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MATHEUS FREIRE E SILVA DO NASCIMENTO

TV WHITE SPACE FOR DIGITAL INCLUSION IN BRAZIL

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TV WHITE SPACE FOR DIGITAL INCLUSION IN BRAZIL

Dissertação apresentada ao Curso de Mestrado em Engenharia de Teleinformática da Universidade Federal do Ceará, como parte dos requisitos para obtenção do Título de Mestre em Engenharia de Teleinformática. Área de concentração: Sistemas de Comunicação.

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MATHEUS FREIRE E SILVA DO NASCIMENTO

TV WHITE SPACE FOR DIGITAL INCLUSION IN BRAZIL

Dissertation presented to the Master Program in Teleinformatics Engineering at the Federal University of Ceará, as part of the requirements for obtaining the Master's Degree in Teleinformatics Engineering. Concentration area: Communication Systems.

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RESUMO

Este trabalho apresenta uma oportunidade tecnológica para fazer o uso eficiente do espectro e, ao mesmo tempo, mostra sua importância para a inclusão digital no Brasil. A metodologia é aplicada em um estudo de caso que investiga a área do Ceará, estado brasileiro, onde uma quantidade significativa de espectro que pode ser desencadeada através da exploração dos Espaços em Brancos de TV é relevante a ser considerada, devido às suas condições geográficas e econômicas. Estes espaços em branco podem preencher alguns buracos no estado que não apresentam qualquer cobertura móvel e melhorar os serviços de telecomunicações em outras áreas. O conceito de tecnologia, situação de regulação mundial e possíveis aplicações usando o recurso são descritos ao longo deste trabalho. A principal finalidade é usar os Espaços em Brancos de TV juntamente com a banda do LTE, para tentar suavizar parte do péssimo serviço de cobertura das redes 3G e 4G.

Palavras-chave: Espaços em Brancos de TV, Mudança Digital, Banco de Dados de Geolocalização, Detecção de Espectro, Dispositivo de Espaço em Branco, Alocação de Recursos, Capacidade de Shannon Modificada.

ABSTRACT

This work presents a technological opportunity to make efficient use of the spectrum and at the same time shows its importance to provide digital inclusion in Brazil. The methodology is applied in a case study investigating the area of Ceará, a Brazilian state, where a significant amount of spectrum that can be unleashed via TV White Space exploitation is relevant to be considered, due to its geographic and economical conditions. These white spaces can fill up some holes in the state that do not present any mobile coverage and improve the telecommunication services in other areas. The technology concept, world regulation situation and possible applications using the resource are described throughout this work. The main purpose is to use TV White Spaces together with the LTE band, as a way to soften part of the poor coverage services of 3G, 4G.

Keywords: TV White Space, Digital Switchover, Geolocation Database, Spectrum Sensing, White Space Device, Resource Allocation, Adjusted Shannon Capacity.

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LIST OF ABBREVIATIONS AND ACRONYMS

Anatel	National Telecommunications Agency
BS	Base Station
BST	Based Segmented Transmission
CDF	Cumulative Distribution Function
CQI	Channel Quality Indicator
CR	Cognitive Radio
CDMA	Code Division Multiple Access
DTED	Digital Terrain Elevation Data
DSO	Digital Switchover
DTV	Digital TV
DVB-T	Digital Video Broadcasting - Terrestrial
EIRP	Equivalent Isotropic Radiated Power
ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
FDD	Frequency Division Duplex
FUTEBOL	Federated Union of Telecommunications Research Facilities for an EU-Brazil Open Laboratory
GLDB	Geolocation Database
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GUI	Graphical user interface
HSS	Home Subscriber Serve
ISM	Industrial-Scientific-Medical
ISDB-Tb	Integrated Services Digital Broadcasting, Terrestrial, Brazilian version
ITU	International Telecommunication Union
ITM	Irregular Terrain Model
LTE	Long Term Evolution
LOS	Line-of-Sight
LSA	Licensed Shared Access
MAC	Medium Access Control
MiniCom	Ministry of Communications
MIMO	Multiple Input, Multiple Output
NLOS	Non-line-of-sight
MME	Mobility Management Entity
NOI	Notice of Inquiry
NPRM	Notice of Proposed Rulemaking
NRA	National Regulatory Authority

OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
Ofcom	Office of Communications
OTT	Over-the-top
PAPR	Peak-to-Average Power Ratio
PCRF	Policy and Charging Rules Function
PMSE	Programme Making and Special Events
PGW	Packet Gateway
QoS	Quality of Service
RAT	Radio Access Technologies
RB	Resource Block
RRS	Reconfigurable Radio Systems
RSSI	Receiver Signal Strength Indicator
RTIC	Revista de Tecnologia da Informação e Comunicação
SBTVD	Brazilian Digital Television System
SINR	Signal to Interference plus Noise Ratio
SFN	Single Frequency Network
SC-FDMA	Single Carrier Frequency Division Multiple Access
SGW	Service Gateway
SINR	Signal to Interference plus Noise Ratio
SRTM	Shuttle Radar Topography Mission
SISO	Single Input, Single Output
SNMPv2	Simple Network Management Protocol version 2
TDD	Time Division Duplex
TTI	Transmission Time Interval
TVWS	TV White Spaces
TV	Television
UHF	Ultra High Frequency
UK	United Kingdom
USA	United States of America
UMTS	Universal Mobile Telecommunications Service
VoIP	Voice over IP
VHF	Very High Frequency
WSD	White Space Device
WCDMA	Wide-Band Code-Division Multiple Access

SUMARY

1 INTRODUCTION

It is difficult to imagine the everyday life in our current moment without the existence of smartphones. These devices sums billions in our hands, many people use them daily as personal purpose, commercial, to study, etc. These machines are transforming the way we face and share information among each other.

In spite of all contributions provided by such devices, these smartphones, for its proper functioning, need to use part of the spectrum to execute their respective functionalities. So, as we know, the spectrum is not only used by the smartphones, but also by Television, Radio, Radars, Sattelite, etc. This resource is becoming scarce, and it is always important the presence of techniques which makes efficient use of spectrum, having in mind the increasing demand for data transmission in 4G systems and considering the emergence of 5G.

The main objective of this work is to provide solutions that make efficient use of spectrum, resulting in a greater amount of radio frequency spectrum available to be used, which leads to the implementation of new mobile services to be offered to the users.

In this work, we establish a study about the benefits and possibilities from the use of the TVWS, considering the geographic and regional condition of the suburban and rural regions of the state of Ceará in Brazil. TVWS will be analyzed as a possible solution to provide digital inclusion and overcome the serious coverage problem in the region, which is a quite common problem. Therefore, the case study of Ceará is representative of many others rural regions throughout Brazil.

1.1 Motivation

"There is no more spectrum available", declared Herbert Hoover, the US Secretary of Commerce in 1925 [6]. Radio spectrum is a term that normally refers to the full frequency range that is used to transmit information through radio waves. It is a national resource, much like water, land, gas, and minerals. However, it is a reusable resource, so it requires techniques for its efficient frequency reuse, allowing more bits per hertz to be transmitted.

The increasing demand for services such as mobile telephony does require changes in how the spectrum is managed, since 5G communication systems will demand thousand to ten thousand times more capacity comparing to the legacy 4G ones [1]. It is visible the need for additional spectrum to provide new wireless services. The radio spectrum is also used in licensed bands for radio and television broadcasts, satellite communications, air traffic control, GPS (Global Positioning System), as well as for military and police communications.

Several measurements performed worldwide showed that spectrum occupancy rates range only from 5% to 15% [2]; this fact has been noticeably verified in the case of TV bands [3]. This happens due to the way the current frequency spectrum allocation regime is done, which is primarily fixed during a period of time through bids and auctioning processes. This fixed allocation scheme has resulted in temporal and spatial spectrum underutilization.

In response to this situation, the concept of CR (Cognitive Radio) has emerged [3], where the radio device is able to reuse underutilized spectrum chunks in an opportunistic manner. These CR devices allowed the emergence of the incumbents also known as the primary spectrum users, since they own the rights to explore the spectrum due to regulatory decisions; and secondary users that are only able to use the spectrum when no primary users are using it, employing opportunistic methods.

The current global analog TV switch-off, or commonly known as DSO (Digital Switchover), has brought an opportunity for reallocating this spectrum resource, opening new opportunities to introduce new business models, players and technologies as TVWS into the market. Some frequency bands that were once used for analog TV broadcasting will be completely cleared, leaving space for deploying new licensed or unlicensed wireless services, but following a careful regime causing no harm to the primary users, the original owners of the rights to explore that range of the spectrum.

With the appearance of TVWS due to the DSO process, the CR may use this portion of TV (Television) bands that are unused by licensed services [4]. The white spaces has been recognized as a promising opportunity to obtain new spectrum for emerging wireless broadband services, due to its low utilization rate and excellent propagation properties in the VHF (Very High Frequency) and UHF (Ultra High Frequency) bands [5]. Nevertheless, this work focuses on the UHF band, since it is the only one used by the Brazilian Digital TV System [2].

At the same time, Internet access and mobile services are not available in every geographic region, specially in rural or outside major urban areas. This situation is usually the result of low economic attractiveness of such areas for operators to deploy their telecommunication infrastructure. In the current regulatory scenario, few operators buy spectrum to cover rural areas, but when they buy spectrum to cover urban areas, sometimes the rural spectrum is included essentially for free, as it was the case of the auctioning process of the 2.5 GHz band in Brazil, when the buyers acquired the 450 MHz band free of charge [7]. The use of TVWS comes to soften part of these problems, providing new telecommunication services in rural and suburban regions and improving existing services.

1.2 Spectrum Management

There is a lot of wireless technologies, such as mobile telephony, television, radio, etc. Such technologies were constructed to coexist on the same physical medium and to be selectively detected using the appropriate channel and equipment. The ability to detect a certain signal is based on the ability to isolate it using a physical characteristic of its transmission. An example of a physical characteristic is the radiofrequency spectrum that consists of electromagnetic waves used for communications. The radiofrequency spectrum is subdivided into eight bands according to the ITU (International Telecommunication Union)[1], as seen in Table 1.

Table 1: Subdivision of the radio frequency spectrum according to ITU.

Symbol	Frequency Range
VLF	3 kHz to 30 kHz
LF	30 kHz to 300 kHz
MF	300 kHz to 3000 kHz
HF	3 MHz to 30 MHz
VHF	30 MHz to 300 MHz
UHF	300 MHz to 3000 MHz
SHF	3 GHz to 30 GHz
EHF	30 GHz to 300 GHz

Source: Table from [8].

Radio wave frequencies have different propagation characteristics, each one suitable for a particular application. For example, low-frequency radio waves are suitable for long-range communications (AM Radio) and high-frequency radio waves are best suited for short-range (Bluetooth) wireless communications [9].

As demand grows, spectrum needs to be managed to prevent interference between different users. If users transmit at the same time, at near frequencies and close enough to each other, they usually cause interference that can make both systems unusable. In some cases, “close enough” can be tens or hundreds of meters away [9].

The spectrum management has improved the flexibility of spectrum use and have also opened up new opportunities for different wireless technologies to use the radio spectrum more efficiently. As an example we have the emergence of cognitive radio, a technology that has great potential to access the spectrum under different conditions, improving the frequency reuse [8].

Most of this natural electromagnetic resource being used today is allocated through exclusive licenses; in other words, in the geographical area of applicability of the license, only the licensed one can use the spectrum for some application. There are, however, spectrum bands identified as being license-exempt, reserved for applications such

[1] The ITU is an agency of the United Nations whose purpose is to coordinate telecommunication operations and services throughout the world.

as ISM (Industrial-Scientific-Medical) and to facilitate the use of the spectrum collectively by users, an example is Wi-Fi in the 2.4 GHz and 5 GHz bands.

The traditional access model is the most widely used model to access the spectrum in most countries, where frequency bands are licensed to government-authorized users. In this case, the spectrum auctions are the most common method of spectrum allocation. Any interested party (TV broadcasters, telephone operators, etc.) in the use of the auctioned band can bid to obtain the license. The auction winner is defined by the government, and can use the radio resource within rules and regulations defined by the government for a certain period of time. The advantage of this model is its robustness to interference, due to only licensed users make use of certain band [8].

The major problem with the traditional spectrum management model is its lack of flexibility, which leads to inefficient use of spectrum. To solve this problems, dynamic access models have emerged, using new technologies and concepts that allow greater flexibility to access the spectrum, overcoming the limitations inherent in the traditional management. Among these solutions we highlight the TVWS mechanism that would imply in the redistribution of underutilized resources to secondary users, resulting in greater economic returns and making efficient use of spectrum. However, some precautions must be taken because an incorrect reassignment of the underutilized spectrum could lead to a interference to the primary useres.

1.3 Objectives

The work objectives are described as follows

- Show the inefficient use of the radio spectrum and at the same time its scarcity.
- Diferenciate the use of the spectrum in a licensed basis to unlicensed. Highlighting the existence of primary users, owner of the resource, and the secondary users.
- Clarify the importance of techniques that makes efficient use of spectrum, focusing on the opportunistic use of TV bands.

As main contribution, this work proposes the use of TVWS to provide telecommunication services in rural and suburban regions. The specific objectives are:

- Introduce the concepts, originations, main characteristics, standards, and world situation of TVWS, as well as discuss about the main applications that have been in use so far.
- Explain the use, and set up of the Radio Mobile to simulate a scenario using just one TVWS channel to shows its gain of coverage and capacity in a city of Ceará called Jericoacoara.
- Propose a busines model to explore the benefits of TVWS.
- Determine the best allocation strategy to the scenario using both LTE and TVWS bands.

- Demonstrate the gain of capacity and coverage through the use of LTE along with TVWS on the same cell.

1.4 Thesis Organization

This thesis is organized as follows: in Chapter 2, it is explained the concept and origination of TVWS, the oportunistic methods for its exploitation, the main TVWS standards and its situation in the world and in Brazil. Chapter 3 shows the Ceará case study developed during the FUTEBOL (Federated Union of Telecommunications Research Facilities for an EU-Brazil Open Laboratory) project that illustrates the gain of coverage and capacity by the use of TVWS at Jericoacoara, a rural city of Ceará. Chapter 4 shows a simulation of the cell using at the same time LTE (Long Term Evolution) and TVWS bands, and the respectives gains are discussed. Chapter 5 presents the conclusion and future works.

1.5 Methodology

The Chapter 3 presents a case study that implements the LTE over TVWS scenario in Jericoacoara, a city of Ceará. It was used the Radio Mobile, a free software that simulates the propagation of frequencies from 20 MHz to 2 GHz. The software was used to simulate the propagation of one specific unused TV channel at the region of Jericoacoara. The Radio Mobile was used due to its good characteristics to deal with the geography of the scenario, using proper propagation models that considers the specific conditions of terrain elevation and clime. This chapter presents the gain of capacity and coverage provided by the use of only one TV channel, both gains are calculated using the Radio Mobile, the capacity gain analysis was calculated with the aid of Matlab software that was used to estimate the average data rate of the LTE over TVWS scenario.

The Chapter 4 presents a different scenario that the one presented in the Chapter 3, but the parameters used in both chapters follow the same references. This chapter consists in using the TVWS to alleviate part of the data load in the LTE network, some users are moved to the TV band. It was used the Matlab software to perform this scenario which combines LTE band of 2.6GHz and TVWS on the same system, the gains provided by such combination were compared with one scenario using only the LTE band of 2.6GHZ

1.6 Scientific Production

The following work was submitted and accepted for a Brazilian magazine, RTIC (Revista de Tecnologia da Informação e Comunicação), during the Master period.

This publication served as the basis for this thesis.

- **Matheus F. S. do Nascimento**, Raphael B. Evangelista, Carlos F. M. e Silva, Francisco R. P. Cavalcanti,"TV White Spaces for Digital Inclusion in Brazil", Revista de Tecnologia da Informação e Comunicação, NO.2, vol 6, pages 6-15, 2016.

2 TV WHITE SPACES

Significantly more spectrum and much wider bandwidth than what is available today will be needed in order to reach the targets of future mobile broadband systems, and it is visible that the fixed allocation scheme of frequency has resulted in an underutilization of the spectrum spatially and temporally. So it is expected that in the future, the spectrum will be made available under sharing regimes, however it is not totally clear yet which of the many different proposed spectrum sharing options will become relevant in practice.

Between many others spectrum sharing schemes, the LSA (Licensed Shared Access) is a concept which is gaining strength and consist in a regulatory approach aiming to facilitate the introduction of radio communication systems operated by a limited number of licensees under an individual licensing regime in a frequency band already assigned or expected to be assigned to one or more incumbent users [1]; but in this work it will be covered only about the TVWS technology as an unlicensed sharing mechanism. In an unlicensed regime the systems have to share spectrum with others unlicensed devices while, ensuring the protection of primary users of the band; different from the well-defined conditions which are part of the LSA scheme.

