right]_{\text{dB}} = \left[\frac{N+I}{N}\right]_{\text{dB}} - \left[\frac{I}{N}\right]_{\text{dB}}$$

Proof:

$$\begin{aligned} 10 \log \frac{N+I}{I} &= 10 \log(N + I) - 10 \log I + 10 \log N - 10 \log N \\ &= 10 \log(N + I) - 10 \log N - (10 \log I - 10 \log N) \\ &= 10 \log \frac{N+I}{N} - 10 \log \frac{I}{N} \end{aligned}$$

That is, $\left[\frac{N+I}{I}\right]_{\text{dB}} = \left[\frac{N+I}{N}\right]_{\text{dB}} - \left[\frac{I}{N}\right]_{\text{dB}}$

$$\left[\frac{C}{N+I}\right]_{\text{dB}} = \left[\frac{C}{I}\right]_{\text{dB}} - \left[\frac{N+I}{I}\right]_{\text{dB}}$$

Proof:

$$\begin{aligned} 10 \log \frac{C}{N+I} &= 10 \log C - 10 \log(N + I) + 10 \log I - 10 \log I \\ &= 10 \log C - 10 \log I - (10 \log(N + I) - 10 \log I) \\ &= 10 \log \frac{C}{I} - 10 \log \frac{N+I}{I} \end{aligned}$$

That is, $\left[\frac{C}{N+I}\right]_{\text{dB}} = \left[\frac{C}{I}\right]_{\text{dB}} - \left[\frac{N+I}{I}\right]_{\text{dB}}$

Appendix II

SEAMCAT® Simulation Report

Workspace reference: Case_1.sws

Simulation Scenario:

Victim Link

General: *Reference DVB BS-DVB SS*

Description:

Frequency: *Constant(822.0) MHz*

CDMA/OFDMA: *False*

Victim Link Receiver: *Reference DVB SS_RX*

Description

Antenna Height: *Constant(10.0) meters*

Antenna Azimuth

Antenna is pointing at its transceiver in the azimuth domain

Antenna Elevation

Antenna is pointing at its transceiver in the elevation domain

Blocking Mode

Sensitivity: *-103.0 dBm*

Reception bandwidth: *8000.0 kHz*

Use Power Control Threshold: *false*

Use Receiver Overloading: *false*

C / I: *19.0 dB*

C / (N + I): *16.0 dB*

(N + I) / N: *3.0 dB*

I / N: *0.0 dB*

Intermodulation Rejection: *Constant Function 0.0*

Blocking Mask Constant Function: *0.0*

Noise Floor Constant: *(-110.0)*

Antenna:

Reference: *DVB-T ITU-R BT.419*

Description: *Pattern based on ITU-R BT.419*

Peak gain based on

Peak Gain: 14.15 dBi
Use Horizontal Pattern: true
Use Vertical Pattern: true
Use Spherical Pattern: false

Victim Link Transmitter Reference DVB BS_TX

Description

Antenna Height: Constant (300.0) meters

Antenna Azimuth

Antenna is pointing at its transceiver in the azimuth domain

Antenna elevation

Antenna is pointing at its transceiver in the elevation domain

Power (dBm): Constant(85.15) dBm

Use CR features

Antenna:

Reference DEFAULT_ANT

Description:

Peak Gain: 0.0 dBi

Use Horizontal Pattern: false

Use Vertical Pattern: false

Use Spherical Pattern: false

Victim Link Transmitter to Victim Link Receiver Path Use Correlated distance false

Delta X:0.0

Delta Y:0.0

Path Azimuth: Uniform Distribution(0.0, 360.0)

Path distance factor: Uniform Polar Dist. Distri(1.0)

Coverage Radius Calculation Mode: User-defined radius

Coverage Radius (km): 17.0

Propagation Model:

Selected model: Plugin

Library plugin-class: LongleyRicePlugin_ver1 (embedded)

General Environment: Urban

User defined parameter1: 301

User defined parameter2: 90.0

User defined parameter3: 0.005

Interfering CDMA or OFDMA System 1

General settings

Component reference DEFAULT_Network

Component description

Technology: *ofdma_lte*

Link direction: *Downlink*

Frequency: *826.0*

SINR Minimum: *-1000.0*

Max subcarriers per Base Station: *51*

Number of subcarriers per mobile: *17*

Receiver Noise Figure: *4.0*

Handover Margin: *3.0*

Minimum Coupling Loss : *70.0*

System bandwidth: *10.0*

Bandwidth of Resource Block: *180.0*

Link Level Data

Link Specific Settings

Emissions Mask (MHz, dBc, kHz)

Use Unwanted emissions floor: *false*

Basestation Maximum Transmit Power: *24.0*

Capacity

Users per Base Station: *20*

System Layout

Network Wrap-Around Model: *true*

Wrap-Around option *true*

Positioning

Number of Base stations in the system: *19*

Cell Layout *2-tier, Tri-Sector*

Grid Layout *3GPP-2 grid layout*

Cell Radius: *0.44*

Base Station:

Antenna Height: *Constant(30.0)*

Antenna Tilt: *Constant(3.0)*

Antenna:

Reference ITU-R.F1336 17 dBi k=0.7

Description: *Microcell BS antenna*

Only valid for Freq < 3GHz

Peak Gain: *15.0 dBi*

Use Horizontal Pattern: *true*

Use Vertical Pattern: *true*