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COEXISTENCE BETWEEN DTV AND LTE IN THE 700 MHZ BAND

by

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AN ABSTRACT OF THE THESIS OF

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The introduction of LTE in the UHF band requires a careful analysis of the possibility of coexistence between the mobile service and the broadcasting service in the same or adjacent bands. In this paper, we analyze the coexistence between LTE and Digital TV in the 700 MHz in order to propose operation guidelines such that LTE does not cause any interference to the existing broadcasting service.

Our objective is to study the feasibility of the proposed Out of Band Emission requirements and their effect on the broadcasting service. We have shown that with the 3GPP proposed Out of Band (OOB) emission level of -25 dBm/8MHz, it is not possible to have coexistence under normal operating conditions. However, we show that this coexistence is possible when we use lower OOB levels that reflect higher restrictions on the LTE transmit power even without the use of additional filters.

We then propose alternate solutions to keep the initially proposed high OOB levels and still mitigate interference by having reduced DTV capacity or equivalently lower required signal to noise ratio (SNR). Most importantly, we propose a new carrier aggregation method that allows us to reduce the level of interference obtained with low OOB restrictions. We also perform different analysis to show the effect of each operating parameter on coexistence and interference.

CONTENTS

Chapter

ILLUSTRATIONS

Figure

TABLES

Table

ABBREVIATIONS

ACI	Adjacent Channel Interference
ACIR	Adjacent Channel Interference Ratio
ACLR	Adjacent Channel Leakage Ratio
ACS	Adjacent Channel Selectivity
ADSL	Asymmetric Digital Subscriber Line
APT	Asia Pacific Telecommunity
BS	Base Station
C/I	Carrier to Interference
CEPT	European Conference of Postal and Telecommunications
DL	Downlink
dRSS	Desired Received Signal Strength
DTT	Digital Television Transmission
DTV	Digital Television
DVB	Digital Video Broadcasting
FFT	Fast Fourier Transform
IFFT	Inverse Fast Fourier Transform
IRSS	Interference Received Signal Strength
ISI	Inter Symbol Interference
ITU	International Telecommunications Union
LTE	Long Term Evolution

MCL	Minimum Coupling Loss
MS	mobile Station
MSD	Minimum Separation Distance
OFDM	Orthogonal Frequency Division Multiplexing
OOB	Out of Band
PPDR	Public Protection Disaster Relief
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase-Shift Keying
RSS	Received Signal Strength
RX	Receiver
SEM	Spectrum Emission Mask
SINR	Signal to Interference and Noise Ratio
SNR	Signal to Noise Ratio
TX	Transmitter
UE	User Equipment
UHF	Ultra High Frequency
UL	Uplink
WiFi	Wireless Fidelity
WiMax	Worldwide Interoperability for Microwave Access
WRC	World Radiocommunication Conference
3GPP	3rd Generation Partnership Project

Dedication

To God, who I've always counted on to carry me through life one success after the other,
thank you for all your countless blessings.

To Moussa, my husband and my friend,
To Mom and Dad,
thank you for supporting me and for tolerating me throughout these years as I pursued
academic and career goals.

*"One cannot escape the feeling that these mathematical
formulas have an independent existence and an intelligence
of their own, that they are wiser than we are, wiser even
than their discoverers…"*

Heinrich Hertz

CHAPTER 1

INTRODUCTION

The unprecedented exponential growth in mobile data has exceeded everyone's expectations. Mobile data traffic has increased by 81% in the year 2013 where data consumption reached 1.5 Exabytes per month [4]. .The initial International Telecommunication Union (ITU) studies have estimated that over 500MHz of additional spectrum is needed to support mobile broadband traffic by the year 2020 [37]. This additional spectrum is required in three band ranges:

- low bands <1GHz
- mid-to-high bands 1-3GHz
- high bands 3-6GHz

Among possible bands, the 700MHz band represents a significant amount of highly-desired spectrum for mobile broadband for the below reasons:

- better propagation characteristics and wider range of signals
- better building penetration
- coverage area 4x larger than that of 2.6 GHz [5]
- 45% improvement in cell-edge throughput and over 40% site reduction compared to LTE 1800 [5]

The 700MHz band (694-791 MHz) had been under study for allocation to the mobile service in ITU Region 1 under resolution 232. Other regions have already allocated this band for mobile communication systems. The main concern for a great number of Region

1 administrations is the coexistence of mobile in this band with the broadcasting service in the lower adjacent band 470-694 MHz. Administrations have been conducting studies to determine the minimum required Out of Band emission level as well as the required guard band and the minimum separation distances (MSD) between the two services such that no harmful interference is detected. At this point, there is a global consensus regarding the need for a 9 MHz guard band, however, the OOB limits and the separation distances are still a topic of argument [38].

The Asia Pacific Telecommunity (APT) region has adopted the plan in Figure 1for their 700 MHz band. The European Conference of Postal and Telecommunications Administrations (CEPT), however is currently using the 800 band which was allocated for mobile communication systems in WRC-12 [33]. There have been several proposed channeling arrangements for the 700 MHz band as shown in Figure 2. Administrations will have the option to adopt any channel plan they find suitable. Some of the proposed band plans include a specified portion for Public Protection Disaster Relief (PPDR) service which is of great interest to many administrations and public safety forces.

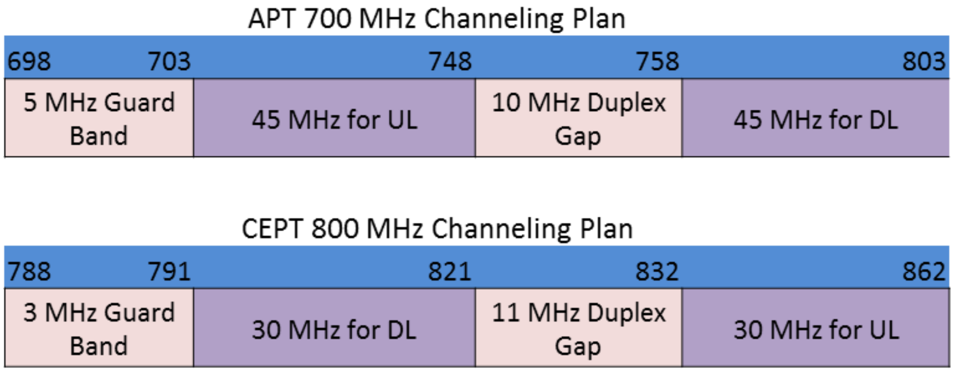

Figure 1-APT 700 and CEPT 800 channel plans

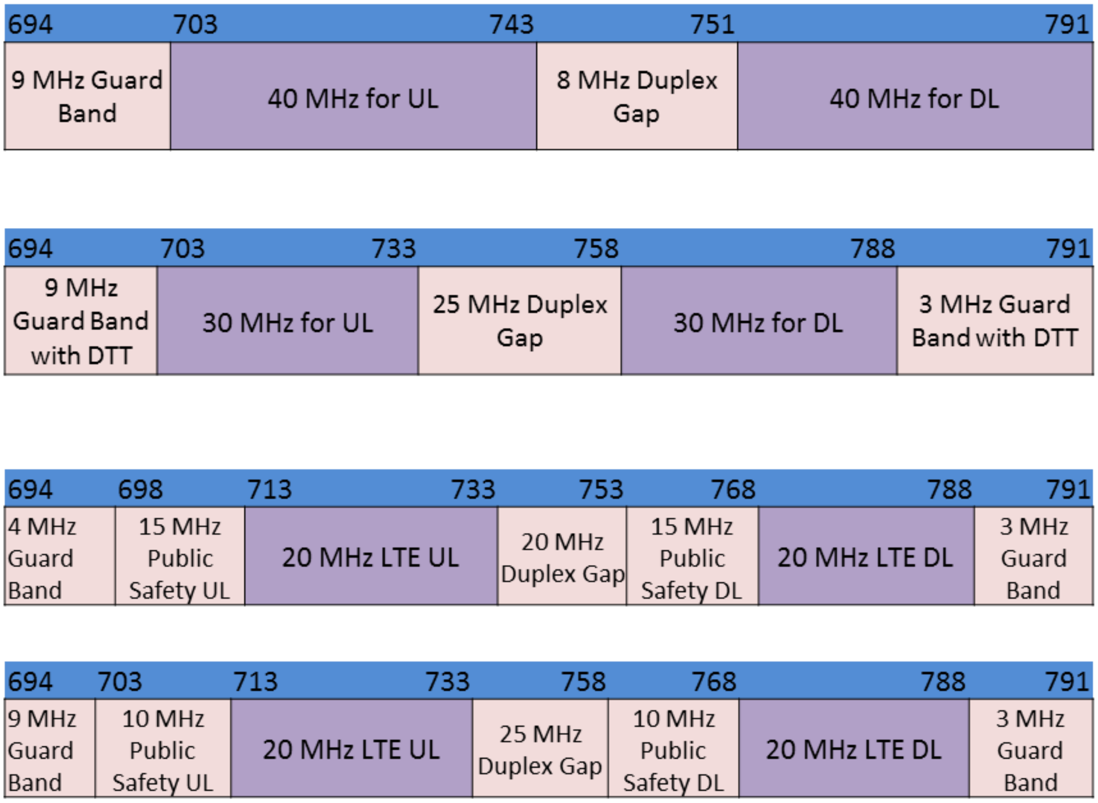

Figure 2-Possible Proposed Channeling Arrangements for Band 700 MHz

1.1 Objectives

In this document, we will be analyzing the effect of the LTE system in the 700 MHz band (694-791 MHz) to the DTV system operating in the adjacent band (470-694 MHz). Our objective is to study the feasibility of the 3GPP OOB level -25dBm/8MHz [23] and to determine the separation distances required should this limit be enforced. Furthermore, we aim to study the effect of different coexistence parameters on the interference probability to determine a set of guidelines that enables operators and regulators to set the technical restrictions of operation of both systems. Technically, the possible interference scenarios for the 2 systems operating in adjacent bands are the following [16]:

- DVB-T downlink interfering with LTE downlink
- DVB-T downlink interfering with LTE uplink
- LTE downlink interfering with DVB-T downlink
- LTE uplink interfering with DVB-T downlink

The LTE transmitter is the user equipment on the uplink channel or the Base Station on the downlink channel. The DTV transmitter is the TV Base Station. The DTV receiver is the set-top box. Knowing that the existing service that requires protection is the broadcasting service [27], the possible interference on the broadcasting receiver can be observed from both the LTE BS and the LTE UE as shown in Figure 4. The channeling arrangement of LTE 700 MHz places the uplink in the band adjacent to the UHF band used by broadcasters, specifically adjacent to channel 48 (centered at 690 MHz) as shown in Figure 3. The downlink starts about 64 MHz away from channel 48, so it is not in this document's interest to analyze the effect of the LTE downlink on the DTV receiver due to the vast frequency separation between the 2 bands. Furthermore, the reality that the LTE UE is normally located within proximity of the DTV receiver, especially in households, gives the protection of receivers a higher priority. So in our study, we will consider the LTE UE transmitter as the interferer, and the DTV receiver as the victim. The analysis will be conducted for both the Minimum Coupling Loss (MCL) method and for the statistical Monte Carlo method. The MCL method will be used to analyze the required separation distance for the OOB level under study, and will be used to determine the appropriate OOB required for coexistence and protection of the broadcasting service. The Monte Carlo simulations will be used to analyze the effect of other system parameters on the interference probability. Such parameters are the guard band separation, the LTE system bandwidth, the propagation environment, and the DTV Transmit (TX) power, the number of users, etc.

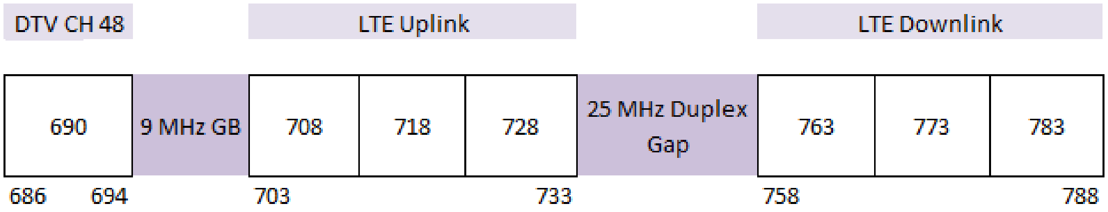

Figure 3-700 MHz Band Plan

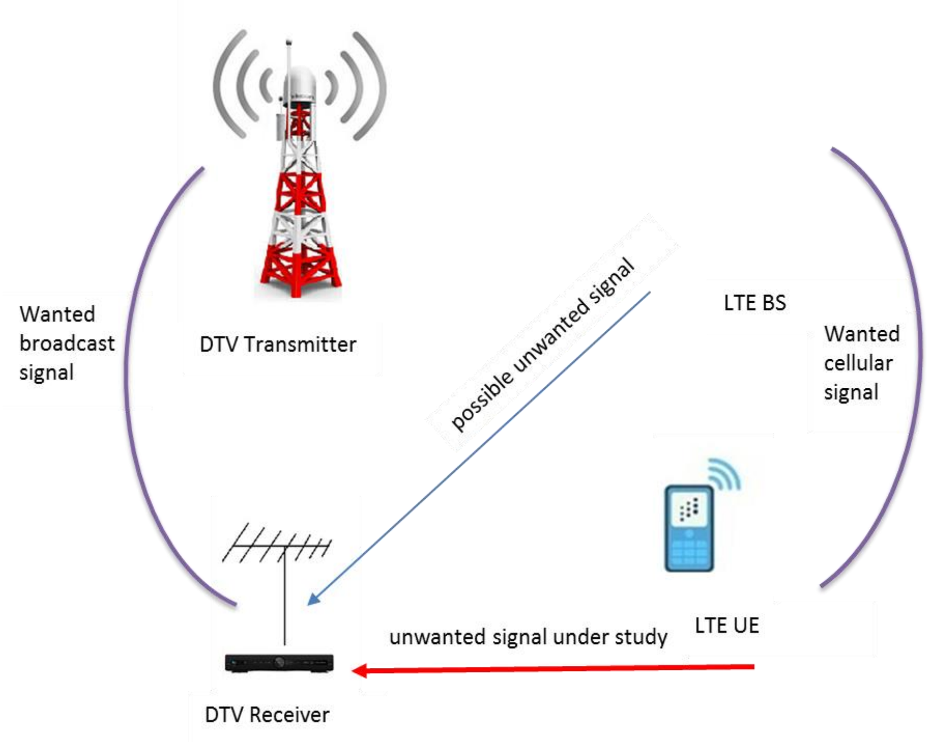

Figure 4-Possible Sources of Interference on DTV Receiver

CHAPTER 2

LITERATURE REVIEW

In this section, we will provide a brief literature review on the different work on interference analysis of LTE on DTV systems. However, we will first start by explaining the main technical principles of the systems under study.