2.1 Origin, Concept and Characteristics

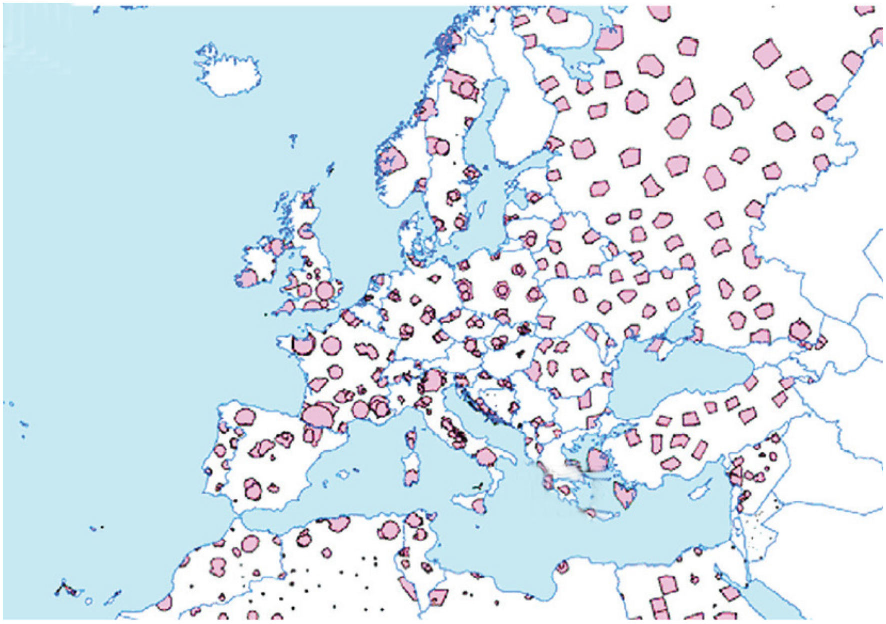
The DSO, also known as the digital television transition, is a process in which analog TV broadcasting is replaced by the digital one. It is the process that has been successfully completed in various countries and it is still in progress in some others. As an example, in Brazil, the Ministry of Communications established in 2014 a new DSO plan. It is important to note that after the analog TV switches off, digital TV will be the only signal available.

The switch off of Brazilian analog TV started in 2015 in Brasília and municipalities in the surrounding areas. The metropolitan regions of São Paulo, Belo Horizonte, Goiânia and Rio de Janeiro went through the same process later that year. The process is expected to end on November 2018, covering all the cities outside metropolitan regions in the country [10]. But recently, the Ministry of Communications published changes in the entire schedule and the final date may even be postponed to 2023.

The advantage of DTV (Digital TV) is the frequency spectrum optimization, allowing more content to be transmitted in the same channels, due to the fact that codification techniques and modulation schemes for digital systems are more efficient. This advantage results in what the ITU calls "digital dividend" [2]; in analog broadcasting a non-used channel is required between two contiguous channels to avoid interference, but digital broadcasting does not need this separation, as the technology enables the use of adjacent channels without mutual interference.

DTV planning followed the strategy of frequency reuse to eliminate the interference between broadcast towers, it is the same strategy used in cellular networks, where in two adjacent areas are generally allocated a set of completely different channels. So the use of the same DTV channel in two neighboring regions is avoided. This naturally leaves a lot of unused spectrum where specific channels are not used. To illustrate this situation, Figure 1 shows the regions using channel 21 in Europe [11], and the remaining space between these regions, or between the service areas of DTV transmitters using channel 21, is the white space for this specific channel.

Figure 1: Europe areas using DTV channel 21.



Source: Figure from [11].

As such, TVWS are locally underutilized portions of the terrestrial TV bands and occurs as a by-product of the DSO. It is a portion of the spectrum in the range of VHF and UHF that is not in use at a particular time and location [12], and therefore, it represents a new opportunity for wireless networking in a frequency band that has good propagation characteristics. The basic principle consists of allowing unlicensed, secondary devices to access spectrum at specific geographic locations and/or during specific time intervals, not interfering with terrestrial TV reception, or any other primary service. Importantly, the TVWS regulations require TVWS devices to obtain authorization before they can transmit, and require those devices to cease operation when they are located inside the protected areas [1].

TVWS occur due to three main reasons [4]. The first was the need for guard spaces between analog TV services in the same license area to avoid interference. They also arise from the need for geographic separation between TV services that are in different license areas, but are broadcasting on the same channel. Finally, they arise in areas where channels are not allocated to broadcasters for TV services, either because of the limited supply of broadcasting services or because there is limited demand for broadcasting services (typically because of low population density; but more commonly because of the increasing range of technologies that can be used to deliver broadcasting services, the main fact considered in this study).

TVWS can be used by an unlicensed WSD (White Space Device)[2],which is a CR device that can use white space spectrum without causing harmful interference to licensed services as DTV, in a license-exempt and opportunistic manner to improve the spectrum efficiency and alleviate today's global spectrum scarcity.

One of the first networks implemented using white spaces was deployed in Wilmington, North Carolina, culminating in a regulatory process initiated by the FCC (Federal Communications Commission) in May, 2004.

2.2 Opportunistic Spectrum Access Methods for TVWS Exploitation

The adoption of mechanisms that safely and in real time determine where and when to use TVWS for secondary users are essential [11]. These mechanisms facilitate the opportunistic spectrum access by the WSD. The focus is to provide precise information about which TV channel(s) to use and the maximum allowed effective EIRP (Equivalent Isotropic Radiated Power) that can be used by the secondary wireless devices. There are two main mechanisms that have been established in the literature for the opportunistic TVWS spectrum access: spectrum sensing and GLDB (Geolocation Database) [11].

2.2.1 *Spectrum Sensing*

Spectrum Sensing is a method of measuring spectrum in a cyclical manner to detect primary transmitters for the express purpose of protecting the primary receivers and to avoid interference with the primary systems. Spectrum sensing enables TVWS devices to detect the presence of TV signals and provides a smart, adaptive, and distributed solution to identify the TV white bands.

Spectrum sensing involves the incorporation of a spectrum scanner in all nodes of the network, which consists in the scanning of the RF energy in a given channel to detect the presence of incumbents. For the WSD to use a specific TV channel, this channel must be reported empty by the scanners [4]. Specific and sophisticated sensing algorithms

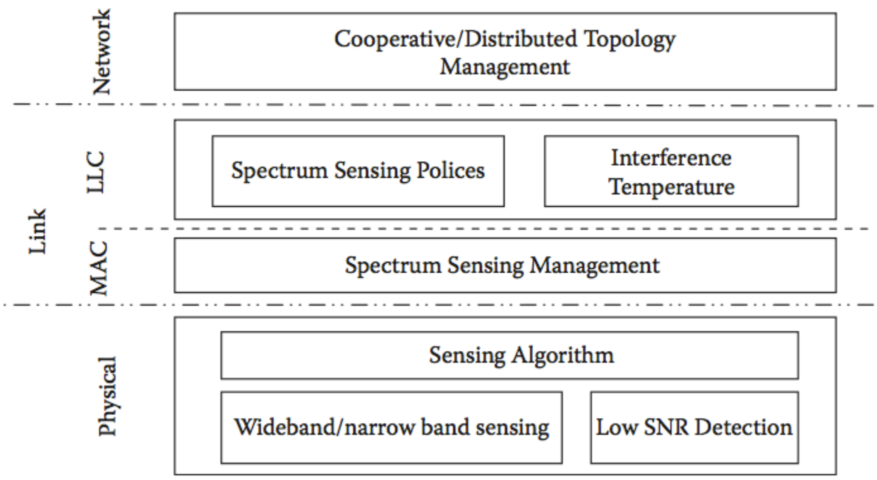
[2]In this work, the BS (Base Station) and end users are considered to be WSDs, however, this definition can be different in other studies.

have been proposed in the literature, which can detect a distant DTV transmission even if the signal is far below the noise level. According to [11], sensing methods can be roughly categorized into blind — that do not require knowledge about the primary signal — and feature-based — that exploit the characteristics of the primary signal which are known a priori.

Figure 2 illustrates the sensing functions in the physical, MAC (Medium Access Control), and network layers, as well as a variety of methods and techniques that can be mapped to achieve the sensing stack functionalities. At the physical layer, sensing can be performed by different sensing methods that is, spectrum sensing can be performed with wide band or narrow band scanning techniques in which the target band can be divided into sub-bands and scanned with a parallel or a sequential scanning method, in which case sensing may exploit the frequency hopping method for a fast scanning of the frequency band [4].

Sensing also requires a networking solution for coordination of a cooperative, whereby a distributed sensing management is needed for topology management, query issues, sensing load distribution, and information exchange. Further sensing is required to map with regularity and to resolve policy issues. A spectrum sensing necessitates the use of a sort of distributed and/or centralized data/decision fusion strategy for the combination of sensing results

Figure 2: Spectrum sensing functions.



Source: Figure from [4].

2.2.2 *Geolocation Database*

The GLDB approach can be employed with or without spectrum sensing, and it is the main focus of this work. As we know, the licensed DTV channels are a fixed system and due to this fact, a database with maps of locations of the TVWS availability could be implemented, along with allowed power for secondary use.

In this approach, the WSDs obtain the available TV channels via querying a certified GLDB instead of sensing the local spectrum environment [5]. Due to this fact, the GLDB needs to periodically update the information about the TVWS availability. The procedure runs like this: WSDs first report their locations to a GLDB; then the database computes and returns the available TV channels that WSDs can use in a certain time period without causing any harm to the primary services [5], the interference between WSDs depends on the architecture adopted, there are some mechanisms that allow WSDs to avoid such interference situations that are called “coexistence mechanisms” [3]. The GLDB takes inputs from the regulators and incumbents to form the basis of the channel occupancy map. Figure 3 illustrates the GLDB approach.

Another important issue is related to how the access to the database is done, there are two ways. The first one assumes that the database is maintained in a centralized manner (e.g., at the NRA (National Regulatory Authority)), and all TVWS devices perform requests to this database to acquire information about the channels. In this case, the geolocation maps can be of virtually unlimited resolution and complexity. The second case involves a version of the geolocation maps statically stored in each WSD and manually updated at specific intervals. With this approach, the TVWS network via embedded GPS receivers, immediately knows which channels to use. This last option eliminates the need for external communication; however, it poses limitations on the size of the GLDB.

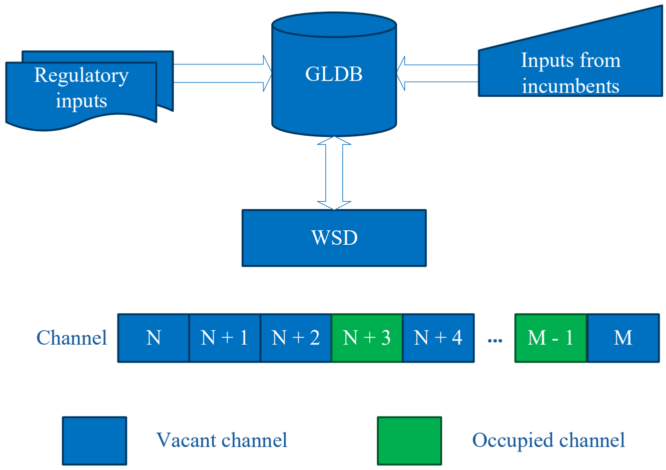
Additionally, the work in [14] describes an experimental testbed that combines the DVB-T (Digital Video Broadcasting - Terrestrial) GLDB with blind sensing techniques in a way to protect primary users from secondary users of the spectrum. The experimental results indicated that this combination is able to achieve better protection of primary users than just using spectrum sensing.

2.3 Main Standards

The following summarizes the main standards for TVWS [2], [16]:

- ECMA-392
  First TVWS standard published and mainly designed for communication between personal devices. Supports channel bandwidths of 6, 7, and 8 MHz for TV channels.
- IEEE 802.22
  TVWS for rural broadband services and supports channel bandwidths of 6, 7, and 8 MHz. Another related standard published by this group is IEEE 802.22.1 to enhance the protection of licensed users from interference by 802.22 systems.
- IEEE 802.11af
  Formed in January 2010 to adopt 802.11 for TV band operation. Implements wire-

Figure 3: GLDB schematic approach and vacant/occupied DTV channels. The regulatory and incumbents inputs specifies the channel and the maximum allowed EIRP that should be used to do not interfere with the primary users.



Source: Figure from [15].

less broadband networks in the bandwidth allocated to TV broadcasters, and has been called Super Wi-Fi and also White-Fi by FCC.

- IEEE 802.19
  The purpose of the standard is to enable the family of IEEE 802 wireless standards to more effectively use TV white space by providing standard coexistence methods among dissimilar or independently operated TVWS networks and dissimilar WSD.
- IEEE DySPAN
  DySPAN-SC formed a new task group, 1900.7, to create yet another MAC/PHY standard for TVWS. The goal is to facilitate a variety of applications, including support of high mobility, both low-power and high-power, short, medium, and long-range, and a variety of network topologies while avoiding causing harmful interference to incumbent users.
- ETSI RRS
  Currently considers the usage of TVWS for adapting existing and/or evolving radio standards, such as LTE, to a possible operation in white space bands.

In the future, we expect that more technologies reach some level of maturity to finally be designated to operate with TVWS, including LTE, which is the focus of this work.

2.4 TVWS in the world

Each country has its own spectrum attribution table that defines which services should be run on which range of the spectrum. It also designates certain frequency bands as unlicensed, e.g., for home wireless phones, remote controls, and Bluetooth devices. But it is up to the NRA to establish the specific requirements for commercial or non-profit usage of the spectrum.

The potential uses of TVWS are still being considered by the industry and regulatory bodies, there are uncertainties about what sort of TVWS availability is realistic [17]. The amount of TVWS spectrum available can change significantly from one to another country [2]. In this work we consider the specificities of the Brazilian regulatory scenario and how DSO will play out in Brazil.

The TVWS also depends on regulations such as the protection margin given to the primary user, height above average terrain, the transmission power of secondary users, and separation of unlicensed users from licensed ones. Since, as it is well known, the actual availability of TVWS varies in both location and time, operators of secondary services are interested in the amount of available white space. The estimation of TVWS has been done in countries like the USA (United States of America), United Kingdom, Europe, Japan, and India. For example, in Japan, out of 40 channels, on average, 16.67 channels (41.67 percent) are available in 84.3 percent of the areas. The available TV white space by area in Germany, the United Kingdom, Switzerland, and Denmark on average ranges between 48 and 63 percent of the 40 TV channel bands [18].

There are some costs related to putting in place the new regulatory regime. The policy making process to enable a new use may require significant resources at the regulator [12]. But as TVWS improves spectrum utilization, new services may be provided and existing ones could be delivered at lower prices and with high quality, benefiting the population.

2.4.1 *FCC and Ofcom Regulations*

Many countries have studied the use of TVWS, but only two countries currently have a proper regulation model that permits the license-exempt use of TVWS: the USA and the UK (United Kingdom).

The FCC is an independent regulatory agency of the USA, which is in charge with regulating interstate and international communications by radio, television, wire, satellite, and cable [19].

In June 2002, it was established the Spectrum Policy Task Force to assist the commission in issues regarding to some possible changes in the spectrum policy. The task force issued a report to FCC in November 2002 where concepts like white spaces and dynamic spectrum access were discussed. Later, in December of the same year, this report led to a NOI (Notice of Inquiry) which describes how in many locations exists unused TV channels. This NOI gathered a set of questions to industry regarding how the rules related to the unlicensed use of unused TV portion of the spectrum should be structured. Based on the answers obtained, the FCC issued in 2004, a NPRM (Notice of Proposed Rulemaking) with the possible rules for use of TV white space.

The NPRM proposes different methods for identification of unused TV channels, requirements that should be followed like maximum transmit power, possible antenna gains, etc. After the NPRM was issued, it was accomplished a set of tests related to the proposed rule, where some TVWS prototypes were proposed by companies. With the information analyzed with the prototypes, it was then released the FCC Report & Order, providing the rules that an unlicensed device must follow in order to be certified to use TVWS. This document was later augmented and revised, giving rise to the Second Memorandum Opinion and Order, which includes used terminologies, definitions, and the proper rules [4], allowing unlicensed secondary operations to develop new communication opportunities for broadband wireless users.

The Ofcom (Office of Communications) is the government-approved regulator and competition authority for the broadcasting, telecommunications and postal industries of the UK and it is among the first regulatory bodies to take regulatory actions to enable cognitive access in the 470 MHz to 790 MHz band. The Ofcom seems to undertake the same approach as the FCC [4]. On February 2009, it started consultation on enabling license-exempt cognitive use of interleaved spectrum without harmful interference to licensed users. The consultation ended on May 2009, and Ofcom published the final statement in July 2009.

The Ofcom intends to make available access to TVWS on a license-exempt basis for devices, which meet a minimum technical specification. Three approaches have been proposed by Ofcom: spectrum sensing, GLDB, and beacon transmitter [17]. Most of the effort is devoted to assess the appropriateness of the sensing and geolocation techniques to provide protection to the incumbent radio services.

2.4.2 *Scenarios Around the World*

The extension of spectrum occupancy of TV white space has opened up a new dimension for a variety of potential applications. The merit of TVWS exploitation is to provide innovative applications not fully supported by existing technologies, and to offer resource expansion to existing applications for enhanced performance [4]. As an example, the work in [18] shows how TV white space can address the challenge in providing broadband connectivity to a billion plus population within India, the resource is used as a backhaul in the network. The study showed that in almost all cases at least 12 out of the 15 channels are available as TV white space at any location in India.