2.1 Orthogonal Frequency Division Multiplexing (OFDM)

Frequency Division Multiplexing (FDM) is the division of a frequency band into several smaller sub channels. This allows different users to use the same band but each on a different channel. Both LTE and DTV systems use Orthogonal Frequency Division Multiplexing (OFDM) [2]. OFDM is technically a combination of both modulation and multiplexing. The main concept behind OFDM is to divide data among several overlapping subcarriers instead of using one single carrier to transmit this data. This allows for stronger protection against interference and specifically Inter Symbol Interference (ISI) [11]. OFDM is used in several other systems mainly WiFi, WiMAX and ADSL. OFDM is used as an access method that allows multiple access for users by assigning each of them a time and a frequency in order to cater for as much users as possible at the same time [10]. The data rate and the bandwidth of every subcarrier is much smaller than the data rate and bandwidth of the overall signal. Every subcarrier must have a bandwidth that is less than the coherence bandwidth of the full carrier which is why the subcarriers have flat fading and thus small Inter Symbol Interference (ISI) [35]. The number of subcarriers must be chosen in such a way that the symbol time of each subcarrier must be greater than the delay spread of the channel which results in significantly less ISI for each subcarrier. If we consider B to be the bandwidth of a linearly modulated signal of data rate R. Let $B_N$be the bandwidth of each subcarrier. Then, $B_N = \frac{B}{N}$ and $R_N = \frac{R}{N}$where N is the total number of subcarriers. N must be chosen to be large enough to have $B_N = \frac{B}{N} \ll B_c$ where $B_c$is the coherence bandwidth. The symbol time T_N of the modulated signal is proportional to $\frac{1}{B_N}$. If we let T_m be the delay spread of the channel, then $T_N \gg T_m$ where $T_m = \frac{1}{B_c}$ [35]. Let us consider an OFDM modulated signal with N subcarriers, we can represent the signal as such:

$$S(t) = \sum_{n=0}^{N-1} S_n\,(t)\cos(2\pi f_{n(t)} + \emptyset_n) \qquad (1)$$

where $f_n$is the orthogonal frequency of the nth subcarrier, and $S_n$is the complex message symbol which is mapped to the used constellation (QPSK, QAM, etc.) and associated with the nth subcarrier. Below are some mathematical representations of the above description:

- $T_s = \text{sampling rate}$
- Δ_f= Spacing between carriers
- T_{ofdm} = Symbol duration of OFDM system
- N = Number of subcarriers
- $T_s = N\ x\ T_{ofdm}$

In OFDM, the initial bandwidth is divided into several hundreds of subcarriers that are generated using Inverse Fast Fourier Transform (IFFT) on the transmitter's side while Fast

Fourier Transform (FFT) is used to recover the symbols of data on the receiver's side [3]. IFFT transforms the signal from time domain to frequency domain by converting the baseband signals into corresponding amplitude and phase signals that will be modulated onto the passband. The diagrams of the OFDM multicarrier transmitter and receiver are shown in Figure 5 and Figure 6.

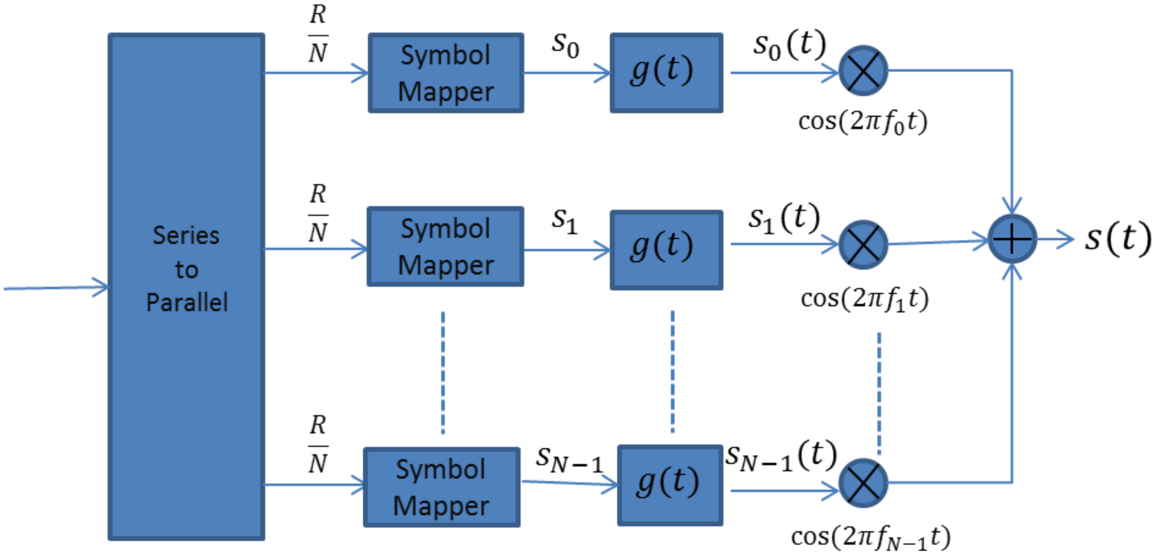

Figure 5- OFDM Multicarrier Transmitter [35]

Orthogonality is a key feature in OFDM; it allows adjacent subcarriers to operate without using guard bands between every single carrier, and still without facing the problem of Adjacent Channel Interference (ACI). Each subcarrier is represented by a Sinc function in the frequency domain. This Sinc function has side lobes that cause an overlapping between the subcarriers as shown in Figure 7. Normally, this would result in interference, however, when the frequencies are orthogonal, each subcarrier will have its peak be positioned at the null part of the other subcarriers. Using orthogonal subcarriers results in an increased bandwidth and thus and increased spectral efficiency [36]. We should not confuse OFDM with regular modulation schemes; the fast serial digital data stream which is being transmitted is divided into slower parallel bit streams that should be individually modulated onto the divided subcarriers using any of the required modulation schemes. For example, LTE uses QPSK, 16-QAM, or 64-QAM modulations along with OFDM [2].

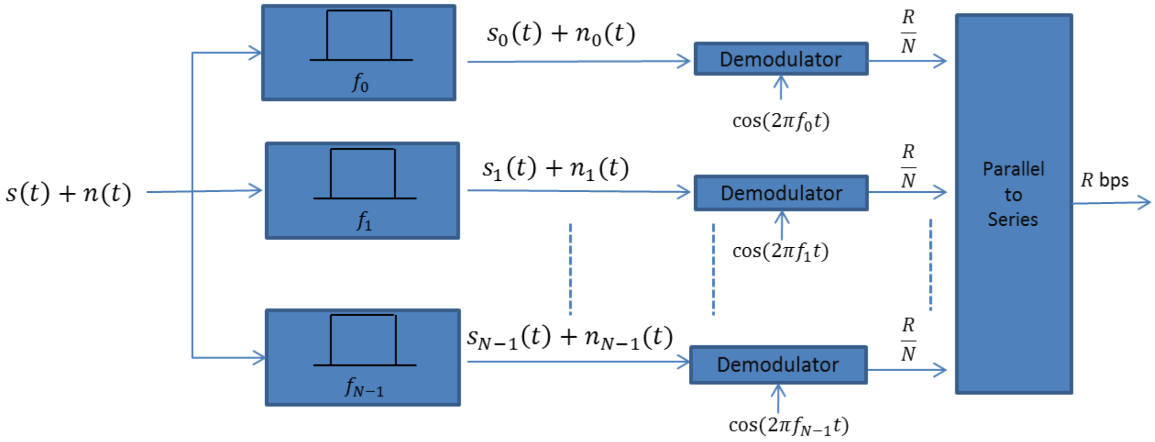

Figure 6- OFDM Multicarrier Receiver [35]

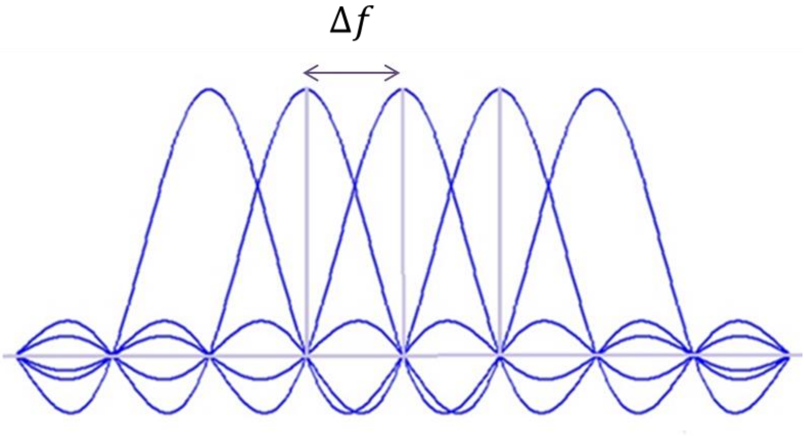

Figure 7- Orthogonal OFDM Signals

2.2 Occupied Bandwidth

The occupied bandwidth is the bandwidth that hosts a specified percentage (100-β) of the total mean signal power, usually taken as 99% with β=1%. According to Article 1 No. 147 of the Radio Regulations[39], the lower and upper edges of the channel can only contain β% of the power, which is β/2 % on each edge. Another method for calculating the occupied bandwidth is to calculate the bandwidth between the 0 dB reference level, which is the peak, and the level where the signal power drops by 26 dB [40]. In most cases, and in LTE and DTV, the occupied bandwidth is taken as 90% of the total bandwidth [41].

2.3 System Performance

In order to measure the performance of a wireless communication system, we need to measure several parameters of transmission and reception depending on which side we want to evaluate. A measure of a transmitter's performance is done by analyzing its transmission power, its Spectrum Emission Mask (SEM), and its Adjacent Channel Leakage Ratio (ACLR). A measure of the receiver's performance can be done by analyzing its sensitivity, selectivity, and received signal strength. Many other factors contribute to the performance of the wireless system, those will be generally discussed below. Detailed parameters and equations of relevant system performance indicators will be discussed in detail in Section 0.

2.3.1 Interference

In telecommunications, interference is the act of disruption of a travelling signal from one end to another. Interference can be harmful when reception of the desired signal is disrupted. However, interference might be encountered in low levels that do not affect the quality of the desired signal. In order to avoid interference, the receiver must have a Carrier to Interference (C/I) ratio above the threshold limit. When this C/I level drops below the threshold, interference happens. The parameters relevant to the C/I ratio are the received signal strength of the desired signal (dRSS), and the received signal strength of the Interfering signal (iRSS). In DTV systems, a harmful interference is any interference that degrades the quality of reception or causes interruption in the reception. It can be sensed as frozen images or black screen. A minimum required C/I ratio is known as the Protection Ratio (PR) since it is necessary to protect the receiver from unwanted interfering signals. A good indication of the quality of the received signal is the Received Signal Strength (RSS). It is the power of the signal received by a reference antenna at a particular distance from that antenna. Received Signal Strength (RSS) is affected by several factors that include transmitter output power, receiver sensitivity, transmitter and receiver antenna gain, and pathloss. Table 1 shows the quality indication of the DTV signal from the RSS values [9].

Table 1-DTV Received Signal Strength (RSS) Index

RSSI Range	Signal Quality
> -40 dB	Excellent
-40 dB to -55 dB	Very Good
-55 to -70 dB	Good
-70 dB to -80 dB	Marginal
<-80 dB	No Operation

One way of avoiding interference is applying filters to the DTV receivers to add protection; however, this is one of the disagreement issues discussed under WRC-15 Agenda item 1.2 because imposing a filter to an incumbent service adds cost to the manufacturers. But still, even with a filter, interference can happen depending on the transmission and reception parameters of both the victim and interferer. In our study, we will be conducting the analysis based on the absence of a receiver filter, which means we are considering a more realistic scenario. When analyzing the interference between two fixed or mobile systems in adjacent channels, we need to differentiate between two approaches; the first calculates unwanted emissions that result from the existence of an interferer signal in the same or adjacent channels, while the second calculates the interferer power affecting the victim as a result of receiver imperfections and its inability to block an interfering signal, which is known as receiver blocking [34]. This is better illustrated in Figure 8.

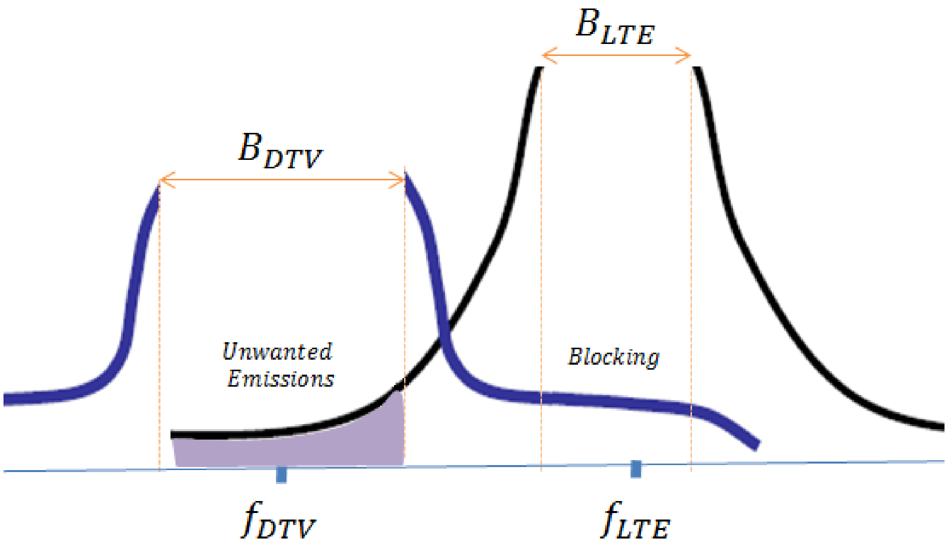

Figure 8-Unwanted Emissions and Receiver Blocking

2.3.2 Receiver Sensitivity

Receiver Sensitivity is an electronic feature of the receiver. It is defined as the threshold power above which a signal can be detected at the antenna port. It is the minimum acceptable Signal to Noise Ratio (SNR_{min}) for a receiver to be triggered. Since the receiver is also affected by other physical parameters, as shown in Figure 9, the equation for sensitivity can be expressed by Eq. (1).

$$Sensitivity = SNR_{min} + KTB + NF \quad (1)$$

Where NF = Noise Figure, K= Boltzmann's Constant, B = Receiver Bandwidth and T= Absolute temperature of the receiver input (Kelvin). KTB is known as thermal noise and it is equal to -174 dB for 1 Hz Bandwidth. In the case of a DTV channel of 8 MHz, the actual occupied bandwidth is 7.6 MHz (90%), so KTB For 7600000 Hz is -105.2 dB. Receiver sensitivity is measured in dBm, and the lower the value, the higher the sensitivity. Sensitivity plays an important role in what’s known as the transmission range which is the distance between the transmitter and the receiver. As this range increases, the transmitted signal loses its power and becomes weaker. However, the more accurate and sensitive the receiver is, the more signals can be detected even over wider ranges.

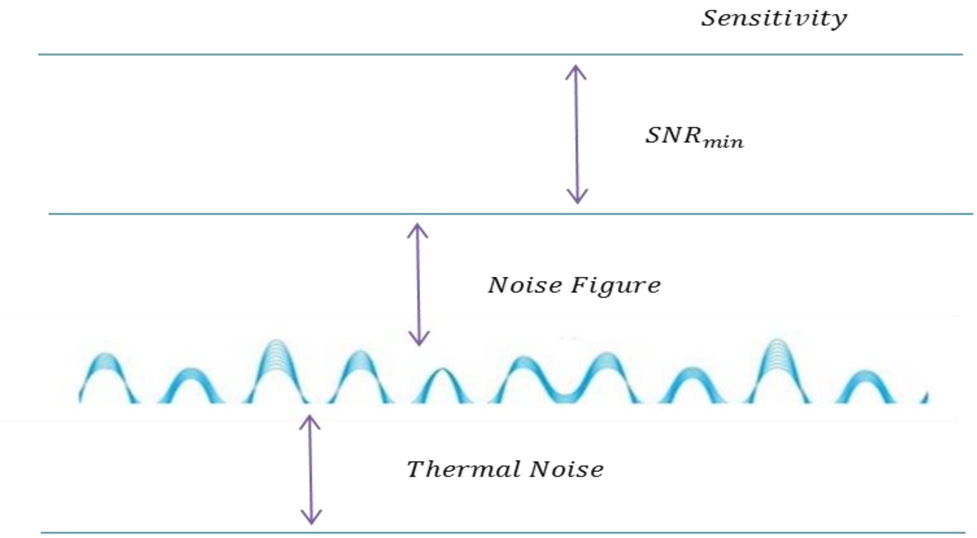

Figure 9-Sensitivity

2.3.3 Receiver Selectivity

Receiver Selectivity or Adjacent channel Selectivity (ACS) is also an electronic feature of the receiver, and it measures its ability to receive the wanted signals at the specific wanted frequency and block the strong signal that is present in the adjacent channel. It is the ratio in dB of the receiver filter attenuation on the wanted channel to the receiver filter attenuation on the adjacent channel [23]. Receiver selectivity is measured in dB and the higher the selectivity is, the better the receiver performance [25]. If a filter is added to the receiver, the total ACS will be improved according to Eq. (2).

$$ACS_{Total} = ACS_{receiver} + ACS_{filter} \tag{2}$$

2.3.4 Out of Band Emissions (OOB)

The OOB emissions are the unwanted emissions immediately outside the operating channel bandwidth. The OOB level is related to the LTE User Equipment transmitted power TX_{UE} and to the Adjacent Channel Leakage Ratio (ACLR) according to Eq. (3). Adjacent power leakage happens when the transmitter on the main channel leaks power to the adjacent channel as shown in Figure 10. ACLR is the ratio of the transmitted mean signal power in the main channel to the mean signal power in the adjacent channel as shown in Figure 11. The aim is to have low leakage. When the output amplifier of the transmitter is highly linear, power in the adjacent channel is low, this is because the main reason we have leakage is the intermodulation products that are produced by amplifiers [25]. An OOB restriction is enforced to ensure protection of services in the adjacent bands. The unit of the OOBE is dBm/8Mhz (considering the DTV channel bandwidth is 8 MHz).

$$OOBE = TX_{UE} - ACLR \tag{3}$$

Avoiding OOB interference from LTE to DTV is directly related to the ACLR of the LTE UE and the ACS of the DTV receiver [33] in the form of the Adjacent Channel Interference Ratio (ACIR). In general, the ACIR is the ratio between the power transmitted by the interferer to the power received by the victim receiver in the adjacent channel [53]. And it is calculated according to Eq. (4)

$$ACIR = \frac{1}{\frac{1}{ACLR} + \frac{1}{ACS}} \tag{4}$$

When a certain OOB level is determined, the Spectrum Emission Mask (SEM) is created to match the OOB restriction. The SEM is a representation of the out-of-band emissions and spurious emissions affecting other systems. It is used to reduce the excess emissions from the intended transmission frequency into other frequencies. Spurious emissions are the emissions outside of the bandwidth of the OOB emissions. Normally, a spurious emission requirement is imposed in order to limit these emissions outside of the required band. According to [42], the OOB domain starts at 50% offset from the occupied bandwidth and the spurious domain is located at an offset of 250% of the occupied bandwidth as shown in Figure 11. More specific spectrum emission masks for the different LTE system bandwidths will be presented later in this document.

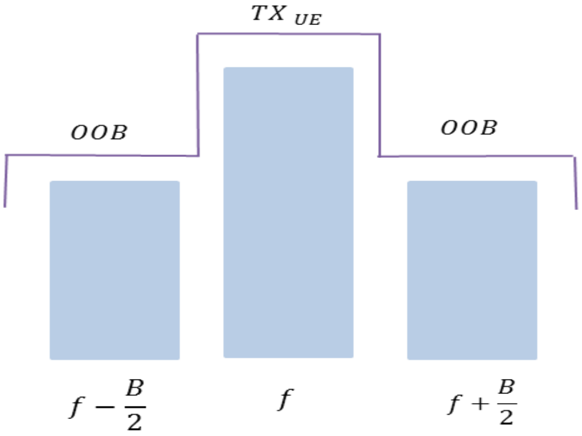

Figure 10-Adjacent Channel Leakage Ratio and OOB

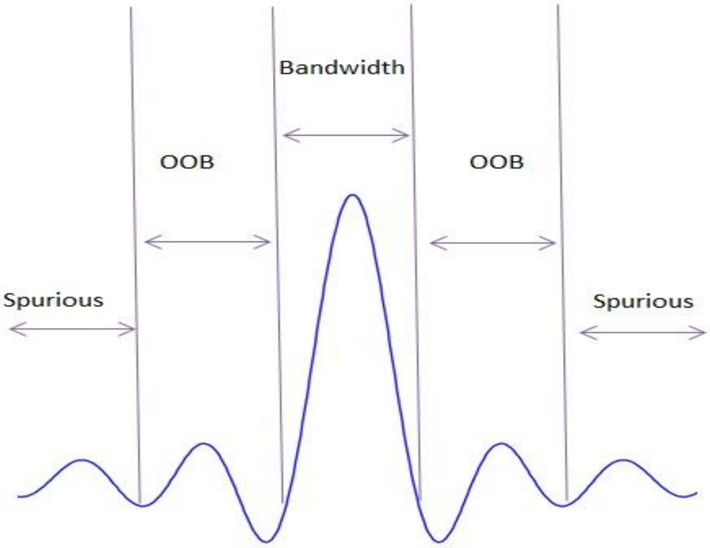

Figure 11-Out of Band Emissions (OOB) and Spurious Emissions

2.3.5 Protection Ratio

The protection ratio is the ability of a receiver to protect itself from interference. It is the minimum value of the ratio of the wanted signal to unwanted signal above which good reception can be guaranteed. In other words, it is the desired Carrier to Interference

Ratio. The Protection Ratio (PR) is measured in dB, and it decreases as the spacing between the wanted and unwanted signal increases. To calculate the protection ratio $PR_{req}(\Delta f)$ at an adjacent channel with Δf separation from the center frequency of the wanted signal, we need to have the minimum required C/I at co-channel frequencies, also known as PR_{IB}. Eq. (5) is used to obtain the required protection ratio.

$$PR_{req}(\Delta f) = PR_{IB} + 10\log(\ 10^{\frac{-ACS}{10}} + 10^{\frac{-ACLR}{10}}) \tag{5}$$

2.4 Interference Calculation Methods

In this section, we will generally describe the 2 main methods used for interference calculations: the Minimum Coupling Loss (MCL) method, and the Monte Carlo method. MCL is the classic traditional method. It depends on the minimum receiver sensitivity to calculate the minimum guard band and the protection distances. However, it is considered a rigid and pessimistic approach for its static assessment that does not take into consideration the random behavior of end users. Furthermore, it is considered a worst-case method since in real life many systems are in fact operating with less protection distances than calculated [54]. The MCL method is considered simple and can be implemented by doing basic calculations without using a computer for simulations. It gives a calculation of the isolation between the victim and the receiver in dB. This isolation can be transformed into separation distance by applying the pathloss formula. However, it is a worst-case method that produces a static result that is spectrally inefficient. Furthermore, it assumes there is a single user-interference pair and that the interferer is transmitting the interfering signal at maximum power at a single channel. MCL method includes the interference effects of both unwanted emissions and receiver blocking [22]. However, it does not consider data about the percentage of time or percentage of the cell’s area. It is considering that the interferer is active all the time and that it is affecting the entire cell.

The Monte Carlo method, considered the most suitable for analysis for complex wireless systems like CDMA and OFDM, is a bit more complicated and requires a computer due to its statistical nature. It generates the probability of interference between the two systems under study. The user distributions, the guard band, and the receiver signal strength can be modeled as desired and are not fixed as in the other methods. The Monte Carlo method is a combination of continuous trials and random variables that compose the system parameters in a dynamic manner (variable antennas, alternating power levels, moving end users etc.).

2.5 Previous Work

Few studies have addressed the issue of coexistence between mobile systems and broadcasting systems in its several parameters such as guard band, separation distance and out of band emissions. In [43], the required protection distance and the guard band between an LTE transmitter and DTV receiver were calculated. The study, which was based on Monte-Carlo simulations, shows that a minimum of 1 DTV channel should be kept as guard band to ensure protection of the broadcasting service and that when 4 MHz guard band is used, the required separation distance between the UE and the DVB receiver is 13 km even with strict out of band requirements. However, when a guard band over 8 MHz is used with about -65 dBm/8MHz OOB limit, the separation distance is negligible. The study also analyzed the effect of the LTE Base Station on the DTV receiver and found that the required separation distance is about 2 km for an 8 MHz guard band. Similarly, in [44], a 800-1000m separation distance between LTE Base Station and DTV receivers was found to be necessary for protection. On the other hand, the interference calculations carried out in [45] between LTE BS and DTV transmitter showed that at a 5 km separation distance, the throughput loss of the LTE system is maximum. More specifically, [45] study showed that the effect of the UE interference in small coverage areas is less severe than those in large DTV coverage areas. [46] showed that in order to keep the coverage loss below 5%, ACIR should be equal or above 79 dB in an urban environment and 75 dB in a rural environment. Another study [48] also performed Monte Carlo simulations for an LTE 10 MHz system and the results showed that for a DTV ACS equal to or greater than 60 dB, an OOB limit of -33 dBm/8MHz is enough to ensure protection for DTV receivers. In [41], it was shown that higher LTE system bandwidths (above 5 MHz) result in higher interference. The protection ratios required for protection between DTV RX and LTE UE uplink were calculated for both Indoor and Outdoor scenarios where it was shown that the portable indoor receiver is more susceptible to interference. The study analyzes the separation distances between the DTV receiver and the LTE UE with a 9 MHz guard band and -55 dBm/8MHz OOB to find that the minimum distance required is 6m for indoor reception. As for the fixed outdoor reception, the study found that a filter with 12 dB attenuation is required to avoid interference. Similarly, the results from [50] show that a filter cannot be avoided if interference is to be prevented in worst cases. The interference probability for different separation distances was also calculated in [51], where a 10m separation distance between the DTV receiver and the LTE UE resulted in a 32% interference probability, and the required separation distance to attain a probability of interference less than 5% is 150m. In [52], implementing lower guard bands such as 2,3, and 4 MHz showed to result in very high interference probabilities. 2 MHz guard band cause about 70% interference probability if the separation distance is 1 Km. Only for a 10 km distance would a 2 MHz guard band be feasible (5% probability).