TV white space is one technology that expands the use of the radio spectrum in a more efficient and effective manner. The applications that it can support are innumerable, some of the possible solutions presented in [4] are described in sequence:

- Emergency and Public Safety — Emergency and public safety network is a communication network used by emergency response and public safety organizations such as police force, fire, and emergency medical teams responding to accidents, crimes, natural disasters, and other similar events. This network covers connectivity from the command/control entity of the public safety organizations all the way down to the end nodes through several hierarchies of intermediate hubs or relays, via the air interface operating in the TV white space.

- Office and Home Networks — This case seeks to establish ubiquitous high-speed connectivity within the area of office and home. The office and home networks typically require a coverage ranging from several centimeters up to several tens of meters. The network consists of one or several interconnected hubs (e.g., access points), which are further connected to multiple nodes (e.g., end user devices), all via air interface operating in the TV white space. The connectivity between the hubs to external networks may be via any alternative radio interface, including a hybrid interface operating in both the TV white space and other existing means.
- Mobile Connectivity — A mobile connectivity network facilitates connectivity for devices that are primarily mobile and portable. The network consists of a main concentrator (e.g., base station) and surrounding mobile nodes (e.g., laptops, tablets, smartphones, etc.) that are connected via air interfaces operating in the TV white space. The targeted area of coverage spans from several kilometers up to several tens of kilometers. Intermediate relay stations (e.g., access points) may be deployed between the main concentrator and the nodes for range extension. In regions where installation of relay stations require a higher level of complexity (e.g., the sea), nodes may form ad hoc based networks to achieve larger coverage. The concentrator is connected to other external networks through a high-speed backbone, possibly with a different means of connectivity.
- Transportation and Logistics — In order to increase the efficiency of transportation systems and logistics, where optimizing resource management is an essential factor, advanced networking systems should be established between nodes (e.g., vehicles, cargo) and hubs (e.g., data collectors, relays) for identification, tracking, management, transaction, and telemetry in transportation and logistics. In such advanced networks, the hubs are connected to the main concentrator (e.g., system mainframes) where the control and management entity is located. The connectivity from nodes to hubs, and hubs to the main concentrator is established via air interface operating in the TV white space.
- Large Area Connectivity — The large area connectivity constructs the wireless backbone and intermediate backhaul links interconnecting multiple hubs, where the hubs are further connected to the nodes (hence a sub-network), forming a wireless large area network, or a wireless metropolitan area network (MAN). The MAN can be connected to external entities through a high-speed external backbone. A metropolitan area typically ranges from several hundred meters to tens of kilometers, covering

several buildings to an entire city. In the rural areas, instead of buildings, the trees, hills, and rivers are the main geographical structures that construct the terrain. Within the large area all the hubs are interconnected by using air interfaces operating in the TV white space. These hubs are further connected to lower hierarchies of nodes by using the same air interface.

2.4.3 *Carlson's RuralConnect*

One company that has begun developing rural broadband equipment is Carlson Wireless Technologies[3] from Northern California, the company has more than a decade of experience in developing effective rural solutions. These wireless radios can provide broadband speeds over much larger distances than existing Wi-Fi routers. As of December 2013, the FCC approved the RuralConnect devices for commercial, unlicensed use in the USA.

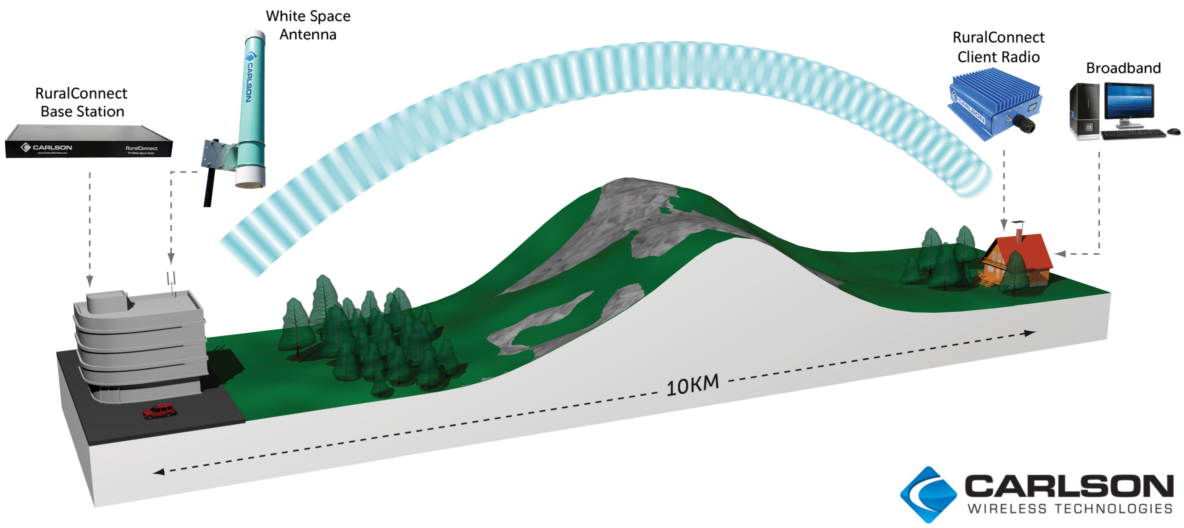
The RuralConnect Gen 3 uses the IEEE 802.11af standard, and it is the best-in-class TV white spaces solution to deliver broadband to customers in non-line-of-sight and rural locations: through trees, foliage, and walls and over hills. Much more affordable than all wireline or wireless network options in the marketplace today according Carlson Wireless Technologies. It provides to the clientes:

- Great data rate and low latency for video streaming/gaming, VoIP (Voice over IP) and OTT (Over-the-top) TV;
- Serve up to 90 broadband subscribers on a single base station;
- Much lower NLOS (Non-line-of-sight) build-out costs than 900 MHz, Fixed LTE or LOS (Line-of-Sight) networks;
- Large and ubiquitous NLOS coverage areas (10 to 40 km radius);
- Multiple applications as public safety, backhaul system, broadband connectivity for education, smart cities, transportations, industry etc;
- Remote Management and Diagnostics through the use of SNMPv2 (Simple Network Management Protocol version 2) and Internet-accessible GUI (Graphical user interface) that provides tools for network management, remote system metrics, diagnostics and network configuration;

Imagine rural broadband where it's never been before, bringing telemedicine, distance learning and residential connectivity to last-mile locations, Carlson alleges that is possible with RuralConnect. Figure 4 illustrates the architecture of such technology and in [20] shows a detail study about its feasibility.

[3] http://www.carlsonwireless.com

Figure 4: The RuralConnect architecture.



Source: Figure from Carlson's website.

2.5 Brazilian Situation

Brazil is an extensive South American country with a surface area of 8.514.877 square kilometers, of which 8.459.417 square kilometers is land and 55.460 square kilometers is water. It is the fifth largest country in the world, occupying almost half of the entire South American continent and has a total population of 202.768.562 [21]. For being a so large country, Brazil presents some problems related to the poor mobile coverage provided by the operators. This situation is more serious in the rural areas all over its 26 states. Due to this problem, many people who live in rural regions do not have any access to the Internet and mobile communications and when they do, the service is precarious and expensive.

Telecommunications in Brazil have been privatized in 1998 and the four major mobile operators that resulted from this process are systematically in the consumers' lists as paradigms for bad service, breached contracts, and very high prices [2]. Moreover, the cost of network infrastructure is a limiting factor for digital inclusion in Brazil. The TVWS means more spectrum with good coverage range which in turn translates into less investment in network infrastructure, which can be a relevant factor to decrease costs and democratize quality access to wireless services in Brazil.

A possible way to soften this coverage problem in Brazil is developing solutions using TVWS technology since the Brazilian TV spectrum is underutilized. White spaces are present even in the densest urban areas as a consequence of the DSO and the number of applications using this resource may be innumerable [11].

Several measurement campaigns have shown that the TV broadcasting spectrum is mostly not used in rural regions, especially in developing countries, for the simple reason that there is not enough return on the investment for the broadcasters to provide many simultaneous channels [2].

While in the USA and Europe have been a significant advance in regulatory strategies associated with CR radio technologies to enable its broad deployment to optimize spectrum usage, in Brazil these initiatives have not occurred, because Anatel (National Telecommunications Agency) considers the technology not consolidated [22]. But, a report from AHCIET and GSMA argues that coverage of mobile broadband could improve from 75% to 95% in Brazil by the use of white spaces [2].

2.5.1 *Brazilian Digital Television System*

Digital TV is regulated in Brazil by decrees 4901/2003 and 5820/2006, with the creation of the SBTVD (Brazilian Digital Television System). It is a modified version of the Japanese platform (ISDB-T) called ISDB-Tb (Integrated Services Digital Broadcasting, Terrestrial, Brazilian version) and several other countries in Latin America have also adopted or are considering the adoption of the Brazilian system [2].

The ISDB-Tb is a SFN (Single Frequency Network), where several transmitters simultaneously send the same signal over the same frequency channel. The video coding used in Brazil is the H.264 and the audio coding is the HE-ACC version 2, also known as AAC+ [23].

The ISDB-Tb uses the concept of BST (Based Segmented Transmission), which allows this system to provide three kinds of services: fixed, mobile, and portable. The ISDB-Tb is also based on OFDM (Orthogonal Frequency Division Multiplexing), being also called BST-OFDM, each OFDM subcarrier has 428.57 kHz. The modulations used on the subcarries can be DQPSK, QPSK, 16QAM, and 64QAM [23].

The Brazilian digital TV channels are in the range of 14 to 69 (470 MHz to 806 MHz); they are all in the UHF frequency band and each channel occupies a bandwidth of 6 MHz [2]. However, the 700 MHz band (698 MHz to 806 MHz) is being used for 4G/LTE mobile broadband, due to the DSO process is almost complete, so this frequency is not considered in this case study as TVWS.

2.5.2 *Entities Responsible for Spectrum Management in Brazil*

Brazil has two federal entities responsible for the spectrum management: Anatel and MiniCom (Ministry of Communications) [22]. Anatel is located in the federal capital, Brasília. Its activities include norms publishing, tariffs definition, verification, and certification of devices involved in transmission and reception. Its general mission is helping to carry out a new economic and regulatory model for telecommunications in Brazil. It was created by the General Telecommunications Law (LGT, Law 9472, July, 1997), modeled after the FCC, with the following attributes :

- Approve, suspend, and cancel authorizations;
- Regulate licensing and service providing processes;
- Oversee incumbents' operations;
- Manage the electromagnetic spectrum, including orbital equipment;
- Certify telecommunications products and equipment.

MiniCom was created in 1967, during the military dictatorship, to centralize all executive tasks related to the sector. It is the main organism of the federal administration in charge of policies on radio and TV broadcasting (broadcasting, rebroadcasting, and repeating of radio and TV emissions).

2.5.3 *Bands: 450 MHz and 700 MHz*

In Brazil, Anatel is mainly concerned in the licensing of mobile services in the 4G/LTE modality in the range 698 MHz to 806 MHz. This process is undergoing in parallel with the DSO process. This band has the signal penetration that would exceed any existing cellular network in Brazil, either 2G or 3G. The Table 2 shows the result of the first Brazilian auction process of the 700 MHz band [24].

Table 2: First Brazilian 700 MHz auction.

Uplink (MHz)	Downlink (MHz)	Operators
708–718	763–773	Vacant
718–728	773–783	TIM
728–738	783–793	Vivo
738–748	793–803	Claro

Anatel plans to provide mobile services to rural areas by using the 450 MHz band, but the auction of this range did not attract the attention of the operators and it was offered along with the slots of 2.5 GHz band. Namely, Anatel allocated two sub-bands of 7 MHz each in the frequency bands of 451 MHz to 458 MHz and 461 MHz to 468 MHz for fixed and mobile radio services operating in a frequency division duplex mode [7]. The operators have committed themselves to meet the requirements on the service penetration and data rates, but the band of 450 MHz has not been used yet.

3 CEARÁ CASE STUDY, LTE OVER TVWS SCENARIO

There is some shift from wired to mobile wire-free communications, but this is a gradual trend rather than a sudden change [17]. Reaching rural regions by means of fixed-line infrastructure is capital-expensive; a wireless alternative is a more cost effective choice, especially if the radio signal can reach large coverage areas with fewer base stations.

The case study presented herein intends to introduce and illustrate the importance of TVWS to solve in part the poor coverage problem in the rural scenario of Ceará.

Ceará is in the northeast region of Brazil. It has a total population of 8.842.791 of which 2.571.896 are located in the capital, Fortaleza, and the rest is distributed all over the state. It has an area of 148.348 square kilometers and it is one of the main tourist destinations in Brazil [21]. In general, the altitude of Ceará is low and there is no mountain chains around the state. This is a good geographic characteristic that allows the signals in the range of UHF to reach further distances.

Figure 5 shows the coverage maps for 3G and 4G/LTE services offered by one of the main cellular operators throughout the state. The image illustrates the poor coverage area around the rural regions: there are many cities without any service of 3G or 4G/LTE. The situation of the 4G/LTE is, as expected, even worst. In general just people located in the capital can count with both technologies, while the rural region is almost ignored by this operator.

The rural scenario of the Ceará represents a challenge, but also a great opportunity, since a reasonable amount of TV spectrum is available for secondary use, given the current situation of DTV according to Anatel. The methodology used to compute these numbers of white spaces is based initially on the total number of licensed DTV channels available in SBTVD. Figure 6 shows the number of already licensed DTV unused channels in each city of Ceará. There are many cities with zero or just one DTV channel in use. This situation is very attractive to TVWS to make use of the unused spectrum of these regions.

According to Figure 6 and considering the total frequency reuse in each city and that there is no interference caused by neighboring cities, which is an ideal situation, there is on average a bandwidth of 210 MHz available in Ceará. For example, in Fortaleza, the capital city of the state, there are 21 unused DTV channels (each channel has a 6 MHz bandwidth in Brazil), this represents a 126 MHz bandwidth which illustrates the worst case scenario, meaning that this is the minimum amount of available spectrum in each city, considering the mentioned restrictions, which is in line with the work in [25] that shows the average of white space capacity is 150 MHz in almost 50% of locations in the UK, according to the modeling studies commissioned by Ofcom.

Anatel is still granting licenses of TV spectrum for a couple of broadcasters since DSO is happening. So the situation of the Figure 6 can change over the years, but it is not going to be a significant change, since many clients from rural cities use the TV service through parabolic antennas instead of VHF/UHF antennas. Furthermore, the deployment of broadcasting towers demands a substantial financial investment.

Figure 5: Coverage maps for the studied Brazilian operator. The colors represent different quality of services: green means good for router, modem, tablet, and smartphone; yellow means good for modem, tablet, and smartphone; red means good for smartphone; and white means without coverage. First figure respresents the 3G coverage and the second one the 4G. Data collected in 2016.

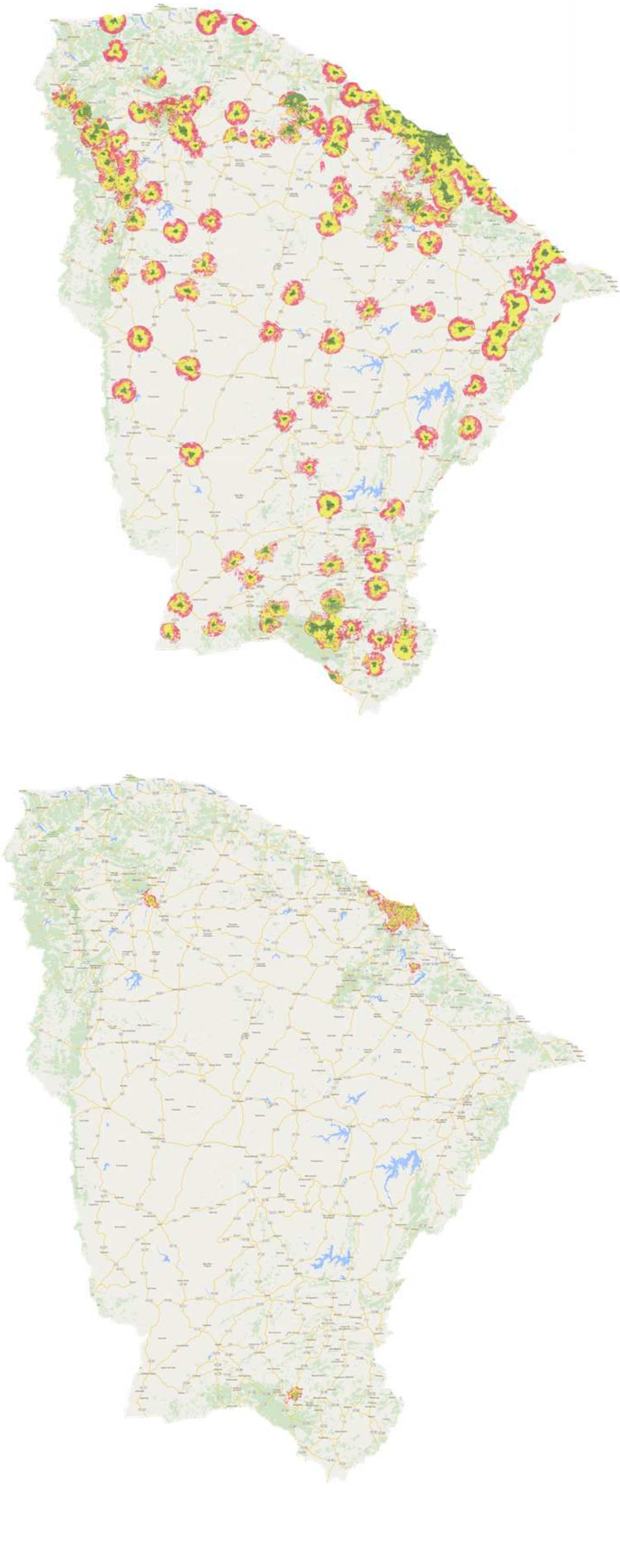
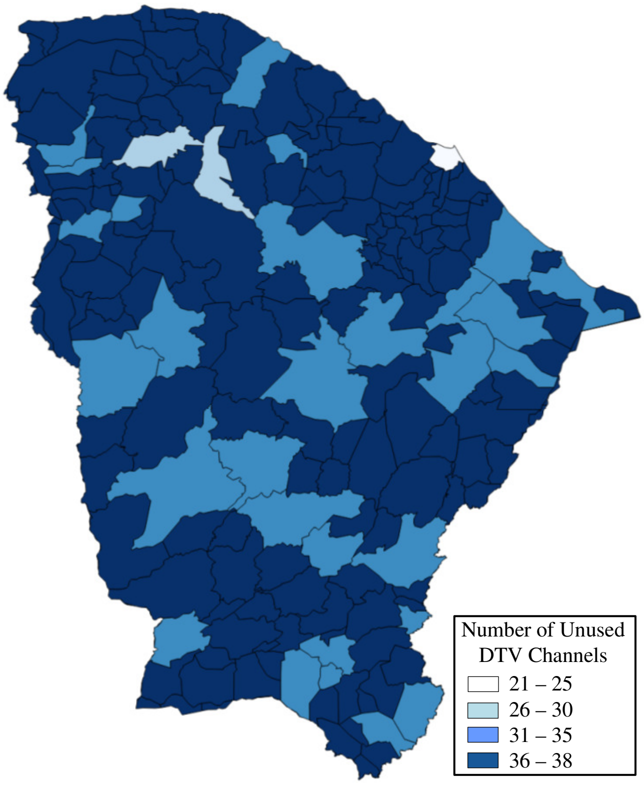


Figure 6: DTV unused channels per city in Ceará State.