CHAPTER 3

METHODOLOGY

3.1 System Parameters

We will use the Minimum Coupling Loss method and Monte Carlo simulations to analyze the feasibility of the -25 dBm/8 MHz OOB emission constraint. Throughout the document, we will evaluate the coexistence through two main metrics: (1) the interference probability; (2) the required separation distance between the LTE user equipment (acting as transmitter, i.e. uplink) and the DTV receiver. The parameters used for DTV and LTE are shown in Table 2 through Table 6. These parameters will be used to conduct studies of scenarios under normal operating conditions and they will be varied later on depending on the parameter under study. Unless mentioned, the normal operating conditions for the simulated scenarios are found in Table 7.

Table 2-System Parameters for Different DTV Reception Methods [55]

System	Portable Indoor
Bandwidth	8 MHz
Modulation	64 QAM

System	Fixed Outdoor
Bandwidth	8 MHz
Modulation	256 QAM

Guard Interval	1/8
FFT Size	16K
Code Error Rate	2/3
Channel	Rayleigh
Required SNR	17.1 dB
Data Rate	26.2

Guard Interval	1/16
FFT Size	32K
Code Error Rate	2/3
Channel	Rice
Required SNR	19.6 dB
Data Rate	37 Mbps

Table 3-Parameters of LTE UE

LTE UE	
TX Power (dBm)	23
LTE Antenna Gain (dB)	0
Center Freq (MHz)	708
LTE BW (MHz)	10
Antenna Height (m)	1.5

Table 4- Parameters of LTE BS

LTE-Base Station	
TX Power (dBm)	43
TX Frequency (MHz)	763
Bandwidth (MHz)	10
Antenna Height (m)	10
Antenna Gain (dB)	15

Table 5- Parameters of DTV TX

DTV Transmitter	
TX Power (dBm)	70
TX Frequency (MHz)	690
Bandwidth (MHz)	8
Antenna Height (m)	200
Antenna Gain (dB)	0

Table 6- Parameters of DTV RX

DTV Receiver	
TX Power (dBm)	0
Bandwidth (MHz)	8
Antenna Height (m)	10
Antenna Gain (dB) Fixed Outdoor	9.15
Antenna Gain (dB) Portable Indoor	2.15
Noise Figure (dB)	7

Table 7-Simulation Parameters

LTE BW (MHz)	10
Environment	Urban
Distance between DTV TX and DTV Rx (km)	22.5
Distance between DTV RX and LTE UE (km)	0.02

Center Frequency for DTV (MHz)	690
Center Frequency for LTE UE (Mhz)	708
Separation Bandwidth (MHz)	9
DTV TX Power (dBm)	70
Max RBs per BS	48
Max RBs per Mobile	12
Number of Users per BS	20
OOB (dBm/8Mhz)	-25
ACS (dB)	80

3.2 OOB and Separation Distance

In this section, we will use the Minimum coupling loss method to analyze the effect of enforcing the proposed 3GPP out of band emission limit -25 dBm/8 MHz [47] currently discussed in Agenda Item 1.2 at WRC-15. We will then move on to finding the actual required OOB level to ensure coexistence. Coexistence in the case of the proposed OOB level can be measured by the required separation distance between the LTE user equipment and the DTV Receiver. This will be done for 2 different scenarios: The first is where we consider a portable indoor TV reception, meaning that the DTV receiver and the LTE UE will be in the same room; the second is where we consider a fixed outdoor reception where we assume a worst case horizontal separation distance between the roof-top antenna and the LTE UE. In order to estimate the feasibility of the proposed OOB level, we need to obtain the received interferer power by the DTV victim receiver at the studied conditions. We will be assuming a 10 MHz LTE Bandwidth and we will be using a 9 MHz guard band between the adjacent services. A transmission mobile data rate of 20 Mb/s will be assumed. Restricting the OOB to a certain level means we can obtain the Adjacent Channel Leakage Ratio (ACLR). The ACLR and the OOB are related as per Eq. (6).

$$ACLR = (TX_{UE} + G_{UE}) - OOB \qquad (6)$$

Where TX_{UE} is the transmission power of the UE, usually transformed from 23 dBm for 10 MHz LTE channel bandwidth into 22dBm/8MHz, and G_{UE} is the antenna gain of the LTE UE. Fixing the OOB level at -25 dBm/8MHz results in an ACLR of 47.03 dB. At this level, we need to obtain the required Adjacent Channel Interference Ratio (ACIR) which represents the difference between the actual received interference power P_{I_RX} and the maximum allowed interference power P_{I_Max} to avoid interference. When we are analyzing a scenario for avoiding interference, we use the required ACIR which is the difference between the In-Band protection ratio $PR_{IB}$and the required adjacent channel protection ratio PR_{req} [50] as per Eq. (7). Required Protection Ratio is simply the minimum allowed Carrier to Interference level as shown by Figure 12. We need PR_{req} to estimate the maximum allowed interference level as per Equation (4). PR_{IB} for the scenario under study is obtained from lab measurements conducted by [50] and its value is 15 dB. In this case, PR_{req} is -32.02 dB having obtained ACIR=47.02 from Eq. (4) which shows the relationship between ACIR, ACLR and ACS.

$$ACIR = PR_{IB} - PR_{req} \tag{7}$$

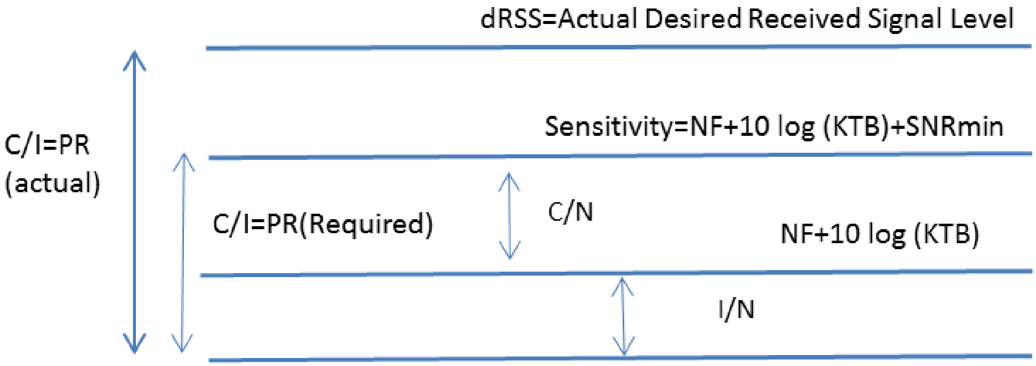

Figure 12-Sensitivity and Protection Ratio

$$PR_{req} = P_{min} - P_{I\_Max} \tag{8}$$

where $P_{min} = Sensitivity = Thermal\ Noise + NF + SNR_{min}$ (9)

For the DBV-T2 transmission mode we are using, the minimum Signal to Noise ratio ($\mathrm{SNR_{min}}$) is 19.6 dB [55]. The Thermal noise is -105.2 dBm as calculated in previously in 2.3.2 . NF is the noise figure and it’s equal to 7 dB. From Eq. (8), we can find the maximum allowed interference level $\mathrm{P_{I\_Max}}$ to be -46.57 dBm. The required separation distance to avoid interference can be calculated by obtaining the Path Loss from Eq. (10).

$$P_{I\_Max} = TX_{UE} + G_{UE} + G_{TV,RX} + G_{Disc} - PL - BL \tag{10}$$

Where TX_{UE} is the transmission power of the LTE UE and G_{UE} is the antenna gain of the LTE UE. $G_{TV,RX}$ is the DTV receiver antenna gain (9.15 dB for Fixed outdoor and 2.15 dB for portable indoor reception) as recommended in [53]. G_{Disc} is the antenna elevation discrimination gain of the DTV receiver, considered to be -0.45 dB [53]. PL is the free space path loss asper Eq. (11). BL is the body loss taken as 4 dB.

$$PL = 20log_{10}(d) + 20log_{10}(f) - 147.5 \tag{11}$$

Where d is the distance in m between the DTV receiver and the LTE User Equipment, and f is the transmission frequency in Hz. Now, we can find the minimum required separation distance from Eq. (12).

$$d = 10^{\frac{147.5 - 20log_{10}(f) + PL}{20}} \tag{12}$$

3.3 Monte Carlo Simulations

In order to fully analyze the effect of the LTE system bandwidth and the guard band, we use the Monte Carlo Simulation. Although the Minimum Coupling Loss Method generates accurate separation distances and protection ratios, it is considered a worst-case method that produces a static result that is spectrally inefficient [54]. Monte Carlo simulation is considered the most suitable for analysis of complex wireless systems; it is a bit more complicated and requires a computer due to its statistical nature. It generates the probability of interference between the 2 systems under study. Monte Carlo Simulations are mostly used to produce a resulting probability of interference that can be compared to the wanted probability of interference (5%-7%). We will be using the Spectrum Engineering Advanced Monte Carlo Analysis Tool (SEAMCAT) software to carry out our simulations. In order to measure the probability of interference,f_{Int}, we provide the probability of no-interference as, f_{No-Int}= 1-f_{Int} , given by Eq. (13) [34].

$$f_{Int} = \frac{Prob(\frac{dRss}{iRss + N} > \frac{C}{I + N}, dRss > Sensitivity)}{Prob\ (dRss > Sensitivity)} \tag{13}$$

Where $\frac{C}{I+N}$ is the DTV carrier to noise and interference ratio, N is the noise, $iRss$ is the received power of the interfering signal , and $dRss$ is the desired received signal strength of the DTV signal. In the simulations, we need to input the required C/I criteria for calculating interference. We can relate them using the following equations:

$$\frac{C}{I}(dB) = \frac{C}{N + I}(dB) + \frac{N + I}{I}(dB) \tag{14}$$

$$\frac{C}{N + I}(dB) = \frac{C}{N}(dB) - \frac{N + I}{N}(dB) \tag{15}$$

$$\frac{C}{N + I}(dB) = \frac{C}{I}(dB) - \frac{N + I}{I}(dB) \tag{16}$$

$$\frac{N + I}{I}(dB) = \frac{N + I}{N}(dB) - \frac{I}{N}(dB) \tag{17}$$

In this section, the DTV receiver is a fixed outdoor receiver, so the required SNR or $\frac{C}{N}$ is 19.6 dB as mentioned earlier in the document. The $\frac{I}{N}$ criteria is considered -10 dB [53].

So, we now have $\frac{\mathrm{C}}{\mathrm{I}}(\mathrm{dB}) = \frac{\mathrm{C}}{\mathrm{N}}(\mathrm{dB}) - \frac{\mathrm{I}}{\mathrm{N}}(\mathrm{dB}) = 19.6 - (-10) = 29.6$ dB

For $\frac{I}{N} = -10\ dB$, $\frac{N+I}{N} = 0.4\ dB$, so $\frac{N+I}{I} = 0.4 + 10 = 10.4\ dB$

Now for $\frac{C}{I} = 29.6\ dB, \frac{C}{N+I} = 29.6 - 10.4 = 19.2\ dB$

If $\frac{I}{N} = 0dB, \frac{N+I}{N} = 3dB$, then $\frac{N+I}{I} = 3dB$

The systems under study will be separated by a guard band varying between -10 to 9 MHz. This will give us the chance to study the co-channel coexistence as well as the adjacent channel coexistence. The distance between the DTV receiver and the DTV transmitter will be varied and the effect of this variation will be analyzed. Regarding the bandwidth, we are mainly interested in a 10 MHz LTE channel Bandwidth, but we will also consider 5 and 20 MHz bandwidth simulation and analyze the effect of the increased channel bandwidth on the interference probability. Another important parameter is the transmit power of the DTV Base Station. We will be studying the effect of the variation of the TX power of DTV station on the level of desired signal strength and interference probability. Several simulations will be conducted under different environment and user parameter. We will study the system behavior under urban and rural environment as well as under different user loads.

Throughout the simulations, it is always made sure that the LTE system is operating as per the quality parameters indicated by maximum allowed capacity loss [34]. The number of active users in the LTE network is the total number of available Resource Blocks (RB), divided by the number of resource blocks per user. Each resource block contains 12 subcarriers of 150 KHz each. The available resource blocks for a certain LTE bandwidth are shown in Table 8.

LTE Bandwidth	Number of Resource Blocks	Number of Subcarriers DL	Number of Subcarrier UL
5 MHz	25	301	300
10 MHz	50	601	600
20 MHz	100	1201	1200

Table 8-Available Resource Blocks for LTE

We know that the Shannon Capacity of LTE is given by $Cap = BW_{LTE} \times \log_2(1 + SINR)$, where BW_{LTE} is the LTE system bandwidth, and SINR is the Signal to Noise and Interference Ratio of LTE. The Interference here includes external interference from DTV system or other systems, the self-interference from other LTE users, and the Noise. The total loss of capacity of the LTE channel is given by Eq. (18).

$$LTE\ Capacity\ Loss = 1 - \frac{Cap}{Cap_{max}} \tag{18}$$

Where $Cap_{max}$is the capacity when no interference exists at all. The maximum allowed capacity loss is usually a percentage of Cap_{max}. For example, for a 20 MHz LTE BW, 50 Mbps is the minimum accepted capacity [34], which represents about 56.8% of maximum capacity of LTE 20 MHz which is 88.04 Mbps, this means that 100-56.8=43.2% is the maximum allowed loss in capacity. All user equipment with SINR below the minimum required SINR will be dropped from the network.