3.1 Case Study Considerations

The following aspects must be considered when analyzing the Ceará case in light of its potential for TVWS application:

- PMSE (Programme Making and Special Events) [4] equipment such as microphones may not be considered, since PMSE are likely to be rare in hard-to-reach locations [12];
- The regulations must be based on the models of FCC and Ofcom, as these approaches provide the most straightforward TVWS regulatory system [17], [19];
- It must be considered suitable propagation models during the development of the GLDB to enhance the system's performance. Works in [26], [27] present appropriate models to work with UHF band.
- It was used a mathematical modeling to develop a sector antenna to be used in the Radio Mobile software, this can be verified in Appendix B.

Since in Brazil there is no regulation about TVWS, this resource could be considered here as a license-exempt service for secondary use. In this sense, TVWS networks could be deployed and operated anywhere and anytime, without requiring a

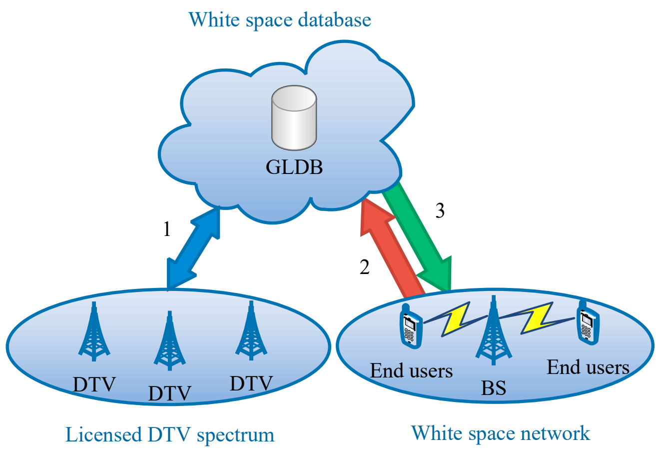
[4] These are generally wireless microphones, talkback devices, or in-ear-monitors. The usage of PMSE can be professional or non-professional. In many countries, PMSE devices operate mostly on an unlicensed basis, without any record. Even so, PMSEs are incumbent users of the spectrum, and, as such, they must be protected from secondary user's interference.

license, but following a strict set of rules to avoid interference with licensed services.

The approach considered here may be GLDB without spectrum sensing, due to the more complexity of sensing mechanism. Additionally, the opportunistic access could be combined with a spectrum broker[5] function that negotiates with a central resource management entity to obtain short-term grants to use spectrum resources [29].

Since it is known the location of licensed DTV transmitters and their corresponding service areas, it is reasonable to assume that a database with maps of possible locations for TVWS networks could be implemented (GLDB). Given the location of a WSD, which can be determined via GPS, a comparison against the database map can be used to immediately assign a set of channels and power levels to be safely used by the white space network without disturbing licensed DTV services in use [8]. Figure 7 elucidates the described process.

Figure 7: GLDB approach for a white space network. The request and grant of TVWS channels are as follows: a map of TVWS (location and maximum EIRP allowed) is built and stored in the GLDB based on the free DTV channels (1); the BS requests TVWS channel to the GLDB (2); the GLDB grants TVWS channels, if available, to a set of BS to be then attributed to the end users (3).



3.2 Possible Scenarios for Ceará

The possible scenarios that could be deployed using TVWS covered in this work follow the description that can be found in [13], [28], [16] and are aligned with the ETSI (European Telecommunications Standards Institute) RRS (Reconfigurable Radio Systems) TR 102907 document [30].

[5]The spectrum broker is a centralized platfrom that facilitates TVWS spectrum trading and its allocation to the interested players [28].

3.2.1 *Spectrum of Commons*

Deploying a fiber network structure to provide some telecommunication service may not be profitable in rural areas [13]. On the Spectrum of Commons, the TVWS can be used to deliver Internet at greater speeds to rural environments, providing a cheaper alternative as it requires little initial investment in comparison to building or extending a fixed network. It allows the sharing, but does not provide a proper QoS (Quality of Service) for some applications.

Therefore, in a rural scenario, the Super Wi-Fi concept, which is a term proposed by FCC, may be used. The Super Wi-Fi uses the TVWS channels to transmit Wi-Fi signals, instead of using the regular 2.4 GHz or 5.8 GHz bands [13].

Due to the use of lower frequency bands, the signal travels further and penetrates better in walls, thus creating larger Wi-Fi networks and new players can enter into the market by taking advantage of some already existing solutions. For example, RuralConnect developed by Carlson Wireless Technologies delivers extended coverage, non-line-of-sight broadband connectivity by transmitting over TVWS [31].

3.2.2 *Secondary Spectrum Market*

The 4G/LTE supports flexible carrier bandwidths, from 1.4 MHz up to 20 MHz. The one used in the Radio Mobile simulation is 5 MHz, considering the DTV channel bandwidth of 6 MHz in the Brazilian case.

The TVWS channels are mostly fragmented, as it comprises usually non-contiguous DTV channels of 6 MHz. But technologies such as LTE-Advanced are capable of exploiting this fragmented spectrum, thanks to carrier aggregation techniques which can introduce more gains to the system [11].

It is possible that TVWS could be used by mobile operators as one way to provide 4G/LTE services in rural regions. Different from the Spectrum of Commons, some prioritized services can exist, because in this scenario QoS is guaranteed [13]. This scenario is used as the basis to illustrate the case study, LTE over TVWS.

3.3 LTE Overview

LTE stands for Long Term Evolution and it was started as a project in 2004 by telecommunication body known as the Third Generation Partnership Project (3GPP). It is the successor technology not only of UMTS (Universal Mobile Telecommunications Service) but also of CDMA (Code Division Multiple Access) 2000. Main characteristics :

- High data rate — High data rates can be achieved in both downlink as well as uplink.
- Low latency — Reduced latency (to 10 ms) for better user experience.

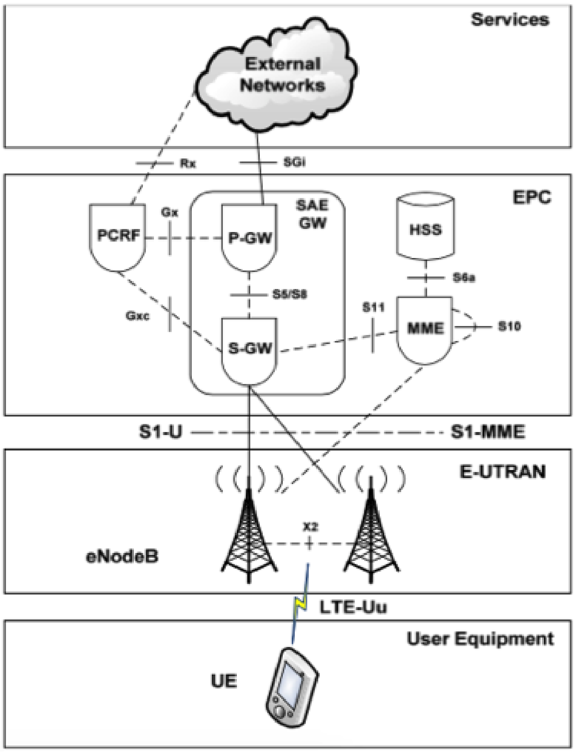
- FDD and TDD — FDD (Frequency Division Duplex) and TDD (Time Division Duplex), both schemes can be used on same platform.
- Seamless connection — LTE will also support seamless connection to existing networks such as GSM (Global System for Mobile Communications), CDMA and WCDMA (Wide-Band Code-Division Multiple Access).
- Simple architecture — Which provides low operating expenditure (OPEX).
- Scalable bandwidth — from 1.5 MHz up to 20 MHz.
- Air interfaces — For the downlink is used the OFDMA (Orthogonal Frequency Division Multiple Access), it is a multi-user version of the popular OFDM digital modulation scheme, the multiple access is achieved in OFDMA by assigning subsets of subcarriers to individual users. In the Uplink is used the SC-FDMA (Single Carrier Frequency Division Multiple Access), due to reduced PAPR (Peak-to-Average Power Ratio) which benefits the mobile terminal in terms of transmit power efficiency and reduced cost of the power amplifier.
- Inter-cell Interference coordination — LTE allows coordination between different base stations in order to identify which users are located in the center or the edge of the cell. The use of different frequency reuse schemes can reduce intercellular interference.
- Multiple antennas — The benefits of using these techniques are the additional protection to the radio channel fading by techniques of spatial diversity or polarization diversity, and to obtain very high data rates by using multiple channels in parallel, also called MIMO (Multiple Input, Multiple Output) techniques.

The LTE architecture is simpler than the architecture of 3G networks. This is due to the elimination of circuit-switched services, eliminating the mobile switching center, as seen in Figure 8. The 4G network is organized around 2 groups of elements: the MME (Mobility Management Entity), which performs a control function;the SGW (Service Gateway) and PGW (Packet Gateway), which perform packet-switched routing and data transfer. The PCRF (Policy and Charging Rules Function) provides policy control and flow based charging control decisions. The HSS (Home Subscriber Serve) component has been carried forward from UMTS and GSM and is a central database that contains information about all the network operator's subscribers, and the E-UTRAN consists of BS's [32].

3.4 Case Study Discussion

As seen in Figure 5, 4G/LTE mobile broadband is almost not provided by the operator in focus throughout the state of Ceará. This issue brings an opportunity for the operators to make use of the good propagation characteristics of TVWS to overcome this situation.

Figure 8: LTE architecture.



Source: Figure from [33].

The initial planning of any radio access network begins with a radio link budget. A link budget is simply the accounting of all the gains and losses from the transmitter and the receiver in a telecommunication system. In this work, the link budget calculation is done by the Radio Mobile software, a free tool dedicated to amateur radio and humanitarian use [34].

Table 3 shows the main parameters used in the simulation of the LTE over TVWS scenario, following 3GPP recommendations [35]. For a more detailed set of parameters Appendix C. As long as the network design is driven by coverage, the TVWS bands keep the advantage of a better propagation and coverage area compared to the current bands used to 4G/LTE services.

Table 3: Parameters – Downlink Macro Scenario.

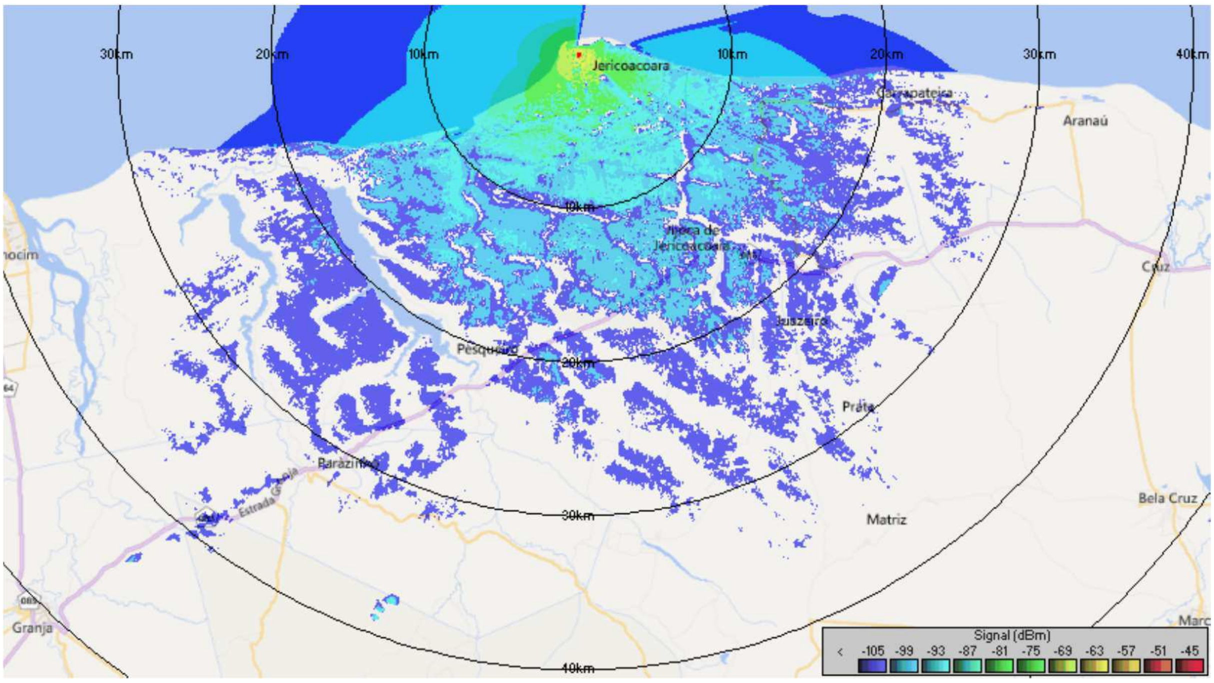
Parameters	BS	End user
Power transmission	43 dBm	24 dBm
Antenna gain	14 dBi	0 dBi
Cable loss	3 dB	not considered
Receiver sensitivity	−112 dBm	−105 dBm
Antenna height	30 m	1.5 m
Noise figure	5 dB	9 dB

3.5 Coverage Evaluation Study

Figure 9 illustrates the gain of coverage reached by the use of TVWS in the region of Jericoacoara, one of the main touristic regions of the state. From Figure 5, the mobile operator in focus offers only GSM service in that area. Now consider that the same structure of the GSM tower could work with CR technology that allows TVWS to be used by secondary devices, so new advanced mobile services as LTE over TVWS and Super Wi-Fi can be offered to the clients.

The BS, in the radio mobile simulation, uses the DTV channel 51 (692 MHz to 698 MHz) — but many other channels could also be considered since most of them are available — for a possible LTE over TVWS scenario. From this channel, a carrier bandwidth of 5 MHz is used by 4G/LTE, which supports 25 resource blocks[6].

Figure 9: Coverage map generated using the Radio Mobile software, illustrating the LTE over TVWS scenario at 51 DTV channel at Jericoacoara city.



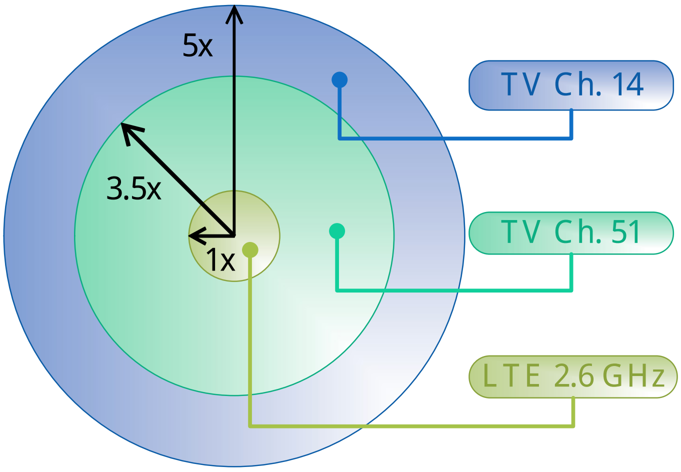
In this manner, the Figure 9 shows the potential of TVWS. This technology not only can bring coverage of new advanced mobile services throughout the city of Jericoacoara, but also new opportunities to all rural and touristic places around the state.