Furthermore, in our simulations, we consider the interferer to be active 50% of the time, which is a more realistic scenario than static MCL calculations which considers the interferer to be transmitting at all times. Another advantage of conducting the Monte Carlo simulations is that we use power control at the LTE UE and we do not have to make the rigid assumption that the mobile is transmitting at maximum power the entire time. We set the maximum power $P_{max}$to be 23 dBm and the minimum power $P_{min}$to be -30 dBm. All active users undergo power control which sets their transmit power according to pathloss and distance relative to the serving Base Station. The UE transmit power is chosen according to Eq. (19):

$$TX_{UE}{}^{i} = P_{max} \times min[1, \alpha], and\, \alpha = max\left[\frac{P_{min}}{P_{max}}, \frac{PL^{i}}{PL^{x}}\right] \tag{19}$$

Where $TX_{UE}{}^{i}$ is the transmit power of the ith UE, PL^{i} is the pathloss between the ith UE and its serving cell, and PL^{x} is the power scaling threshold such that users with pathloss greater than PL^{x} are not power controlled and will be transmitting at full power [34].

3.3.1 Simulation Layout

We consider multiple interferers randomly deployed across the network in a uniform geographical positioning as shown in Figure 13. Contrary to many previous simulations that only consider a single interferer, we simulate with the consideration of multiple interfering transmitters which forms a more realistic scenario. Regarding building losses, we are considering a 5 dB wall loss and an 18 dB loss between adjacent floors.

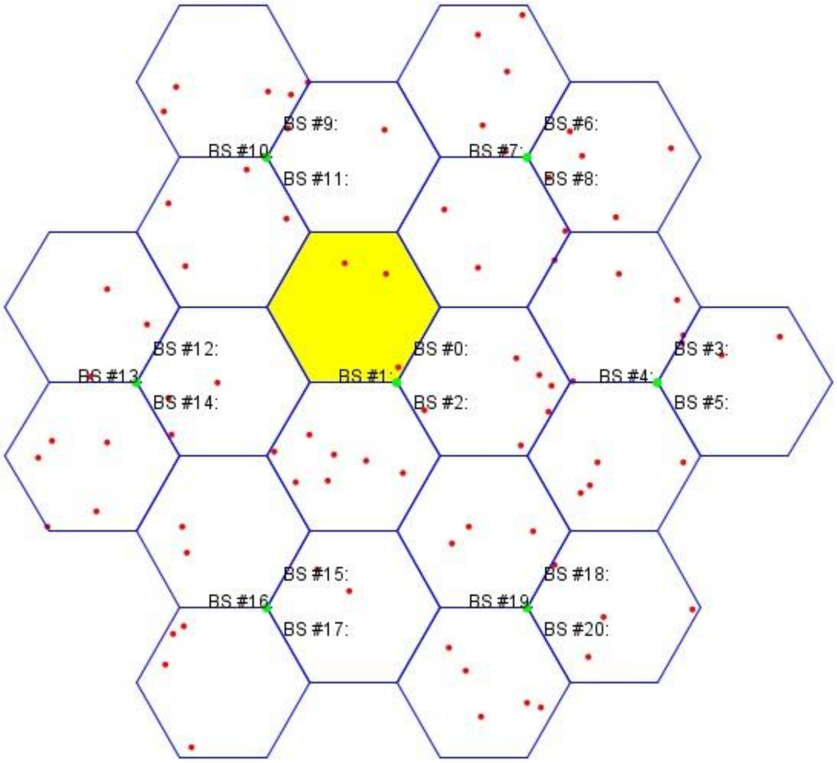

Figure 13- Simulation Cell Layout

In order to reflect the OOB restriction under study, which is -25 dBm/8mhz, we impose a spectrum emission mask on the LTE UE. This varies according to the LTE system bandwidth. The relative SEMs according to [23] for LTE 5, 10, and 20 MHz are shown in Figure 14, Figure 15, and Figure 16 respectively. The spectrum emission mask for 1.4 Mhz is also shown in Figure 17. We will be using the 1.4 Mhz system later in this document when we propose the carrier aggregation solution.

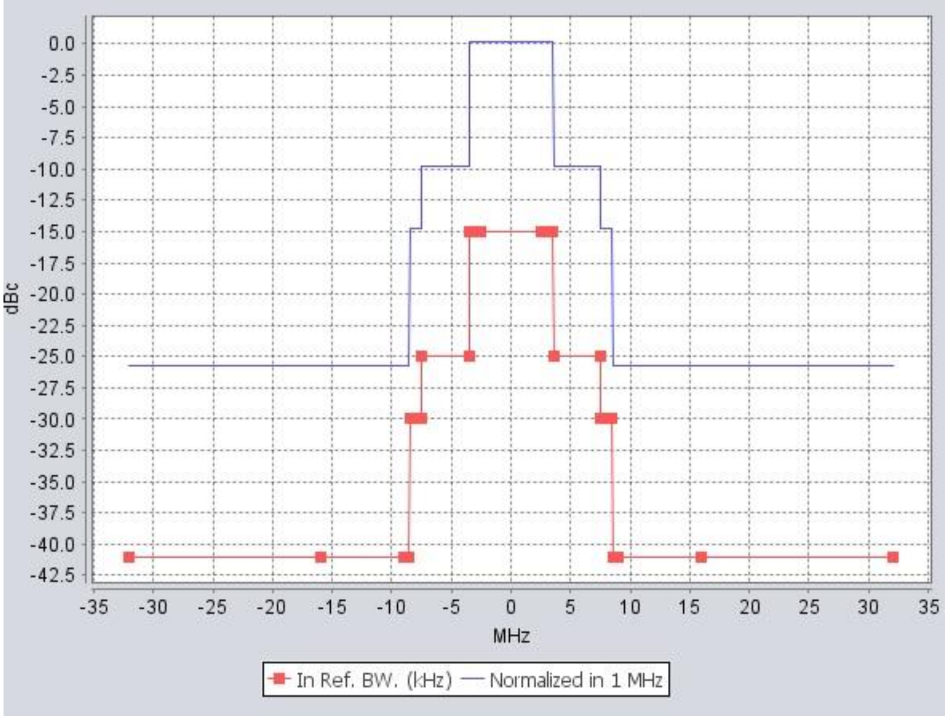

Figure 14-Spectrum Emission Mask for LTE 5 MHz

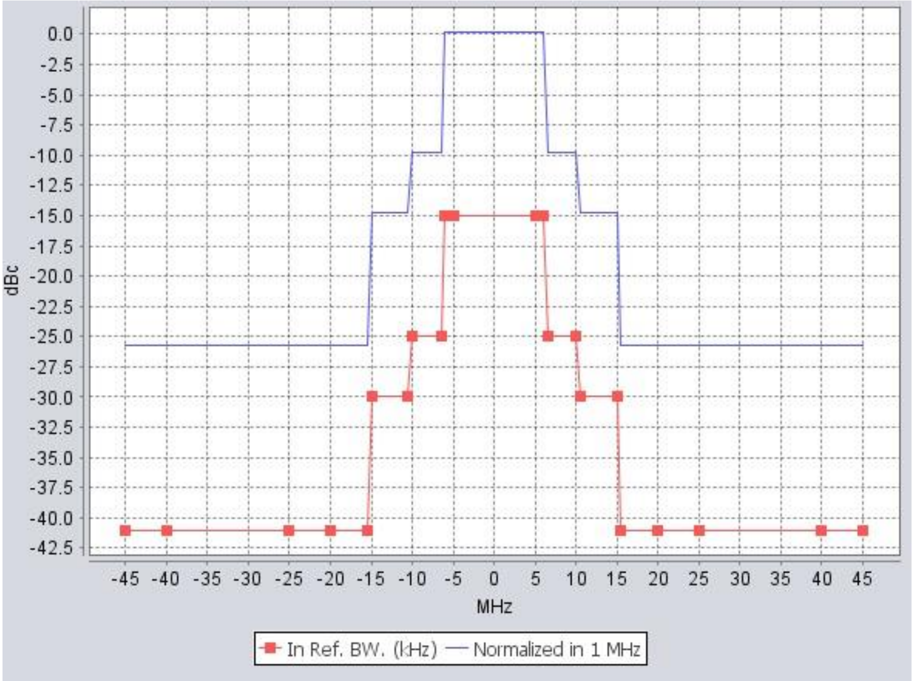

Figure 15- Spectrum Emission Mask for LTE 10 MHz

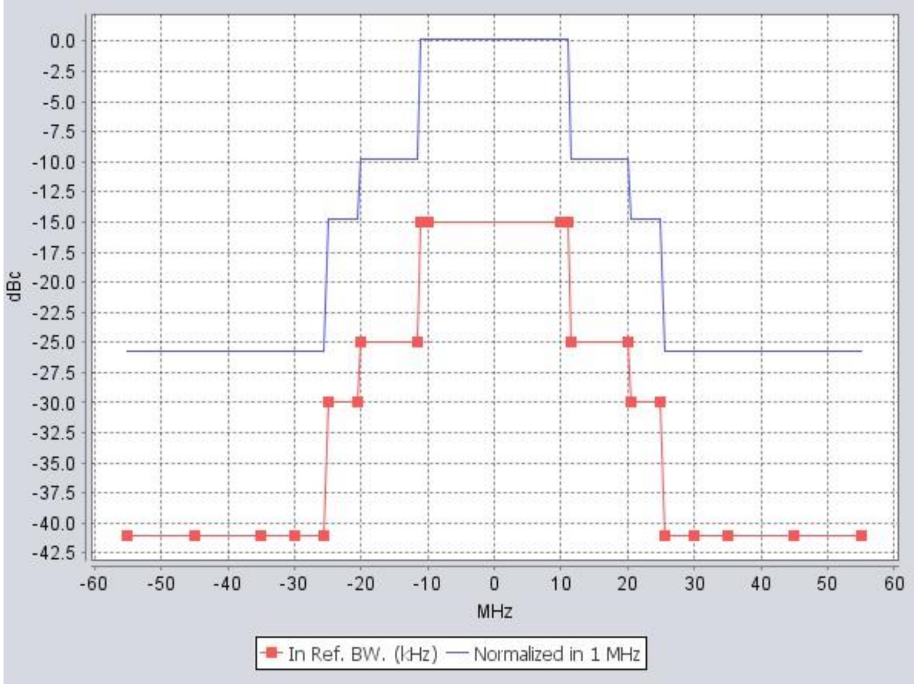

Figure 16- Spectrum Emission Mask for LTE 20 MHz

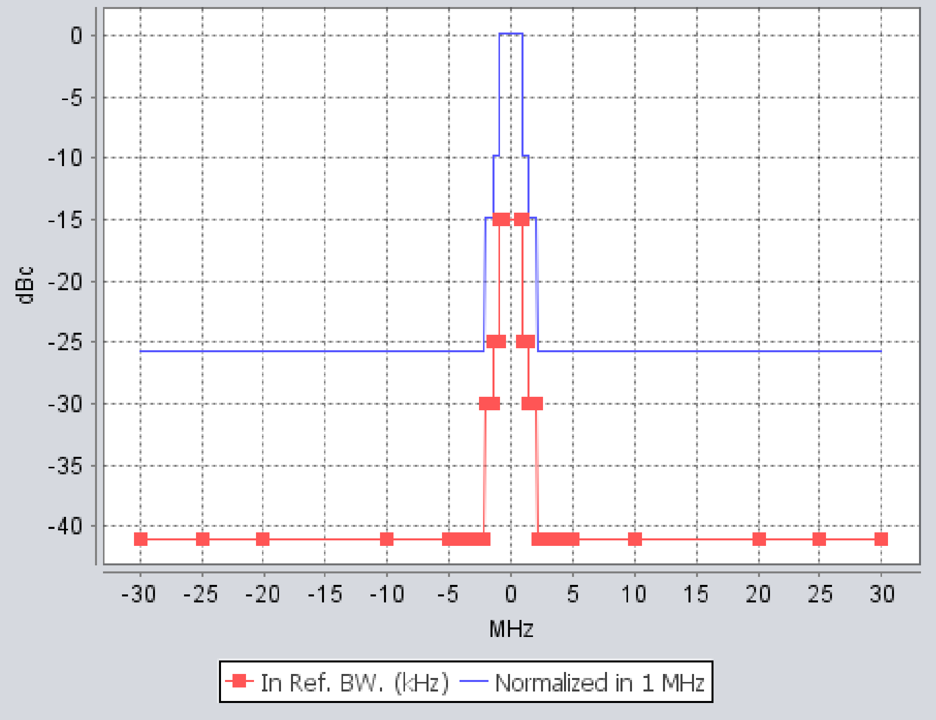

Figure 17- Spectrum Emission Mask for LTE 1.4 MHz

CHAPTER 4

RESULTS AND DISCUSSION

The results of the simulations show that a for an OOB level of -25 dBm/8Mhz, the minimum required distance between the UE and the DTV portable indoor receiver to ensure protection is 111m. For the case of fixed outdoor reception, a minimum distance of 176m is required. Considering the proximity of user equipment and TV receivers within the household, a 111m separation distance is not much feasible. Similarly, for fixed outdoor reception, it is not always possible to accommodate almost 176m separation between the roof top antenna and LTE mobile users. Table 9 and Figure 18 show the variation of the distance with the OOB restriction for both indoor and outdoor scenarios. It is clear that a lower OOB level is required to avoid interference at close distances. In this case, the required separation distances are negligible: 6.26m and 4.22 m for outdoor reception, and 3.92m and 2.66m for indoor in case of -55 dBm/8MHz and -60 dBm/8MHz respectively.