As seen in Figure 9, the coverage area gain using the TVWS is expressive. Figure 10 gives a quantitative idea of the coverage for 3 different frequency bands, i.e., the 2.6 GHz, used in the current LTE systems; channel 14 (470 MHz to 476 MHz); and channel 51 (692 MHz to 698 MHz), the same used in the radio mobile simulation. This figure shows a normalized comparison for these three bands, overlapping each coverage

[6] The resource block has a total size of 180 kHz in the frequency domain and 1 ms in the time domain [32].

circular cell on its center. It is clear to see that for TVWS frequencies (channel 14 and 51) the coverage region is considerably larger. The propagation model used for generating Figure 10 was the "Cost-231 Extension to Hata Model" [36] which covers the frequency range from 500 MHz to 2 GHz. The model was extended to 2.6 GHz according to correction factors proposed in [37].

Figure 10: Coverage area comparison for channel 14 (470 MHz to 476 MHz), channel 51 (692 MHz to 698 MHz), and LTE 2.6 GHz.



Another possibility to provide digital inclusion in the region could be the deployment of a Super Wi-Fi scenario using the TVWS. This solution could use modems in indoor environments to work with TVWS, the equipment would process the signal received and forward it at 2.4 GHz or 5.8 GHz, providing wireless Internet services to the end users.

3.6 Capacity Evaluation Study

For the capacity study, it was used the raster [7] data log exported from the Radio Mobile tool. The raster is a file that contains a list of points that cover the area of the active map window. The number of points depends on the pixel size that is set in the Combined Cartasian settings window. The matrix of points provides the Latitude, Longitude and RSSI (Receiver Signal Strength Indicator) relative to the receiver sensitivity from the receiving mobile.

It is considered only the case where the BS is transmitting (downlink), and using the DTV channel 51 (692 MHz to 698 MHz) for a possible LTE over TVWS scenario. From this channel, a carrier bandwidth of 5 MHz is used by 4G/LTE, which supports 25 RBs (Resource Blocks).

The capacity study is calculated for the coverage area of a BS located at Jericoacoara city. For this study, it is considered the mean value of the capacity of the

[7] http://radiomobile.pe1mew.nl/?The_program:File_formats:Cartasian_raster_export_format

whole area of the picture which has the minimum requirement for a acceptable service, i.e. the LTE end user receiver must work in a proper condition; receiving at minimum data rate of 512 kbps (this value follows the work in [18] as the adopted definition of broadband connection.).

With the values of SINR (Signal to Interference plus Noise Ratio), the corresponding transmit rate could be evaluated using Table 4. With the suitable rate in each pixel, the mean capacity of the study area can be easily evaluated.

Table 4: Relation between downlink SINR and transmit rate for LTE systems.

SINR (dB)	Rate per RB (Kbps)
-7.28	19.1899
-4.78	29.5344
-2.04	47.502
0.66	75.8016
2.84	110.502
4.73	148.1508
6.38	186.0516
8.78	241.1766
11.49	303.1938
13.27	344.043
16.52	418.6098
19.71	491.6898
23.12	569.9584
26.37	644.5152
28.79	699.8922

Source: Table from [32].

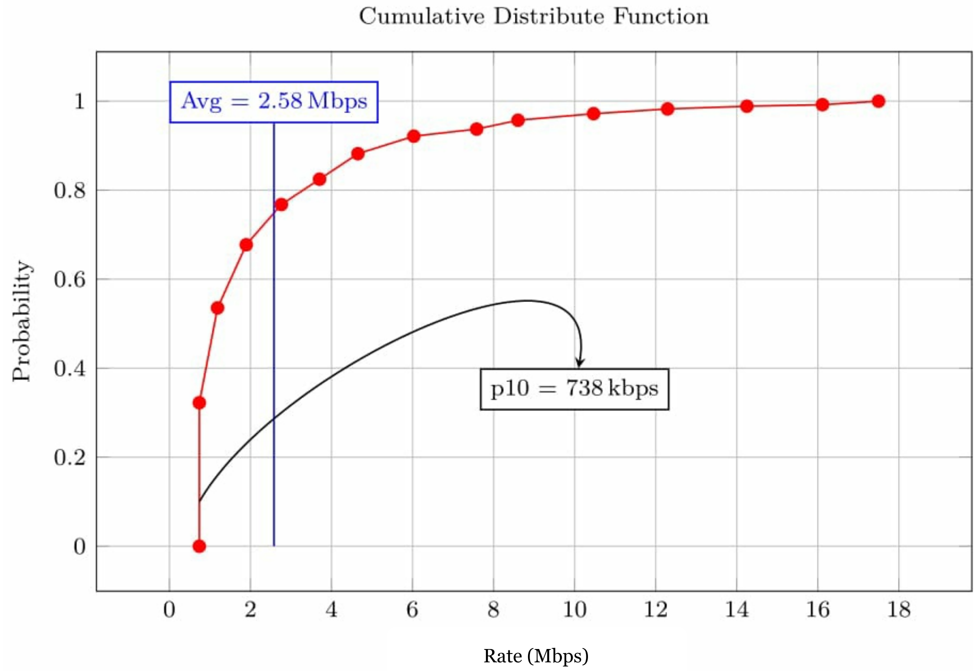
Using the Matlab code that was developed during the FUTEBOL[8] project. The average capacity calculated from the coverage area in Figure 9 is 2.58 Mbps, following the CQI (Channel Quality Indicator)[9] table, which indicates the suitable downlink transmission data rate according to a modulation and coding scheme value, given a SINR [32]. This average capacity is calculated in the downlink direction and assuming that the user gets all the 25 resource blocks.

Figure 11 represents the cumulative distribution function of the capacity for the area under study. It can be noticed that 90 % of the area can be served with at least a rate of 738 kbps.

[8] A partnership consortium among European and Brazilian institutions that seek the convergence point between optical and wireless networks.

[9] The CQI is based on the observed downlink SINR at the UE (User Equipment). The CQI estimation considers the UE capability in terms of number and type of receiver used for detection in order for the BS to select an optimum modulation and coding scheme (MCS) level for the transmission. The reported CQI indices are used by the BS for donwlink scheduling and link adaptation [32].

Figure 11: Cumulative distribution function of the users' rate.



3.7 Business Modeling for TVWS Network in Ceará

The business model is a planning instrument that is essential and necessary for any company, it describes how a company creates value to customers, owners, and other stakeholders. It is also important in case the services are provided in cross-company collaboration in complex value nets, like in the TV white space scenario where different entities are involved in exploiting the vacant spectrum resource [4].

Broadcasters and mobile operators in Ceará should see TVWS as a new business opportunity, not just considering the license-exempt scenario (opportunistic basis), but especially the approach of flexible secondary spectrum market. In USA, the FCC has certificated some IT companies, including Google and Microsoft, as GLDB operators [5].

The commercial deployment of such GLDB and broker requires proper business models that gives to the players the opportunity, either in the public or commercial sectors, to create and capture sufficient resource in order to be profitable. Considering the two scenarios described in the Section 3.2, it is important to highlight that the TVWS opens an opportunity for new players to get into the market.

3.7.1 *Business Models*

As an example, one of the world's first FCC-certified GLDB operator in the USA was SpectrumBridge Inc. They offered two different commercial models: SpecEx and White Space Plus. These examples lead to two different types of business models for TVWS networks, the spectrum market and the information market [5]:

- In the spectrum market model, TV broadcasters temporarily lease their licensed TV channels to unlicensed WSDs for additional revenue. During this process, the GLDB acts as a spectrum broker, purchasing licensed TV channels from TV licensees in advance and reselling the purchased licensed TV channels to WSDs.
- In the information market model, the database sells advanced information regarding the quality of unlicensed TV channels to unlicensed WSDs for profit. This model is motivated by the fact that the GLDB knows more information regarding the quality of unlicensed TV channels than unlicensed WSDs, and such information can potentially be used by WSDs to improve their performance.

The spectrum market and information market target different types of TV channels in TVWS networks: licensed and unlicensed TV channels[10], specifically. The licensed TV channels are registered to some TV broadcaster, but underutilized by them. Hence, the broadcasters may temporarily lease the underutilized (licensed) channels to WSDs for exclusive use during a short time period. The unlicensed TV channels are those not registered to any TV broadcaster at a particular location, and hence are a public resource at that location. Unlicensed TV channels are usually assigned by spectrum regulators for public and shared usage among unlicensed WSDs, and not allowed for trading in a spectrum market. Moreover, due to the shared usage by unlicensed WSDs, the quality of unlicensed TV channels is usually not guaranteed. Hence, the GLDB can potentially sell its advanced information regarding the quality of unlicensed TV channels to WSDs.

3.7.2 *A Model for Ceará*

The WSDs obtain the TV channel availability information through querying a GLDB residing in the cloud, rather than directly sensing the current activity levels in the TV channels, the GLDB is the central network entity considered in such business models, since it was not considered sensing mechanism in this case study. It is important to note that although the unlicensed or licensed TV channels can be used by GLDB without any payment to the licensees, GLDB may still incur some cost when accessing the unlicensed TV channels. For example, a GLDB needs to consume some time and energy to request, analyze the TV channels to construct and update its database. Meanwhile, the GLDB also needs to exert some effort to help WSDs use these TV channels and accordingly charges WSDs a certain fee.

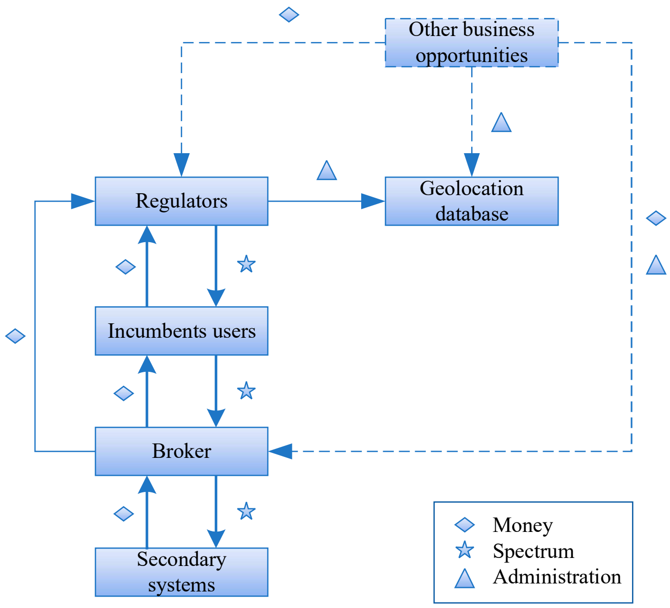
Figure 12 can illustrate a possible cash flow process that could be adapted to the Ceará case. The regulator (Anatel) is responsible for managing the spectrum (the licensed DTV channels) and the GLDB management can be outsourced to a company, thus aiming new business opportunities. The same reasoning applies to the broker.

[10] In this work, a survey was made only about the licensed DTV channels in Ceará, as seen in Figure 6.

Anatel promotes the primary spectrum market and the resource is sold. The spectrum slices are fixed which follows a long-term licensing scheme, nevertheless some of them are not even used. Thus, primary users may resell this unused spectrum to other entities (GLDB/broker), and when the spectrum is sold, the incumbent and regulators receive money for that. Lastly, the spectrum now owned by these entities (GLDB/broker) enters in the short-term licensing scheme, where it could be used by the secondary systems to implement the scenarios described in Section 3.2 [13] or to enhance its performance.

Furthermore, it must be highlighted that herein it is considered a "dynamic" spectrum market to the rural scenario with channel allocation periods of days, months, or even a year; which contrasts with the more traditional Brazilian spectrum market, whereas allocations last from 15 to 20 years [2]. In view of the facts cited, the business model is essential for the practical commercialization of the GLDB and to make a TVWS network to work properly. It was provided some ideas to propose a strategy for the Ceará or even Brazilian operators to be aware of the possibilities in exploring the TVWS resource in a way to be profitable.

Figure 12: Example of cash flow process. Other business models could be adopted.



Source: Figure from [13].

3.8 Conclusion

In this chapter, a case study of Jericoacoara was developed, a tourist city from Ceará. At first, it was shown the poor 3G and 4G coverage from a certain operator. This was used as motivation for the deployment of the case study. TVWS was used as a way to provide LTE communication in the area of Jericoacoara, the scenario implemented was the LTE over TVWS, this was possible to reach due to the availability of many white spaces channels in the region of Ceará.

It was verified that in Ceará there is, on average, a TVWS bandwidth of 210 MHz per city, following some restrictions defined throughout the chapter. The main idea of this case study was to show the importance of TVWS as a way to provide digital inclusion for some rural and suburban regions, places that usually present bad telecommunications services, which is a quite common situation in Brazil and in underdeveloped countries.

The LTE over TVWS scenario was implemented using the Radio Mobile, it was verified that for one unused DTV channel the average capacity for downlink calculated was 2.58 Mbps, this value could be much larger if it was used all the unused DTV channels in the region. Also it was shown the coverage gain through the use of this frequency which is a very important fact to reach rural places. Through these results, the TVWS offers an opportunity to the NRA, mobile operators, and new players to formulate a proper business model to enhance the telecommunication services.

Finally, future work may be related to the use of more than one DTV channel, considering the presence of interference sources to evaluate the gain that this resource can bring to urban scenarios.

4 BAND ALLOCATION STRATEGY FOR DOWNLINK SCENARIO USING TVWS ALONG WITH LTE

The cellular networks are in a constant evolution, the demand for data capacity is growing faster. The users are looking always for better solutions to attend their needs. Due to these facts, many studies and technologies about how to make efficient use of spectrum are emerging. Among them, as we discussed in the previous chapters, the TVWS shows up as a way to reach or, at least, to soften this scarcity of the spectrum, mainly in under-developed countries.

The rural regions of Brazil are extensive and often they are not well served in terms of mobile services; there are many regions without any service or with a bad one. It is not profitable for operators to develop and implement a backbone to connect these regions. The TVWS emerged as one possible way to contour this situation, since it presents better propagation characteristics covering larger regions than normal frequencies used in the current mobile systems, and it is a resource that has been underutilized, mainly, in the rural regions of Brazil.

The main idea in this chapter is to use the TVWS to alleviate part of the data load in the cellular network. In other words, some users will be served with white spaces and others will remain using the frequency of the cellular system, this will provide a capacity gain to the system due to more bandwidth that will become available and a coverage gain due to the better propagation characteristics of the TV band. It is analyzed just the downlink scenario, and the users are randomly positioned with no moviment.

Despite the numerous benefits of TVWS when compared to the 3G and 4G cellular networks, its exploitation requires some technical challenges. In this case, we take into account some aspects considered in the Ceará case study:

- The use of GLDB without spectrum sensing (since it is well known the actual availability of white spaces in the region, based on the case study of the previous chapter), due to the more complexity of spectrum sensing techniques;
- No PMSE system is considered, it is considered just TVWS and LTE bands in the region to ensure no interference from other sources which is not the focus of this work, it is even considered a scenario with only one cell;
- The regulations and rules are considered as well-defined, the resource is seen as licensed-exempt, since in Brazil there is no regulation about TVWS. The only concern is to avoid interference with primary services.

The main questions that comes in mind are related to:

- How to use TVWS along with LTE to improve the total cell capacity and the individual users' performance?
- Which allocation strategy must be followed to reach the best advantage of the available TVWS spectrum such that system performance is optimized, but maintaining the fairness between the users?

Some users of the cellular network will pass to use white spaces which lead to more LTE spectrum available to guarantee a certain quality of service to the other users that remained in the LTE network. The SNR criteria will play out the decisive role to determine the kind of band that will be allocated to a certain user. We use here the concepts of high geometry (user closer to the BS) and low (user distant from the BS), both definitions from [39], almost always the users in the higher geometry present a better SNR than in the lower geometry. The mathematical problem to be studied consists in: given an underutilized TV band as well as the cellular band, what is the allocation strategy that must be adopted to maximize a certain objective function?

The initial idea is to allocate the TVWS band to the low geometry users, since this frequency presents better coverage area and reach further distances than the LTE frequency, attending the demanding of users in the border of the cell or users even out of the coverage zone of the LTE network, and at the end of the allocation strategy process, both systems and users will present an optimized capacity due to the addition of white spaces spectrum into the network system.

4.1 Resource Allocation Algorithms

Scheduling policy plays an important role on system performance such as data rate, delay, jitter and fairness. Different from wired cases, scheduling in wireless networks needs to consider the unique characteristics of time, frequency and location-dependent channel status.

In general, the scheduling algorithms are divided into two classes: channel independent and dependent. The channel's independent algorithms seek to achieve justice and equity in the distribution of resources to the user, as an example in this work will be used Round Robin. The class of the channel's dependent algorithms allocates resources to the users taking into account the channel conditions of the same, as an example in this work we use the Maximum Rate and Proportional Fair [40].

The resource allocation refers to the activity of allocating radio resources required for the transmission of data to the user equipment and it is performed at each TTI (Transmission Time Interval). The role of the scheduler is to determine the allocation of a number of resources available to a set of users, in order to maximize some objective function, in this work the objective function to be optimized is the total network capacity. As an example, in the LTE systems, the scheduler is located in the BS, and it is responsible for the dynamic allocation of resources in the downlink and uplink channels of the network.