4.1 Adjacent Channel Selectivity

Similar to the OOB, the Adjacent Channel Selectivity of the receiver plays an important role in blocking the unwanted emissions. Figure 18 and Figure 19 show the results of the minimum separation distance required for different ACS values for both OOB=-25dBm/8MHz and OOB=-55dBm/8MHz respectively. The exact results are listed in Table 10 and Table 11. The results show that the OOB has a more dominant effect on the separation distances, mostly because the higher distances are only attained at very low ACS values which are not usually employed in receivers. Furthermore, the results show that an ACS value of 70 should be considered a minimum requirement below which high interference can be detected and thus higher separation distances would be required.

Table 9-Minimum Required Distance for different OOB Levels

	Indoor	Outdoor
OOB (dBm/8MHz)	Minimum Distance (m)	Minimum Distance (m)
-25	111.03	176.99
-30	62.4	99.55
-35	35.15	56.03
-40	19.82	31.59
-45	11.24	17.91
-50	6.48	10.34
-55	3.92	6.26
-60	2.66	4.22
-65	2.08	3.32

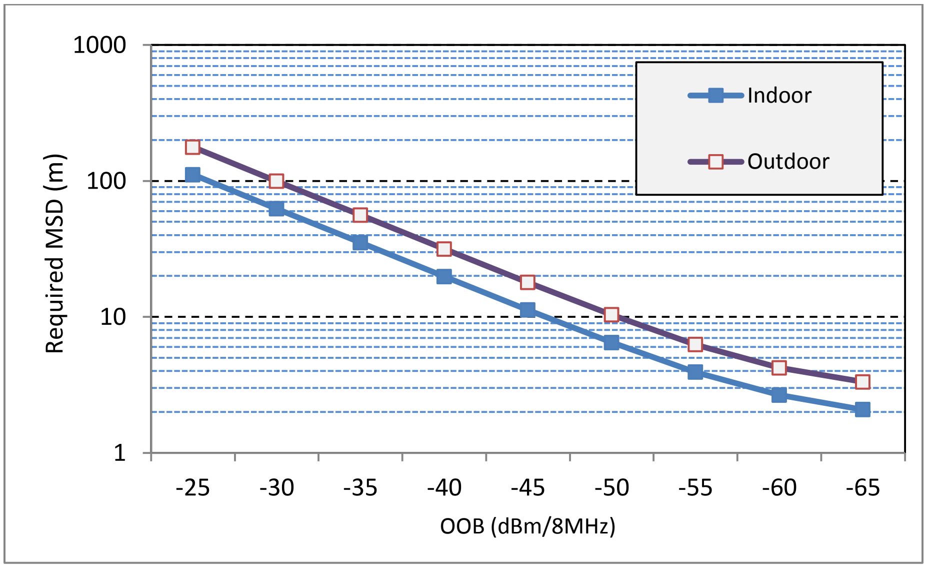

Figure 18-Variation of Required Separation Distance with OOB

Table 10- MSD for different ACS Levels at OOB=-25dBm/8Mhz

	Indoor	Outdoor
ACS	Minimum Distance	Minimum Distance
30	569.33	907.5
40	208.58	332.49
45	148.94	237.43
50	124.2	198.09
60	112.4	179.19
70	111.16	177.19
80	111.03	176.99
90	111.02	176.97
100	111.02	176.97

Table 11- MSD for different ACS Levels at OOB=-55dBm/8Mhz

	Indoor	Outdoor
ACS	Minimum Distance	Minimum Distance
30	558.4	890.13
40	176.6	281.53
45	99.3	158.38
50	55.95	89.18
60	18	28.69
70	6.59	10.51
80	3.92	6.26
90	3.55	5.66
100	3.51	5.6

4.2 Guard Band

The Monte Carlo simulations that were conducted for different transmission parameters result in a total interference probability that is calculated from the dRSS and iRSS levels over multiple iterations. Throughout these simulations, the 3GPP Emission

Mask relative to an OOB of -25 dBm/8mhz will be used, so the high level of interference probability is an indication of the inadequacy of this protection criteria.

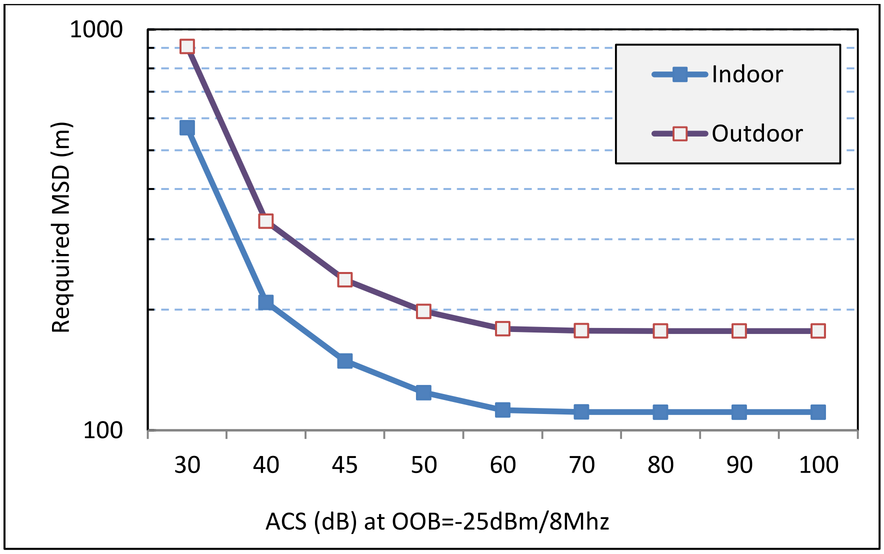

Figure 19-Effect of ACS on Required Separation Distance for OOB=-25 dBm/8MHz

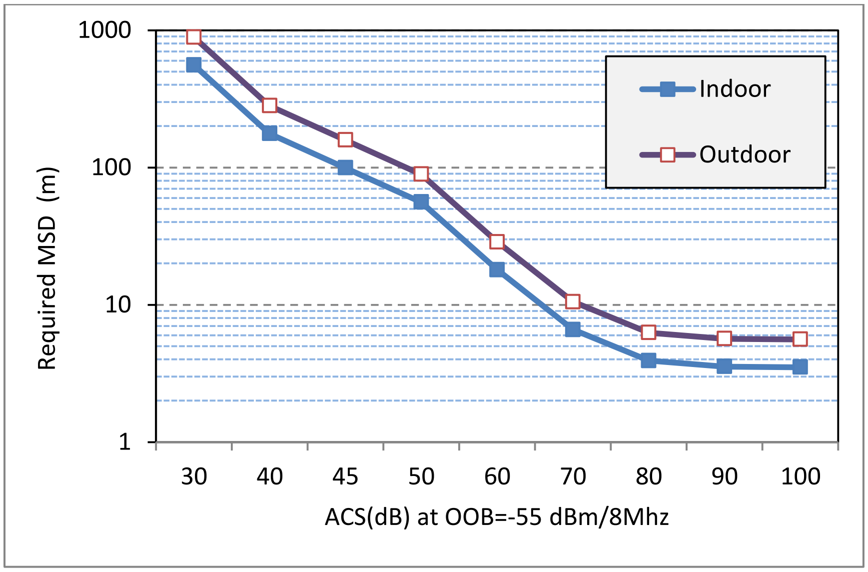

Figure 20- Effect of ACS on MSD for OOB=-55 dBm/8MHz

In order to study the effect of the guard band between the two systems, we varied the frequency separation in our simulations to reflect co-channel operation (guard band in negative values), null guard band, 5 MHz guard band, and 9 MHz guard band. The summarized results are shown in Table 12. Similarly, Figure 21 below shows the variation of the interference probability as a function of the guard band between LTE and DTV. The results reflect how critical the separation frequency is. Coexistence (0 MHz Guard band or even less) was shown to be almost impossible with an interference probability of over 90%. These high interference levels are all obtained under the OOB emission limit of -25 dBm/8Mhz and the purpose is not just to show the inadequacy of this OOB restriction, but to reflect the difference in interference probabilities for the parameters under study. This is also the case for all different parameters under study.

Table 12-Effect of Guard band on Interference Probability

	LTE 5 MHz	LTE 10 MHz	LTE 20 MHz
Separation Bandwidth (MHz)	Interference Probability	Interference Probability	Interference Probability
9.00	37.08	63.8	99.45
5.00	80.4	91.3	100
0.00	99.5	99.7	100
Overlapping	100	100	100

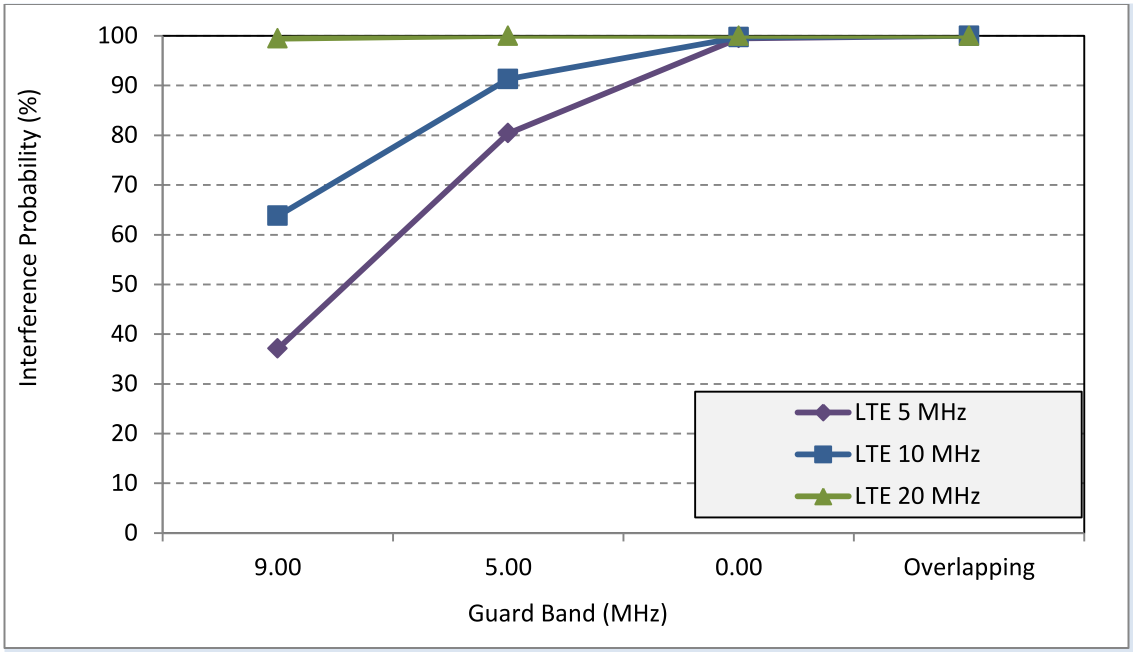

Figure 21-Effect of Guard Band on Interference Probability

4.3 Coverage Area

On the other hand, the performance of the network measured by the dRss is shown to be highly impacted by the separation distance between the DTV Transmitter and the DTV Receiver. From Table 13, we can see that the interference probability has dropped from 63% to almost 15% after changing the distance between DTV TX and DTV RX from 22.5 km to 15 km. Figure 22 show the variation of the interference probability and the dRSS with the variation of the distance between the DTV base station and receiver. It is clear from that the main contributor is not just the separation distance between the unwanted interferer and the victim receiver but also between the wanted transmitter and target receiver. In practice, this could be controlled by having much smaller DTV coverage areas. However, this would require more base station transmitters which will entail higher network implementation cost and lower efficiency. However, it is not the topic of this document to propose any restrictions or modifications onto the existing DTV networks.

Table 13-Effect of distance between DTV TX and RX

Distance between DTV TX and DTV Rx (km)	Interference Probability	dRss (dbm)
10.00	15	-61.06
15.00	40.42	-67.63
17.00	49.1	-69.86
19.00	58.54	-71.82
20.00	60.39	-72.78
22.50	63.8	-75.4

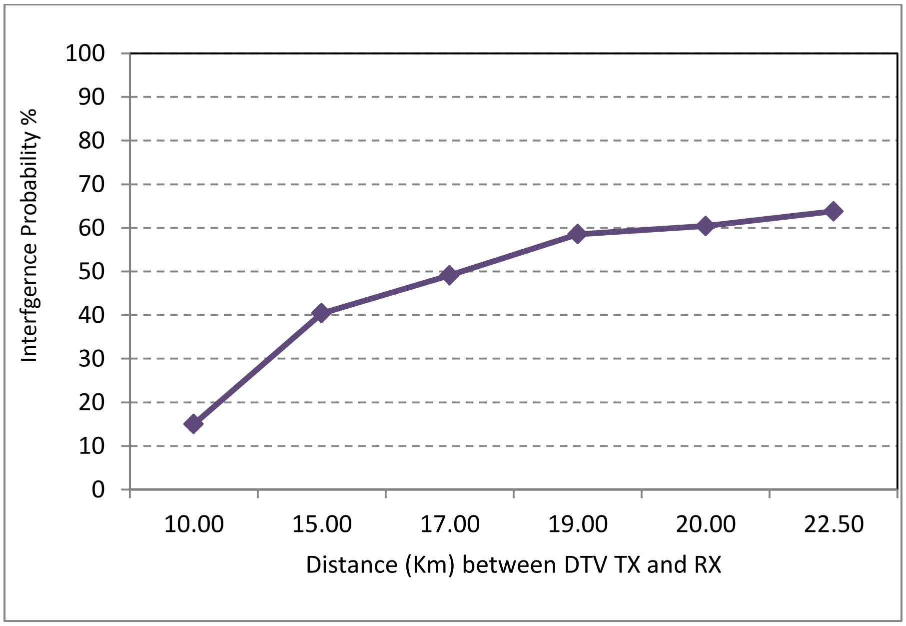

Figure 22-Effect of distance between DTV TX and RX

4.4 Bandwidth

Another factor that affects the level of interference is the bandwidth of operation of the LTE signal itself. Figure 23 shows the effect of the different system bandwidths on the interference probability. The results in Table 14 show that as the bandwidth increases, the interference probability increases.

Table 14-Effect of LTE System Bandwidth

	9 MHz Guard Band	5 MHz Guard Band
LTE Bandwidth (MHz)	Interference Probability	Interference Probability
5	37.08	80.4
10	63.8	91.3
20	99.45	100

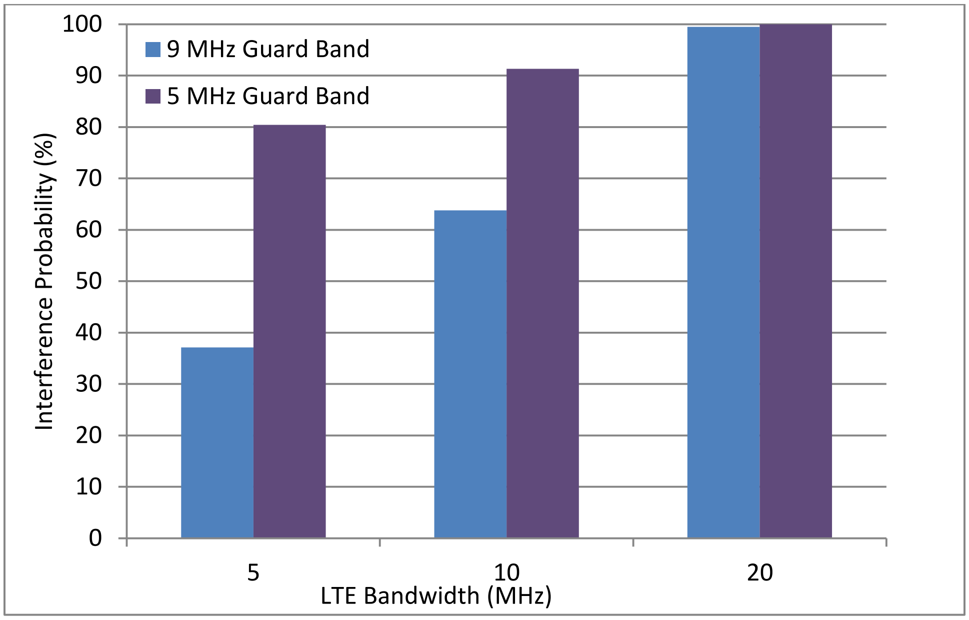

Figure 23-Effect of LTE Bandwidth

4.5 Transmission Power

In order to study the effect of the DTV Transmitter power, we varied the power between 65, 68, 70, 72, 75 and 80 dBm throughout all the different scenarios. The results showed that the increase of TX power has a direct effect on the signal performance where the desired received signal strength increased from -80 dBm to -64 dBm between 65 and 80 dBm TX power respectively. Similarly, the interference probability dropped remarkably to almost half from 51% to 10% between 65 dBm to 80 dBm TX power respectively. Figure 24 and Table 15 show the interference probability as a function of the DTV TX power. Similarly, Table 16 shows the variation of the desired signal strength dRSS as a function of the DTV TX power. On the other hand, the effect of the UE transmit power has very low impact on the OOB level required. In other words, lowering the UE transmit power can only result in a negligible reduction in the required OOB level. Table 17 and Figure 25 shows the variation of the TX power and its effect on the required OOB level as calculated by the MCL method.

Table 15- Effect of DTV TX Power on Interference Probability

	LTE 5 MHz	LTE 10 MHz	LTE 20 MHz
DTV TX Power (dBm)	Interference Probability	Interference Probability	Interference Probability
65.00	51.56	80.95	100.00
68.00	41.36	72.54	99.15
70.00	37.08	63.80	99.45
72.00	33.41	60.12	98.57
75.00	24.92	50.50	95.51
80.00	10.88	30.06	83.11

Table 16- Effect of DTV TX Power on dRSS

	LTE 5 MHz	LTE 10 MHz	LTE 20 MHz
DTV TX Power (dBm)	dRss (dbm)	dRss (dbm)	dRss (dbm)
65.00	-80.23	-79.98	-79.95
68.00	-77.27	-77.12	-77.5
70.00	-75.05	-75.4	-75.2
72.00	-73.45	-72.77	-73.16
75.00	-70.11	-70.45	-70.22

80.00	-64.83	-64.91	-65.36

4.6 Number of Users

In section 3.3, we discussed resource blocks and active users. The number of active users per cell influences the amount of interference present. To study the effect of the number of active users on the interference probability, we varied the number of assigned resource blocks per user for 5, 10, and 20 MHz bandwidth systems with 9 MHz Guard band, and the results are shown in Table 18 and Figure 26.

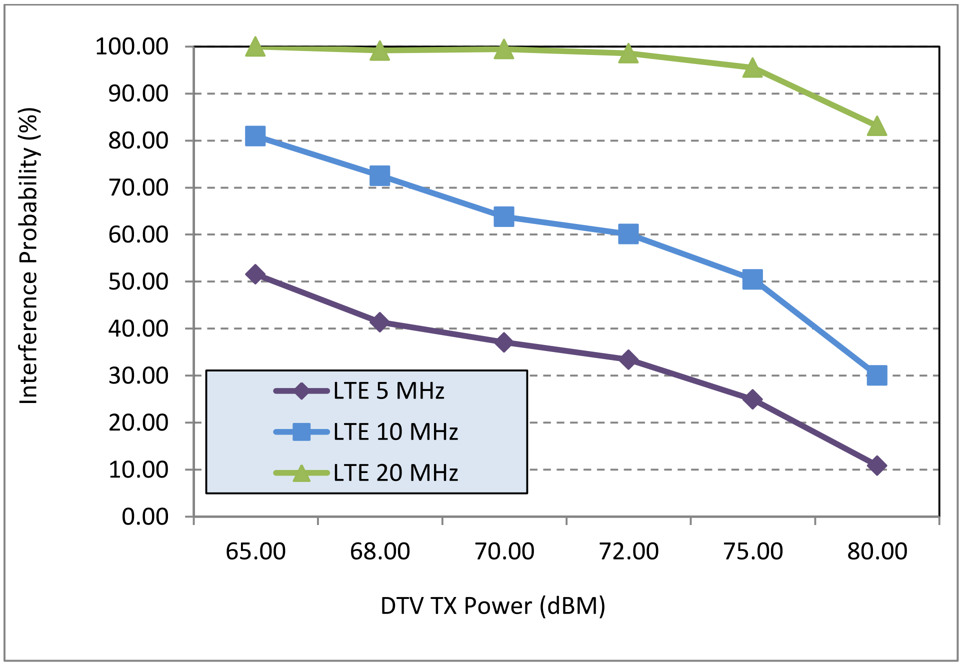

Figure 24- Effect of Variation of DTV Base Station TX Power

Table 17-Variation of Required OOB Level for Different LTE Transmit Powers

UE TX Power (dBm)	Required OOB (dbm/8mhz)
10	-55.9
11	-55.9

12	-56.03
13	-56.09
14	-56.16
15	-56.25
16	-56.36
17	-56.51
18	-56.71
19	-56.97
20	-57.32
21	-57.81
22	-58.51
23	-59.6

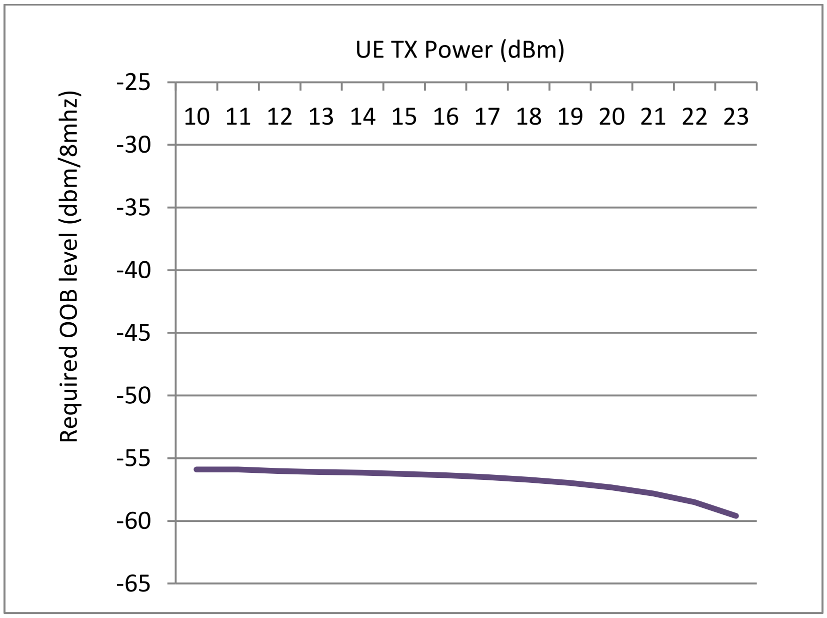

Figure 25-Effect of Variation of LTE TX Power on Required OOB

We are assuming here the worst case scenario of having a fully loaded system where the entire bandwidth is occupied. In order to study the effect of the loading, we simulated LTE systems using only a portion of the allocated bandwidth. Table 19 and Figure 27 show the decrease in interference probability with the decrease of the system loading.

Table 18-Effect of Resource Allocation on Interference Probability

	Interference Probability		
Number of Active Users	LTE 5 MHz	LTE 10 MHz	LTE 20 MHz
2	18.07	36.29	71.2
3	26.53	51.07	83.25
4	37.08	63.8	91.52
6	47.54	77.63	96.14
8	55.75	85.85	100
12	72	90.38	99.54

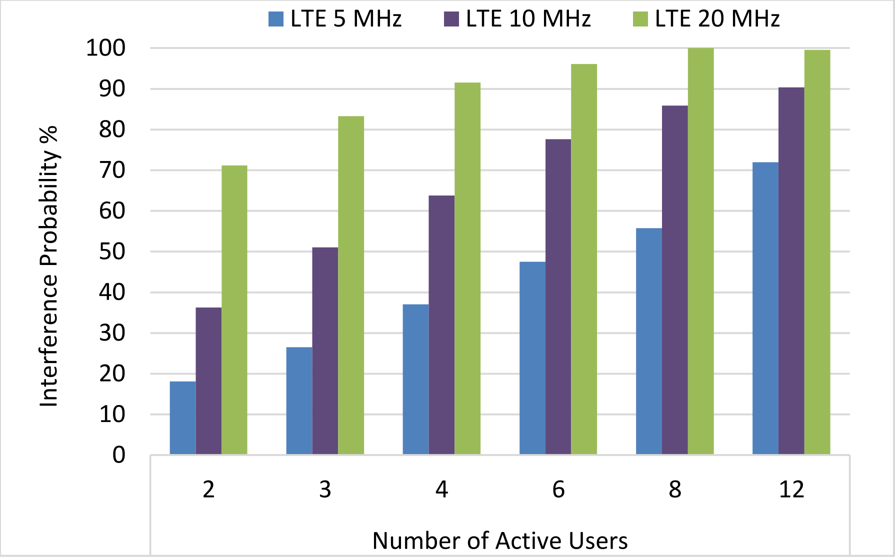

Figure 26- Effect of Resource Allocation on Interference Probability

Table 19- System Loading and Interference

	Interference Probability		
	LTE 5 MHz	LTE 10 MHz	LTE 20 MHz
Fully Loaded System	37.08	63.8	99.45
1/2 Loaded System	34.15	56.13	89.3
3/4 Loaded System	32.36	40.27	89.69
1/4 Loaded System	26.57	38.98	89.3

4.7 Environment

The simulation environment is another important parameter that can affect the levels of interference received by DTV receivers. When an urban environment is considered, the user distribution as well as propagation conditions change dramatically from when a rural environment is under study. Choosing the appropriate environment condition depends on the area in which the network is being deployed.