4.1.1 ***Maximum Rate***

In the Maximum Rate algorithm the system capacity is maximized by assigning the resource block p to a certain user u with the highest instantaneous data rate $\overset{*}{T}{}_u^p$ on that resource, this scheduler offers excellent cell data rate but it is not fair, because it performs unfair resource sharing for users with poor channel conditions [41].

$$\overset{*}{u} = \arg\max_u \{\overset{*}{T}{}_u^p\} \tag{1}$$

4.1.2 ***Round Robin***

The scheduler assigns resources cyclically to the users without taking channel conditions and QoS into account. This is a simple procedure giving the best fairness, but offers a poor performance in terms of cell data rate.

Initially, the Round Robin randomly orders the connected users; if the number of available resource blocks is greater than the number of users connected to that TTI, all the users will be allocated on the same TTI. Otherwise, the users that did not get the resource will be allocated in the next TTI and so on until all the users are served sequentially [40].

4.1.3 ***Proportional Fair***

Among various related researches on scheduling, the Proportional Fair algorithm has been widely conceived as an attractive solution since it provides a good compromise between the maximum data rate and user fairness [40]. The Proportional Fair is one of the most well-known and researched strategies for the LTE network.

This algorithm schedules the resources in a fair way among the users of the network, with similar service probability, regardless of the channel conditions of each user. It uses a scheme in which the user chosen by the packet scheduler is the one with the highest ratio between the instantaneous data rate and the average transmitted data rate [41]. Thus, the Proportional Fair scheduling assigned sequentially each frequency-time resource on the considered resource block p at each TTI t to the user u according to:

$$\overset{*}{u} = \arg\max_{u} \left\{ \frac{\overset{*}{T}{}_{u}^{p}(t)}{M_u(t)} \right\} \tag{2}$$

Where $\overset{*}{T}{}_{u}^{p}(t)$ is the estimated instantaneous data rate and $M_u(t)$ the average data rate. The low-pass filtered average data rate of each user u after transmission at TTI t is given by:

$$M_u(t+1) = (1 - \frac{1}{N_p})M_u(t) + \frac{1}{N_p}T_u(t) \tag{3}$$

Where $T_u(t)$ denotes the total received data rate of user u over all resource blocks it got assigned to it at the TTI t and N_p is the length of the exponentially weighted time window [41].

4.2 Simulation Environment

The new trend in spectrum management is to aggregate both the licensed and unlicensed spectrums to extend available system bandwidth, since the unlicensed spectrum has plenty of bandwidth. In particular, utilizing a larger amount of system bandwidth guarantees an increase in the capacity by allocating more frequency resources to each user in the system.

The scenario consists of one cell with a central BS providing a LTE network for a random number of static users distributed randomly in the area. It is supposed that the cell is in the same region of the scenario studied in Chapter 3, and that the system is SISO (Single Input, Single Output), and the direction considered is the downlink.

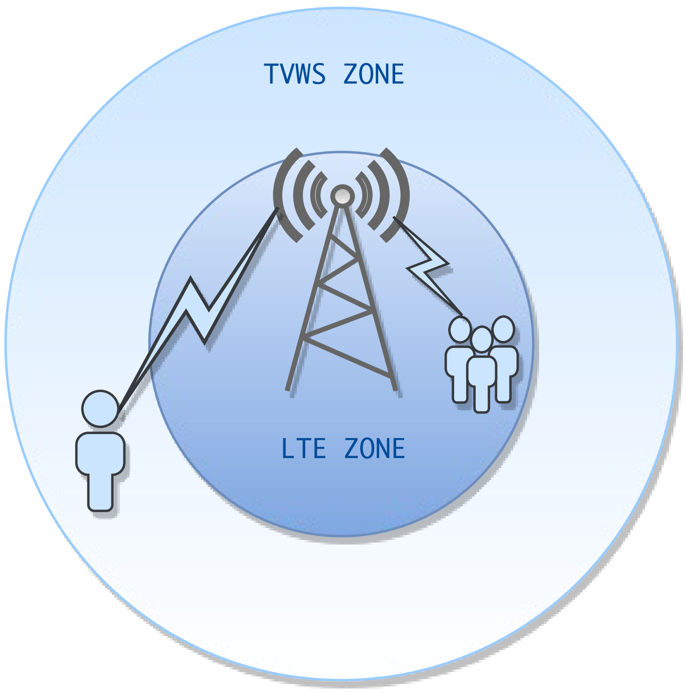
It will be added to the system a part of the TVWS spectrum available in the region, considering a Multi-RAT network scenario which combines several RAT (Radio Access Technologies) to deliver some service to users, in this case white spaces and LTE technologies, as seen in Figure 13. The system takes advantage of the unique characteristics of each RAT, improving the system performance as a whole.

Only one BS is going to be responsible for both systems (TVWS and LTE), since their frequencies operation are in different ranges there is no interference between them, and from any other system, since it is considered just one cell with no more interference sources.

Notice that we know about the amount of the TVWS spectrum unoccupied due to the Ceará case study in Chapter 3. It is considered just a tiny part of the white space spectrum just one channel (channel 51), since the previous chapter showed that there is, on average a bandwidth of 210 MHz available around the Ceará state, see Figure 6. But it is possible to use many other channels, however, it is considered the gain provided by only one TVWS channel in a LTE cellular network with an already 5 MHz allocated for its downlink system.

After the placement of each user in the cell, the radio link is modeled according to a distance-dependent path loss plus shadow fading component. The resulting local average SNR of each user is mappep into the radio link capacity. It must be applied a resource allocation strategy to determine which will be the best condition to optimize the capacity of the system and users. The effective data rate for each user depends on the radio link capacity and the actual amount of radio resources granted by the system. Figure 13 illustrates the simulated scenario and Table 5 presents the main parameters used.

Figure 13: Scenario for LTE and TVWS zones.



4.2.1 *Problem Formulation*

It is assumed that there are N users, $U \triangleq [u, 1 \leqslant u \leqslant N]$, randomly distribuited in a cell, served by an omnidirectional antenna in a LTE network using a bandwidth BW_c of 5 MHz and a central frequency of 2.6 GHz.

Table 5: Parameters for LTE along with TVWS for downlink scenario.

BS Parameters	LTE	TVWS
Power transmission	43 dBm	43 dBm
Path Loss	COST 231	Okumura-Hata
Frequency	2.6 GHz	698 MHz
Bandwidth	5 MHZ	5 MHz
Cable loss	3 dB	3 dB
Antenna height	30 m	30 m
Antenna gain	14 dB	14 dB
Number of users	Varied	Varied
BS sensitivity	−112 dBm	−112 dBm
Noise figure	5 dB	5 dB
Min and Max SNR	−7.28 dB and 28.79 dB	−7.28 dB and 28.79 dB
Shadowing	8 dB	8 dB
Number of TTIs	1000	1000

Source: Parameters from [32], [35], [42].

The reachable capacity of each user $u \in U$ in this traditional LTE network is calculated usind the adjusted Shannon capacity that serves to facilitate accurate benchmarking of LTE, the same reasoning is applied later to the TVWS system. The well-known Shannon capacity as showed in Equation 4 relates the maximum capacity (transmission bit rate) that can be achieved over a given channel with certain noise characteristics and bandwidth, but can not be reached in practice due to several loss mechanisms, to represent a more realistic version it is used the modified Shannon capacity formula in Equation 5.

$$S = BW * log_2(1 + SNR) \tag{4}$$

Where in Equation 4:

- S represents the channel capacity in bits per second.
- BW represents the Bandwidth in Hz.
- SNR represents the Signal-to-noise ratio.

$$S(u) = \frac{BW_c}{|U|} * BW\_eff * \eta * log_2(1 + \frac{SNR_u}{SNR\_eff}) \tag{5}$$

Where in Equation 5:

- BW_eff adjusts for the system bandwidth.
- SNR_eff adjusts the SNR efficiency of LTE.
- The factor η is a correction factor.
- The respectives $BW_c/|U| = BW_c/N$ and SNR_u are the bandwidth allocated to each user and Signal-to-noise ratio perceived by user u .

The BW_eff is calculated based on system parameters, this value is reduced by several issues listed in [44]. The *SNR_eff* is much more complicated to compute than *BW_eff*, but the value of *SNR_eff* is extracted from a detailed link level study, the work in [44] demonstrates the process. The values of these variables used in the simulation follows [44], considering a SISO channel.

Now it is assumed that some users in U, i.e, $U_t \subset U$ are allocated to a vacant TV band (TVWS) with a bandwidth of BW_t and the rest of the users, $U_c = U - U_t$, remains using the cellular band. The new data rate for a user in the cellular band, $u \in U_c$, thus becomes :

$$S_c(u) = \frac{|U|}{|U_c|} * S(u) \tag{6}$$

Whoever stays in the cellular band enjoys a $[|U|/|U_c|]$ times increase in the data capacity due to more bandwidth that becomes availuable, since some users were moved to the TV band. The users U_t moved to the TVWS presents a capacity of:

$$S_t(u) = \frac{BW_t}{|U_t|} * BW\_eff * \eta * log_2(1 + \frac{SNR_u}{SNR\_eff}) \tag{7}$$

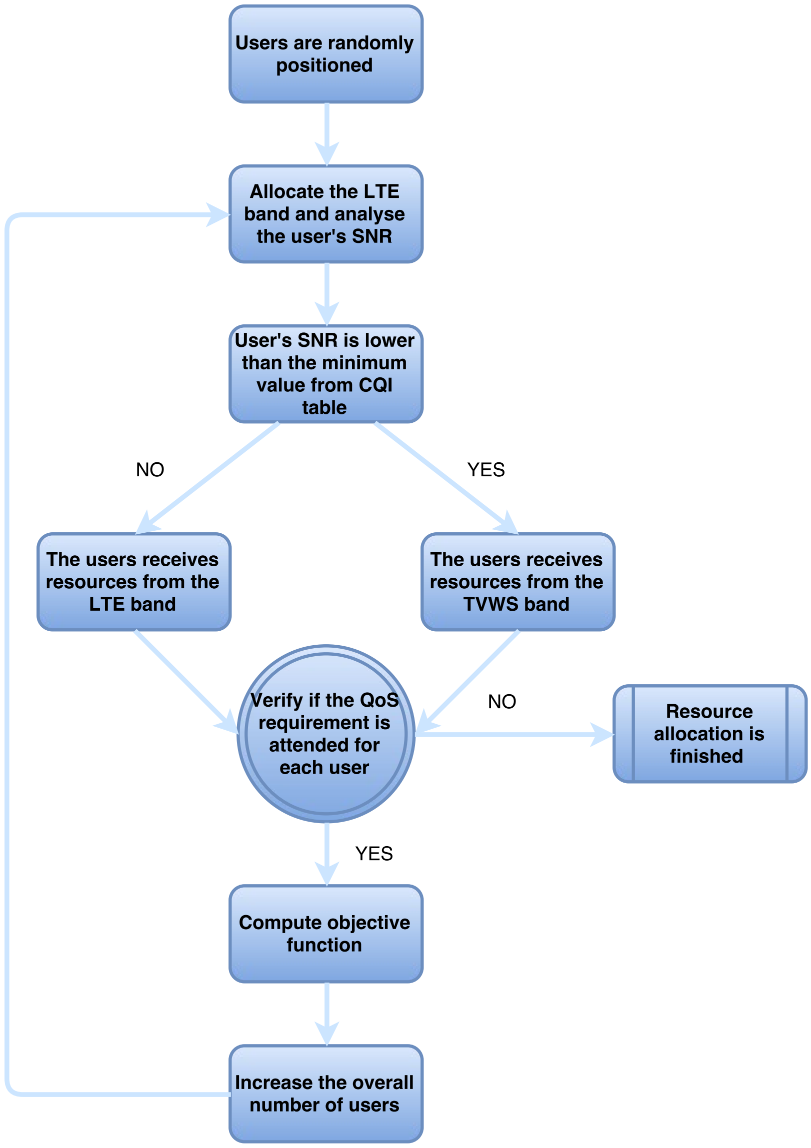
This scenario is implemented using the same physical structure for both services (TVWS and LTE), the TV band will provide a gain of coverage due its propagation properties and a capacity gain to the system due to more bandwidth that becomes available. It will be used only 5 MHz of the TV channel, since 1 MHz will be used as guard band. Assuming the same bandwidth for both services, i.e, $BW_c = BW_t = 5\,\text{MHz}$, so the new bandwidth of the system becomes $BW_c + BW_t = 10\,\text{MHz}$. The user's geometry will determine often his type of bandwidth utilized. Normally, users in a low geometry are served by TVWS and the ones in the high geometry with LTE band. The SNR calculated for each user positioned in the cell follows the limits presented in the CQI table used in the previous chapter, the CQI table provides the SNR minimum and maximum values.

An allocation strategy is proposed to best utilize the TVWS resource for improving the capacity of each user $u \in U$ and the system performance. The objective function to be maximized is the total capacity of the system, and at the same time to improve the condition of each user.

$$\overset{*}{S}_t = \arg\max_{S_t} \left[\sum_{u \in U_t} S_t(u) + \sum_{u \in U_c} S_c(u) \right] \tag{8}$$

The idea is to determine which algorithm maximizes Equation 8, among Proportional Fair, Maximum Rate and Round Robin. Scheduling algorithms with different properties, functions, and with unequal visions of fairness. During the allocation strategy of the new sum of the bandwidth (10 MHz), the simulation tries to guarantee for each user at least a data rate of 512 Kbps [18] as the minimal requirement considered in this work to provide a certain quality of service to each user randomly distributed in the cell (QoS requirement), this consideration will change as the number of users placed in the cell grows, but the main requirement must be always followed, the maximization of the objective function. The Figure 14 illustrates the process.

Figure 14: Downlink band allocation flowchart using LTE and TVWS.



One of the main contributions by the use of the TV band is the coverage gain reached by its good propagation characteristics, this helps users that were without any communication before in the LTE band due to its position to have now an opportunity to get a fair portion of the spectrum to transmit information through the new network system. Beyond this coverage gain, the other contribution is the gain in capacity due to more bandwidth that becomes available. These contributions will play an important role to solve part of the problem of lack of mobile services through the rural and suburban regions which is a quite common problem around the Brazilian territory.

4.3 Results

This section presents two simulation steps. The first one shows the three scheduling algorithms, discussed before, using 5 MHz of bandwidth to be distributed to N users in the cell, this simulation serves to determine which algorithm is the best to maximize the total capacity of the system, but maintaining the minimal QoS requirement and fairness, as well as to show the gain provided by the use of TVWS band in relation to the LTE band.

The second simulation adopts the best of the three algorithms to be used in a new scenario with 10 MHz of bandwidth, 5 MHz of each service (LTE and TVWS). The scheduler will be used to maximize the system and user capacity, maintaining the requirements of QoS and fairness. The simulation will be realized with different quantities of users, and at the end the respective gains provided by the combination of LTE and TVWS bands will be compared with a scenario using only LTE in 2.6 GHz band with 10 MHz of bandwidth. It is supposed that before the availability of this TVWS channel (to be shared between the users), only LTE in 2.6 GHz band was available.

and at the end the respective gains provided by the TVWS will be compared with a scenario using 10 MHz of bandwidth in LTE system.

The two simulations follows the parameters from Table 5, the test is performed using Monte Carlo with 500 iterations, and at each Monte Carlo, the users are redistributed in the cell which generates new Shadowing and Path Loss for them.

4.3.1 *Analysis of the Scheduling Algorithm and Demonstration of the Gain Provided by the Use of TVWS*

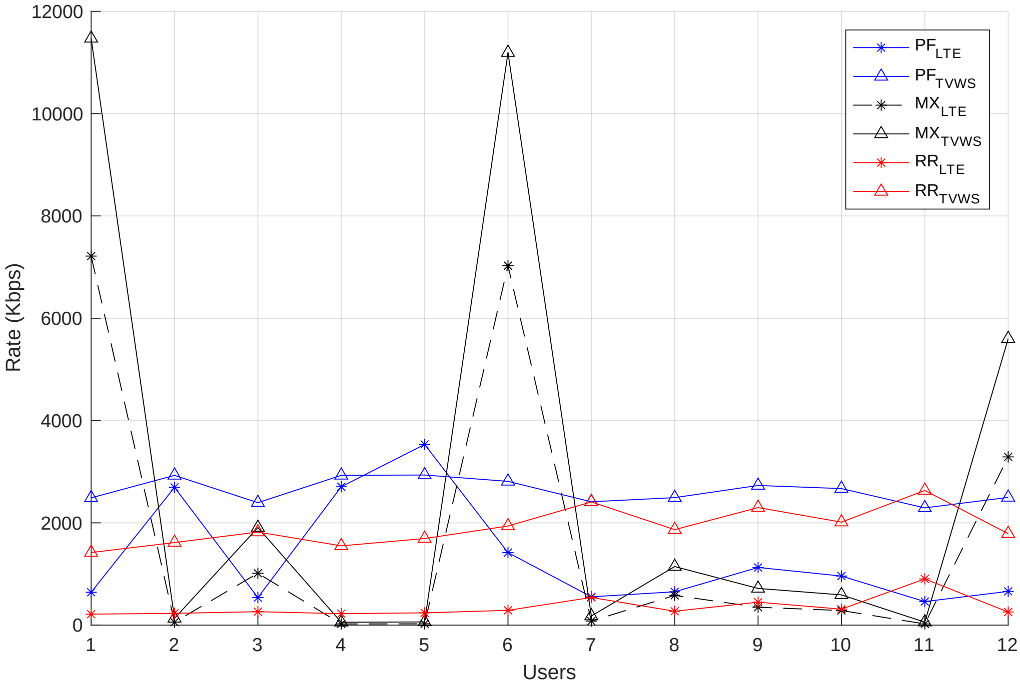
The simulation in this section uses the three scheduling algorithms discussed before.

Figure 15: Scenarios to Select the Scheduling Algorithm.

Scenario	Algorithm	System	Bandwidth
1	Maximum Rate	LTE	5 MHz
2	Maximum Rate	TVWS	5 MHz
3	Round Robin	LTE	5 MHz
4	Round Robin	TVWS	5 MHz
5	Proportional Fair	LTE	5 MHz
6	Proportional Fair	TVWS	5 MHz

Figure 15 represents the first simulation implemented in this chapter, where each scheduler algorithm was used for both systems to allocate 5 MHz of bandwidth for N users distributed in the cell. These six scenarios were implemented independently to evaluate which algorithm attends the prerequisites established which are the maximization

Figure 16: The capacity of each user in 6 different scenarios using 5 MHz of bandwidth.



of the total system capacity and fairness between the user's capacities.

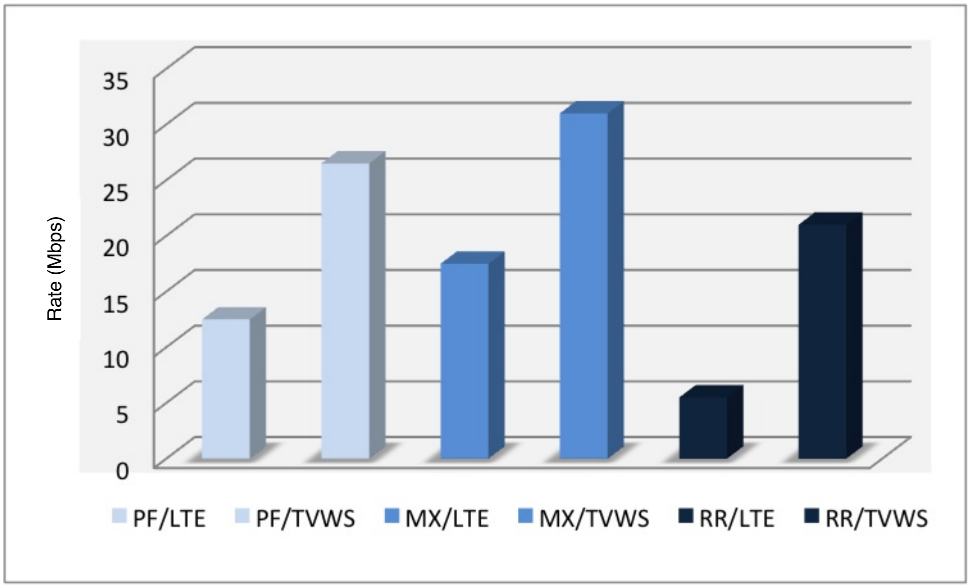
Figure 16 represents the capacity of each user in the 6 different scenarios, this figure was used to evaluate the fairness between the user's capacities. Figure 17 was used to evaluate which algorithm managed to maximize the system capacity.

The Round Robin provides the lowest variation in the capacity of the users, but at the same time does not guarantee for them a good rate, since this algorithm does not consider the channel quality of the users. Figure 17 shows that this algorithm did not maximize the total system capacity as the others.

The Figure 17 shows that Maximum Rate provides the best total system capacity since it allocates the resources to the user with the best channel conditions, but this algorithm is not fair. Figure 16 shows that the users using the Maximum Rate present a large variation in their capacities, some users with high transmission rates and others with low rates. This result can be verified analyzing the variation and standard deviation of the capacity matrix of the users.

According to the Figures 16 and 17 the Proportional Fair among these algorithms is the one which presents the best relation between fairness and capacity per user and it will be used in the simulation of the next section.

Figure 17: The total system capacity provided by the use of 5 MHz of bandwidth in 6 different scenarios with 12 users.



4.3.2 *Improving the Cell System Capacity by the Use of LTE along with TVWS*

The simulation in this section consists of one cell using two different frequencies at the same time. The SNR of each user will determine which frequency will be used, the simulation first allocates a part of the LTE band for a user, if its SNR is not between the limits presented in the CQI table, the TVWS band is allocated to it. The TVWS spectrum comes into the system to improve the situation of the users who are not well served in the LTE band due its position in the cell, and used as well when the number of users grows which increase the need for more resource to maintain everyone with good conditions of exchanging information in the cell.

Besides the capacity gain provided by the amount of TV bandwidth that becomes available, another great benefit provided by the use of this band it is to reach users out of the LTE cell zone, normally users located in the rural regions of certain localities, due to its good propagation characteristic that was discussed in the previous chapters.

The considerations about Monte Carlo, Path Loss and Shadowing described before are applied here, the difference now is that both technologies live together to provide a better condition for the users. The simulation is performed using 12, 24, 48, and 70 users randomly distributed, and the Proportional Fair algorithm was used as the scheduling algorithm. At the end, it is done a comparison of the respective gains provided by this scenario with one using only LTE service with 10 MHz of bandwidth.

Figures 18, 19, 20, 21 show the CDF (Cumulative Distribution Function) for 12, 24, 48 and 70 users respectively, showing the gain provided by the use of only one TVWS along with LTE band, but many others unused DTV channels could be explored

Figure 18: The Cumulative Distribution Function of the 12 users randomly distributed in the cell.

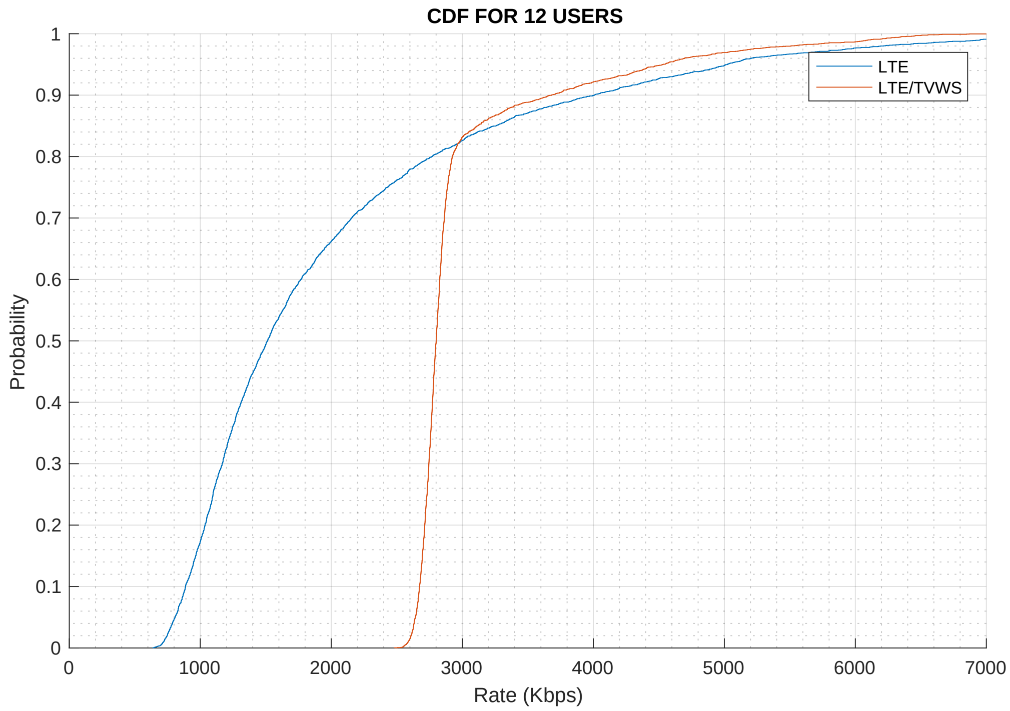


Figure 19: The Cumulative Distribution Function of the 24 users randomly distributed in the cell.

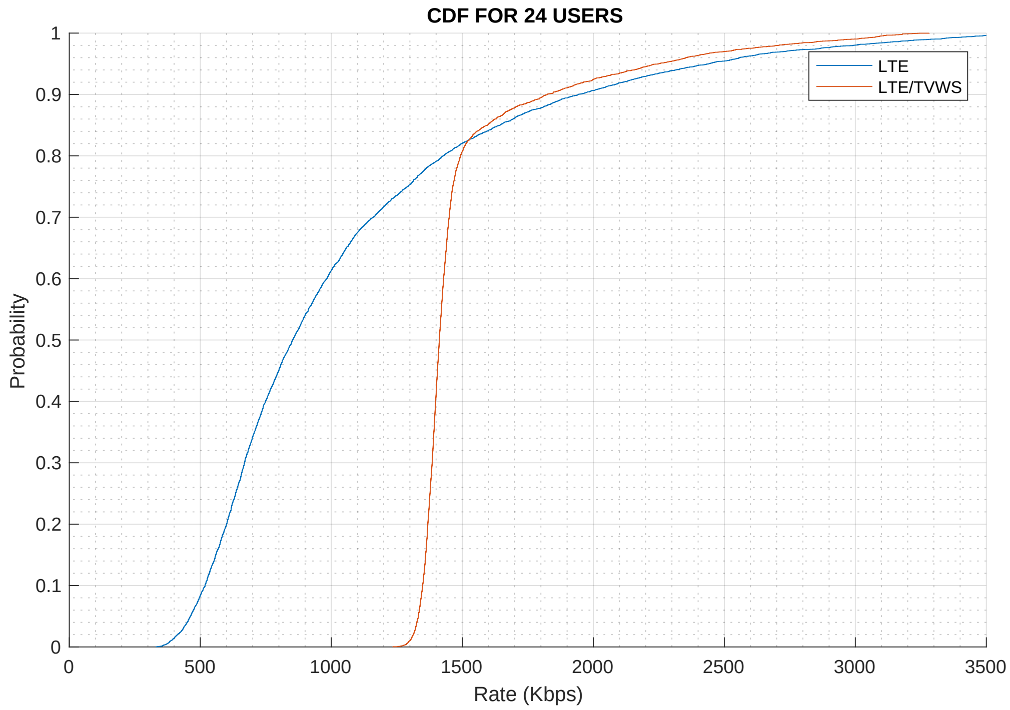


Figure 20: The Cumulative Distribution Function of the 48 users randomly distributed in the cell.

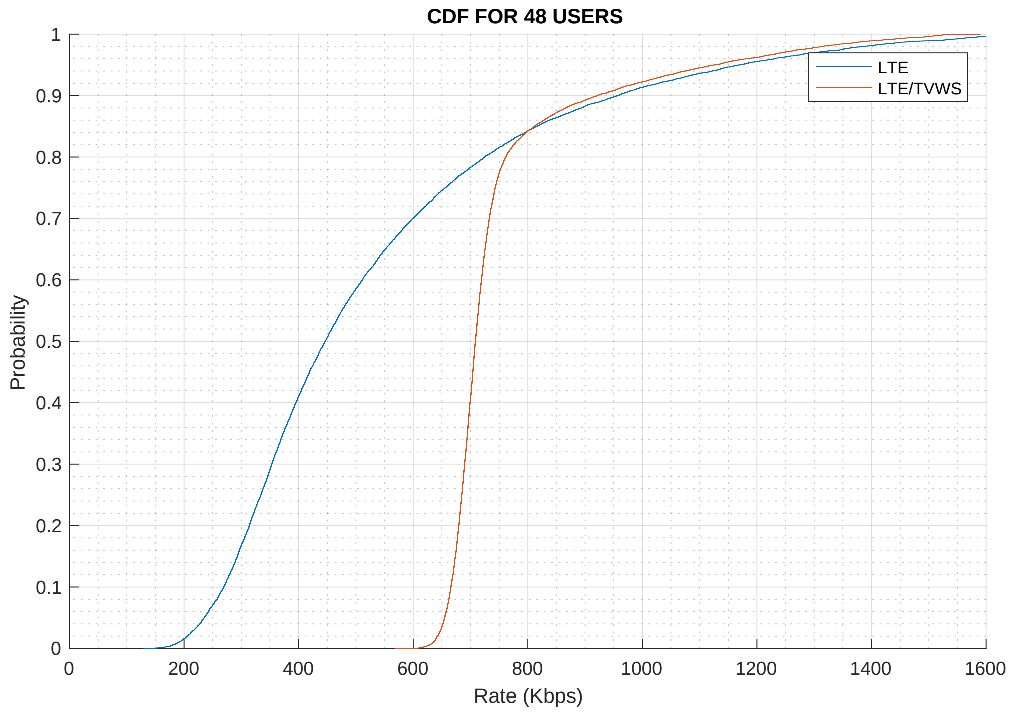


Figure 21: The Cumulative Distribution Function of the 70 users randomly distributed in the cell.

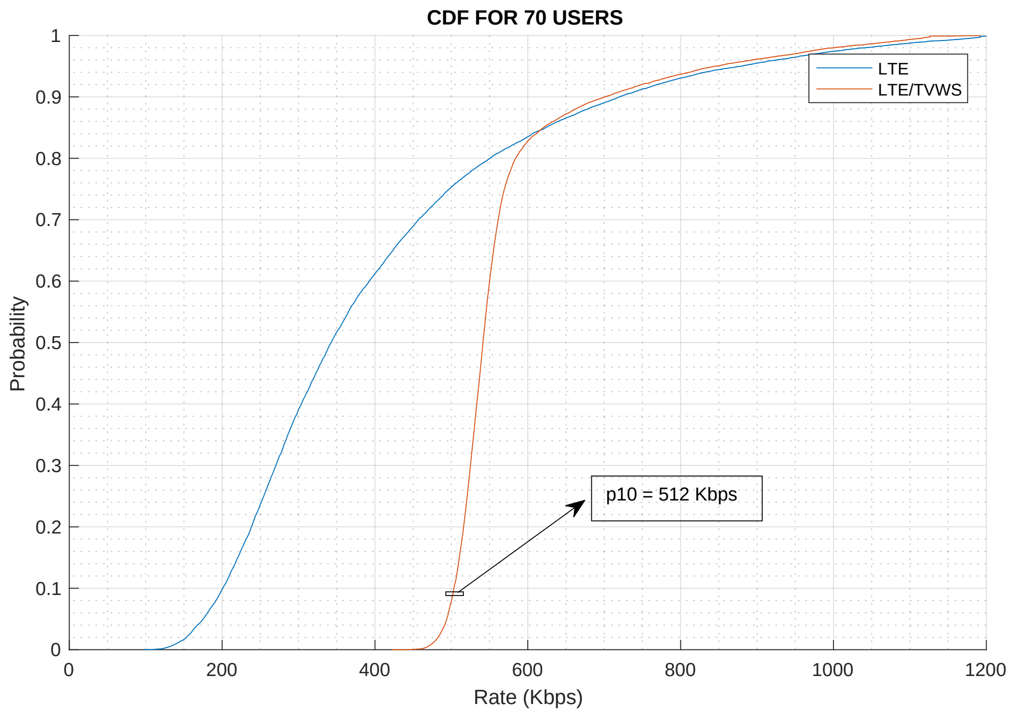
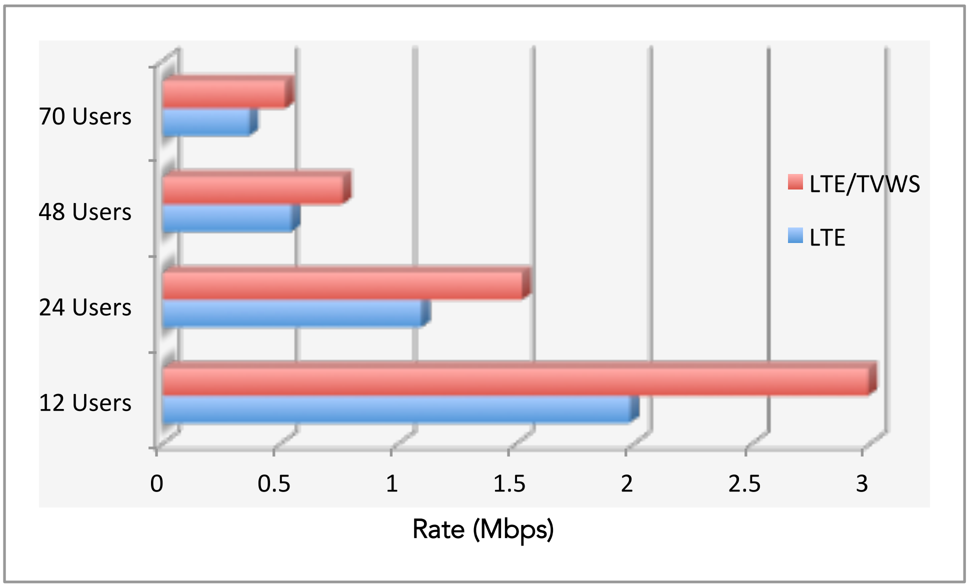


Figure 22: Average capacity of the users in both scenarios.



according to Figure 6.