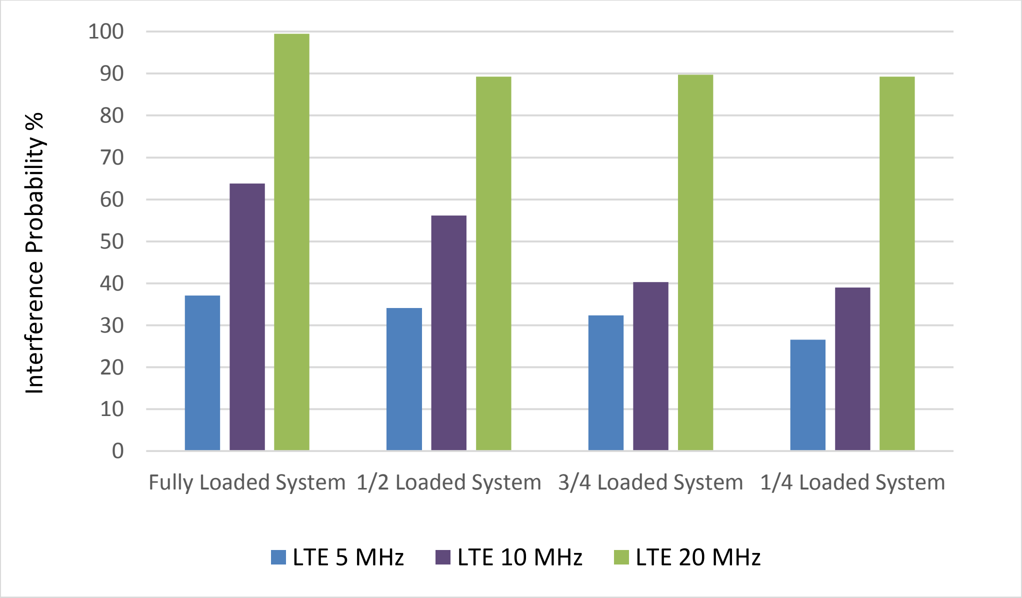

Figure 27- System Loading and Interference

SEAMCAT allows us to vary the simulation environment to study its effect on interference probability and dRSS. For 5, 10, and 20 MHz LTE systems with 9 MHz guard band, the results of the interference probability and dRSS for different environments are shown in Table 20 and Table 21 respectively. Figure 28 shows that the rural environment yields much lower interference levels and higher signal strengths.

Table 20-Results of Interference Probability for Different Simulation Environments

	LTE 5 MHz	LTE 10 MHz	LTE 20 MHz
Environment	Interference Probability %	Interference Probability %	Interference Probability %
Urban	37.08	63.8	99.45
Rural	5.2	12	65.9

Table 21- Results of dRSS for Different Simulation Environments

	LTE 5 MHz	LTE 10 MHz	LTE 20 MHz
Environment	dRss (dbm)	dRss (dbm)	dRss (dbm)
Urban	-75.05	-75.4	-75.2
Rural	-56.47	-56.32	-56.35

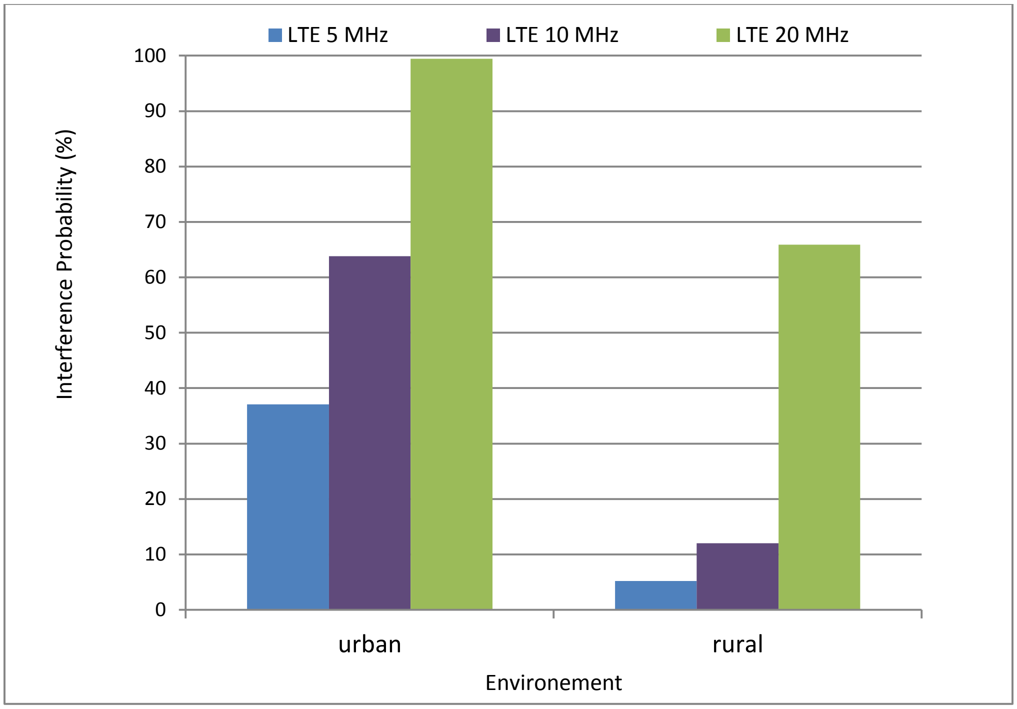

Figure 28-Interference Probability for different Simulation Environments

4.8 Reduced Capacity Systems

In this section, we show that by using a DVB-T2 system with a less required SNR, we can dramatically reduce the levels of interference. The implemented system can be varied according to the bit rate-SNR compromise. Using lower modulations and reducing the achieved bitrate allows a more susceptibility to interference with lower accepted SNR values. Such systems are described in [56] and are summarized in Table 22. In our simulations, we created multiple scenarios with lower bitrate DVB-T2 systems to analyze the effect of the required SNR on the coexistence between LTE and DTV. Table 23 and Figure 29 shows the different interference probabilities for different SNR values of a 10 MHz LTE system. We can see that even at the proposed OOB level of -25 dBm/8Mhz, we can have coexistence for DTV systems with SNR levels below 5 dB.

Table 22-Required SNR values for Lower Capacity DVB-T2 Systems [56]

Modulation	Code Rate	Required SNR (dB) in Rice	Required SNR (dB) in Rayleigh	Data Rate (Mbps)
QPSK	1/2	0.9	2	7.49
QPSK	3/5	2.7	4.1	9
QPSK	2/3	3.6	5.3	10
QPSK	3/4	4.6	6.6	11.2
QPSK	4/5	5.3	7.4	12.02
QPSK	5/6	5.9	8.3	12.53

Table 23-Variation of Interference Probability with Required SNR

Required SNR	Interference Probability %
20	68.77
19.6	63.8

17	52
15	41.47
13	29.71
11	22.10
10	17.81
9	13.32
8	10.57
7	10.5
6	7.05
5	5.58

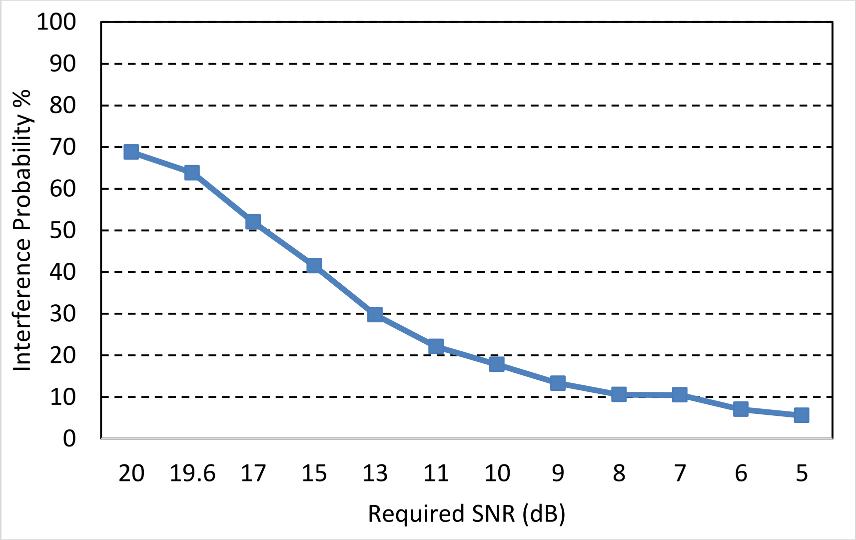

Figure 29- Variation of Interference Probability with Required SNR

4.9 Carrier Aggregation

Carrier Aggregation in LTE is usually used to increase the bandwidth and enable higher data rates in similar or different bands. In this paper, we will employ an intra-band contiguous carrier aggregation to enhance coexistence under low OOB restrictions. In order to mitigate the high levels of interference while keeping the OOB level at -25 dBm/8Mhz, we propose a new coexistence method based on aggregating adjacent LTE carriers of different bandwidths and powers to substitute the traditional system. By placing a lower bandwidth and lower power system in the first part adjacent to the broadcasting band, and then following it with the main LTE carrier, we are lowering the effect of the UE transmitter onto the victim DTV receiver. We have simulated several combinations of carriers either with same power levels (23 dBm) or with different power levels (one with 23 dBm and one with 15 dBm). Furthermore, we simulated 2 different required SNR levels (19.6 dB and 5 dB) to reflect the results from the previous section. The carrier combinations under study are shown in Figure 30. The results are shown in Table 24.

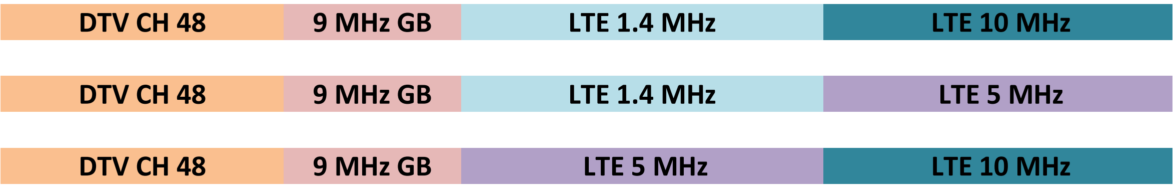

Figure 30-Carrier Aggregation Scenarios

Table 24-Interference Probability for Carrier Aggregation Scenarios

Carrier1 Bandwidth	Carrier 1 Power	Carrier2 Bandwidth	Carrier 2 Power	Carrier 1 Frequency (Mhz)	Carrier 2 Frequency (Mhz)	Required SNR (dB)	Interference Probability %
1.4 MHz	15	10 MHz	23	703.7	709.4	5	0.14
1.4 MHz	15	10 MHz	23	703.7	709.4	19.6	8.24
1.4 MHz	23	10 MHz	23	703.7	709.4	5	1.38
1.4 MHz	23	10 MHz	23	703.7	709.4	19.6	30.47
1.4 MHz	15	5 MHz	23	703.7	706.9	5	0.13
1.4 MHz	15	5 MHz	23	703.7	706.9	19.6	6.21

1.4 MHz	23	5 MHz	23	703.7	706.9	5	1.22
1.4 MHz	23	5 MHz	23	703.7	706.9	19.6	31.57
5 MHz	15	10 MHz	23	705.5	713	5	0.4
5 MHz	15	10 MHz	23	705.5	713	19.6	10.34
5 MHz	23	10 MHz	23	705.5	713	5	2.98
5 MHz	23	10 MHz	23	705.5	713	19.6	38.47

For a 5 Mhz LTE carrier aggregated with 1.4 Mhz carrier at a power of 15 dBm, we can see that the interference probability drops to 6.21%, which could be an appropriate coexistence scenario. The combinations with acceptable interference levels are shown in Table 25. When implementing lower data rate systems, coexistence becomes more possible with levels of interference reaching as low as 0.13%.

Table 25-Acceptable Coexistence Aggregation Scenarios

Carrier1 Bandwidth	Carrier 1 Power	Carrier2 Bandwidth	Carrier2 Power	Carrier 1 Frequency (Mhz)	Carrier 2 Frequency (Mhz)	Required SNR (dB)	Interference Probability %
1.4 MHz	15	5 MHz	23	703.7	706.9	19.6	6.21
1.4 MHz	23	10 MHz	23	703.7	709.4	5	1.38
1.4 MHz	15	5 MHz	23	703.7	706.9	5	0.13
1.4 MHz	15	10 MHz	23	703.7	709.4	5	0.14
1.4 MHz	23	5 MHz	23	703.7	706.9	5	1.22
5 MHz	15	10 MHz	23	705.5	713	5	0.4
5 MHz	23	10 MHz	23	705.5	713	5	2.98

CHAPTER 5

CONCLUSION

The allocation of the 700 MHz band to the Mobile Service requires a careful consideration of the sharing conditions between the Broadcasting Service in the adjacent UHF Frequencies and the newly introduced mobile system.

We analyzed the coexistence between LTE and DTV in the 700 MHz. The influence of the 3GPP proposed Out of Band (OOB) emission level of OOB=-25 dBm/8MHz was studied and it was found to cause higher interference levels that lead to higher separation distances. Under normal operating conditions, this OOB levels makes coexistence impossible to attain. However, when employing lower OOB levels, and increasing the restrictions on the LTE User Equipment, the 2 systems can coexist. Using OOB values as low as -55 dBm/8MHz or -60 dBm/8 MHz result in almost negligible separation distances. The results show that for a -55 dBm/8MHz and -60 dBm/8MHz, the minimum separation is 6.26m and 4.22 m for outdoor reception, and 3.92m and 2.66m for indoor respectively.

In order to provide the necessary protection for the broadcasting service, the effect of the different operation parameters were studied to assess sharing under these different conditions. We analyzed the effect of the receiver ACS to find that a minimum of 70 dB is required to ensure protection. In addition to that, it was shown that guard bands below 9 MHz are incapable of providing the necessary protection for DVB in the adjacent channel. In this case, the coexistence is impossible in overlapping frequencies. As for the effect of the LTE system bandwidth, the results showed that the higher the bandwidth is, the more severe the interference is. The effect of loading and number of active users was also analyzed. The results have shown that the more loaded the network is, the higher the interference is. Similarly, the number of active users is also related to the interference probability where it was shown that having a higher number of active users causes a higher level of interference.

Finally, and in order to propose a solution to the coexistence dilemma under high OOB levels, we proposed two different approaches that involve reduced capacity systems and carrier aggregation. We have shown that when using systems of lower required signal to noise ratio (SNR), we are able to drastically reduce the interference level from LTE. Furthermore, when using a combination of two carriers of different bandwidths and transmission powers, we are able to mitigate the interference even with low OOB restrictions.

In summary, it is not one factor only that contributes to interference or enhances coexistence; it is a compilation and compromise that needs to be studied carefully for every scenario being deployed.

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