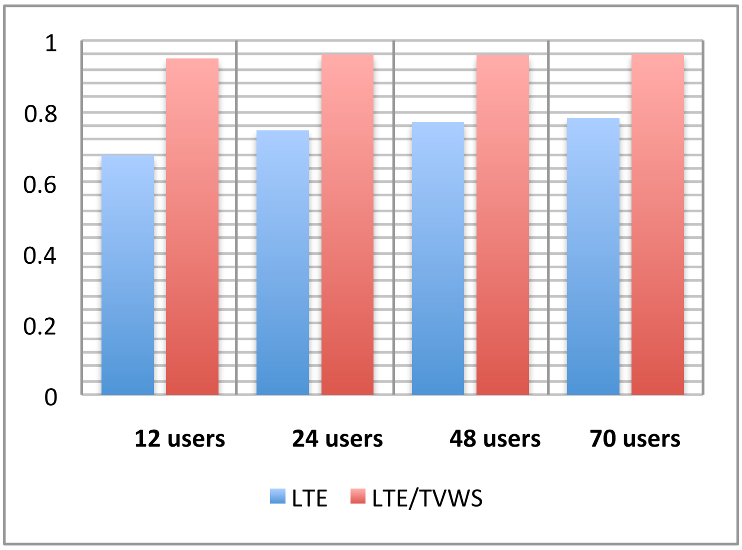
The system that uses both technologies (LTE/TVWS) managed to accomplished the minimum requisite established of QoS [18] to 70 users, the mean rate of more than 90% of the users in this scenario exceeded the 512 Kbps, Figure 21. While the scenario using only LTE managed to attend only 75% of these 70 users attended by the LTE/TVWS scenario. The total capacity gain of the system provided by the system LTE/TVWS is almost 30% greater than the system only using LTE, this can be verified in the Figure 22 which shows the average capacity of the users.

The results are quite convincing, the use of TV band managed to maximize the objective function, and assured that some users that were not attended by the LTE band, due to its position in the cell, to be able to transmit information, this is an extremely important factor for users located in rural and suburban zones which are regions that are almost always located far from the BS.

Figure 23 shows the index level of fairness for both scenarios with 12, 24, 48 and 70 users. The closer the index is to one, the fairer the scenario will be. Observing this figure, it is possible to see that the scenario which combines LTE band and TVWS, LTE/TVWS, is the fairest, providing a fair distribution of the resources to the users in the network. The CDF figures commented before offers an opportunity to check the fairness as well, observing the inclination of the line in the graph we notice that the LTE/TVWS scenario provides a better distribution of the available resources.

This experiment was performed varying the power transmission of the BS as well, and the gains followed almost the same direction of the ones shown before. Regarding the use of DTV channel in lower frequencies, the main contribution relates to the gain in the coverage area proportioned by the good propagation characteristic of these frequencies, as seen in Figure 10, where shows the coverage area of channel 14 (470 MHz).

Figure 23: Fairness analysis.



4.4 Conclusion

In this chapter, it was analyzed a scenario using at the same time LTE and TVWS frequency in the same network, the main objective was to show the gain provided by the use of the TVWS frequency along with LTE. It was analyzed three scheduling algorithm in a separated way to determine which one would be better to be used in the combination of the LTE and TVWS.

Considering the requirement defined through the chapter, the Proportional Fair showed as the best option, due to this algorithm reached the best relation between total system capacity and fairness. This scheduler was used to allocate the LTE and TVWS frequency, a scenario using 5 MHz of each technology, the results offered by this scenario were compared with one using only 10 MHz of LTE service. The gain in the total system capacity provided by the LTE/TVWS scenario was almost 30% greater than the one using only LTE; and some users that were not attended before by the LTE, managed to have some portion of the resources in the cell, due to the good propagation characteristic of the TV band.

These results, along with the ones shown in Chapter 3, highlights the importance of TVWS and show directions to explore this resource as a way to enhance the current telecommunication services. As a continuation of this work, it may be considered a multi cell scenario and more than one TVWS channel, taking into account interference sources to develop a more realistic study to be applied in urban regions.

5 CONCLUSION AND FUTURE WORK

In this work, it is provided information about the importance of TVWS to reach digital inclusion in Brazil and the numerous possibilities that could be deployed using this resource to find a way to overcome the lack of coverage in suburban and rural regions of Brazil. TVWS is a part of TV spectrum that is being underutilized in a given place at a certain time that helps to soften the scarcity of spectrum faced by some applications and presents good propagation characteristics.

Also, the main idea behind the case study that was described in the work is to show the potential of the technology considering the geographic and economical characteristics of Brazil. To elucidate the case study, it was considered the analysis of the availability of TVWS in the state of Ceará, and it was deployed a scenario using both technologies (LTE/TVWS) to show the gains resulted from this combination. The DSO process was considered to be complete, and the study was based on the total number of licensed DTV channels on the SBTVD pattern.

It was verified that in Ceará there is, on average, a TVWS bandwidth of 210 MHz per city, following some defined restrictions. Furthermore, applying the LTE over TVWS approach on a BS at Jericoacoara city, for one unused DTV channel, offered an average capacity of 2.58 Mbps for downlink inside the coverage area. The scenario using both technologies (LTE/TVWS) with a bandwidth of 10 MHz managed to be superior than the scenario using only LTE with the same amount of bandwidth, the total capacity of the system in the LTE/TVWS case was almost 30% superior than the one using only LTE, besides more users were attended with this combination. These results bring the opportunity to the NRA, mobile operators, and new players to formulate a proper business model to explore this resource, benefiting the population around suburban and rural regions, since many others TV channels are available.

As a continuation of this work which was part of the FUTEBOL project, it is considered adapting the scenario described in this work to be replaced by the LSA technology, since the main partners of the project in Europe are directly involved with LSA experiments.

REFERENCES

[1] MUECK, M.; SRIKATHYAYANI, S. Spectrum sharing – Licensed Shared Access (LSA) and Spectrum Access System (SAS). **Intel**, 2015.

[2] HORVITZ, R.; RYSZARD, S.; SONG, S. **TV White Spaces a Pragmatic Approach**. Dec, 2013.

[3] FILIN, S.; BAYKAS, T.; HARADA, H.; KOJIMA, F.; YANO, H. IEEE Standard 802.19.1 for TV White Space coexistence, in **IEEE Communications Magazine**, v. 54, n. 3, p. 22-26, March 2016.

[4] SAEED, R.; SHELLHAMMER, J. TV White Space Spectrum Technologies – Regulations, Standards and Applications. **CRC Press**, 2012.

[5] LUO, Y.; GAO, L.; HUANG, J. Business modeling for TV White Space networks, in **IEEE Communications Magazine**, v. 53, n. 5, p. 82-88, May 2015.

[6] JITAC: **Spectrum Engineering – The Key to Progress**. New York, IEEE, 1968.

[7] JULIAN, B. **LTE 450 global seminar notes**. Jun, 2014.

[8] EKRAM, H.; NIYATO, D. Dynamic Spectrum Access and Management in Cognitive Radio Networks. **Cambridge**, 2009.

[9] MARTIN, C.; DOYLE, C. Essential of Modern Spectrum Management. **Cambridge**, 2007.

[10] SOARES, T. A. Anatel – Analog TV switch-off in Brazil. **In International Symposium on the Digital Switchover**, 2015.

[11] MAKRIS, D.; GARDIKIS. G; KOURTIS, A. Quantifying TV White Space capacity, in **IEEE Communications Magazine**, v. 50, n. 9, p. 145-152, September 2012.

[12] CEPT – Guidance for national implementation of a regulatory framework for TV WSD using geo-location databases. 2015. **ECC** report 236.

[13] SILVA, C. F. M. Contemporary Electromagnetic Spectrum Reuse Techniques TV White Spaces and D2D Communications. December 2015.

[14] RIBEIRO, J. C. Testbed for combination of local sensing with geolocation database in real environments, in **IEEE Wireless Communications**, v. 19, n. 4, p. 59-66, August 2012.

[15] SER, W.; CHOY, C. **Geo-location database with support of Quality of Service for TV White Space**. Institute for Infocomm Research. Jun, 2014.

[16] DAMIEN, L.; MARQUES, P. Cognitive radio systems for efficient sharing of TV White Spaces in European context. **COGEU D3.2**, 2010.

[17] OFCOM – Implementing TV White Spaces. Statement, February, 2015.

[18] KUMAR, A. S. Toward enabling broadband for a billion plus population with TV White Spaces, in **IEEE Communications Magazine**, v. 54, n. 7, p. 28-34, July 2016.

[19] FCC – Second Report and Order and Memorandum Opinion and Order. November, 2008.

[20] ROUZBEH, Y. Television White Spaces – Assessing TVWS for rural broadband access. University of New Hampshire, Broadband Center of Excellence. **Technical report**, November, 2014.

[21] IBGE – Estimativas da população dos municípios brasileiros. Diretoria de Pesquisas; Coordenação de População e Indicadores Sociais; Gerência de Estudos e Análises da Dinâmica Demográfica. **Nota técnica**, Julho 2014.

[22] CARLOS, A.; VALENTE, J. Open Spectrum for Development Brazil Case Study. **Association for Progressive Communications (APC)**, November 2010.

[23] JUNIOR, H. C. Sistema de transmissão no padrão brasileiro de TV digital. Departamento de Engenharia de Telecomunicações - Universidade Federal Fluminense, 2008.

[24] ANATEL – Edital de Licitação Número 2/2014-SOR-SPR-CD, Radiofrequências na faixa de 700 MHz, 2014.

[25] NEKOVEE, M. Cognitive radio access to TV White Spaces Spectrum opportunities, commercial applications and remaining technology challenges. **IEEE Symposium, New Frontiers in Dynamic Spectrum**, p. 6-9, April 2010.

[26] MURTY, R.; CHANDRA, R. Senseless – A database-driven white spaces network. **IEEE Transactions on Mobile Computing**, February 2012.

[27] ALMESAEED, R.; DOUFEXI, A. TVWS extension of the 3GPP/ITU channel model, **IEEE 24th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications**, p. 36-40, 2013.

[28] BOGUCKA, H.; PARZY, M. Secondary spectrum trading in TV White Spaces. **IEEE Communications Magazine**, November 2012.

[29] IRNICH, T.; KRONANDER, J. Spectrum sharing scenarios and resulting technical requirements for 5G systems, **IEEE 24th International Symposium, PIMRC Workshops**, p. 127-132, 2013.

[30] ETSI – Reconfigurable radio systems (RRS), Use cases for operation in white space frequency bands. TR 102 907, version 1.1.1, October 2011.

[31] CARLSON, Broadband and Voice Products – RuralConnect Generation II. Faster Speed, Better Coverage and Lower Cost TV White Space Broadband Radio, 2012.

[32] ELNASHAR, A.; EL-SAIDNY, M. Design, Deployment and Performance of 4G (LTE) Network – A Practical Approach". **Wiley**, 2014.

[33] JOCKSAM, M.; JUNIOR, J. Avaliação da qualidade de vídeo e voip em sistema LTE com diferentes algoritmos de escalonamento utilizando métricas de QoS. **XXX Simpósio Brasileiro de Telecomunicações**, 2012.

[34] COUDÉ, R. Radio Propagation and Radio Coverage Computer Simulation Program. **Radio Mobile Program Operating Guide**, 2013.

[35] 3GPP – 3rd generation partnership project; technical specification group radio access network; physical layer aspects for evolved universal terrestrial radio access (UTRA). TR 25.814, release 7, 2009.

[36] DAMOSSO, E.; LUIS, M. COST Action 231 – Digital mobile radio, Towards future generation systems, final report - European Communities. 1999. TR. EUR 18957, p. 4.

[37] SACHIN, K. An empirically base path loss model for LTE advanced network and modeling for 4G wireless systems at 2.4 GHz, 2.6 GHz and 3.5 GHz. **International Journal of Application or Innovation in Engineering and Management**, September 2013.

[38] NASCIMENTO, M. F. S.; EVANGELISTA, R. B.; SILVA, C. F. M.; CAVALCANTI, F. R. P. TV White Spaces for Digital Inclusion in Brazil, **Revista de Tecnologia da Informação e Comunicação**, n. 2, v. 6, p. 6-15, 2016.

[39] CHEN, X.; WANG, M.; LIU, T.; WANG, L. Optimal band allocation for cognitive cellular networks. Wireless Networking and Mobile Communications, Nanjing University of Science and Technology, 2014.

[40] LIU, E.; LEUNG, K. **Proportional fair scheduling, analytical insight underrayleigh fading environment**, Departament of Eletrical and Eletronic Engineering, Imperial Colege, 2013.

[41] BATISTA, R. L.; SILVA, C. F. M.; SILVA J. M. B.; MACIEL, T. F.; CAVALCANTI, F. R. P. What happens with a proportional fair cellular scheduling when D2D communications underlay a cellular network?, **IEEE Wireless Communications and Networking Conference Workshops (WCNCW)**, Istanbul, p. 260-265, 2014.

[42] 3GPP – LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) system scenarios. TR 36.942 version 10.2.0, release 10, 2011.

[43] 3GPP – 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access Network (E-UTRAN). TS 36.413, v. 8.10, 2010.

[44] PREBEN, M.; NA, W. LTE capacity compared to the Shannon Bound. **IEEE magazine**, 2007.

[45] LONGLEY, A. G.; RICE, P. L. ESSA Technical Report ERL 79-ITS 67, **Prediction of Tropospheric Radio Transmission Loss Over Irregular Terrain**, 1968.

APPENDIX A – RADIO MOBILE SOFTWARE

Radio Mobile is a free propagation simulation program written by Roger Coudé. The program is extensive and has many options, parameters and settings to simulate radio frequency propagation and it is available for free at its official website.It is a computer simulation program used to predict radio coverage of a base station, repeater or other radio network elements. Ground elevation and various radio parameters are taken into account to predict radio coverage around a single or multiple radio sites. After coverage is calculated for a defined geographic area, a map can be overlaid on the coverage plot to show various locations and the resulting coverage along different environments. Moreover, log files with the output information can be generated for further analysis.

Table 6: Main input Radio Mobile parameters used to predict and provide a radio coverage map.

Parameters
Transmitter location
Transmitter power
Operation frequency
Antenna gain, type and pattern
Transmission line losses
Receiver location
Receiver antenna type
Receiver sensitivity
Terrain and elevation data for the area

Source: Table from [45].

The program uses terrain elevation data from either the SRTM (Shuttle Radar Topography Mission) or the DTED (Digital Terrain Elevation Data) databases that are both available for free in the Internet. Other formats for elevation are available; however, these two are the most common ones.

The program generates a coloured plot of radio coverage from one or multiple base stations showing expected receive signal levels. Levels are displayed using the units specified by the user (S-units, µV, dBm, µV/m).

The program has the ability to combine this coverage prediction map together with a road or other geographic map. Coverage can also be displayed using a "rainbow" of coverage, using various colours to represent various signal levels.

Radio Mobile uses a computer algorithm called the Longley Rice model to determine signal loss for non LOS radio paths. LOS paths use a calculation called the"two ray" method, which takes into account the free space loss only. If the signal path exceeds 60 % clearance of first Fresnel zone, the radio signal is considered "clear LOS"and will incur no diffraction loss.

Radio Mobile has the ability to operate using 4 different coordinate systems. All of these locate a radio or user at a unique location on the earth surface. Radio Mobile input makes use of the following coordinate systems as seen in Table 7.

Table 7: Coordinate systems.

Parameters
Latitude and Longitude (Lat and Long),default and always used
Maidenhead Locator System (Maidenhead) or QRA
Military Grid Reference System (MGRS)
UTM Universal Transverse Mercator
WGS 84 Geosys input

Source: Table from [45].

Installing and Setting up

A More detailed description of the program and its features can be found in the official website [11]. Two of the major contributors to the Radio Mobile user information and guides are Ian's website and Remko's website. Both have excellent operating guides explaining the initial procedures to install, configure, and to use such software.

Radio Mobile data input is strictly in metric units. Elevations are in meters, distances are in kilometers, cable lengths and tower heights are in meters. Program input parameters cannot be changed to accept or display British units.

Before a coverage plot can be produced, three radio input parameters must be defined for the Radio Mobile program. In addition, a map of the area of coverage must be defined, including centre of map, map size, and displaying resolution. The map is then extracted from the elevation database and used as a background for the coverage plot.

Radio mobile parameters can be defined in any order; however, all must be defined before a coverage plot can be produced, they are:

- Unit properties — to setup parameters related to the elements which will compose the network, e.g. latitude, longitude, icon, and label formats;
- System properties — to setup parameters related to the system operated on each unit, e.g. transmit power, antenna pattern, antenna height, and line loss;
- Network properties — to setup parameters related to the network that will be implemented, e.g. operation frequency, topology, and membership.

Propagation Model

The propagation model used by Radio Mobile is the ITM (Irregular Terrain Model) [45] (some times referred as Longley-Rice Model) is designed for use at frequencies between 20 MHz and 20 GHz, for a wide variety of distances and antenna heights, and for those scenarios where terrain plays an important role in the system. It is a model concerned

[11] `http://www.cplus.org/rmw/english1.html`

with the generally available received power and not with the fine details of channel characterization.

It is based on the electromagnetic theory and on the statistical analyses of both terrain features and radio measurements. It predicts the median attenuation of a radio signal as a function of distance and the variability of the signal in time and in space. In the physical world, received signal levels vary in time because of changing atmospheric conditions, and they vary in space because of a change in terrain. It is this variability that the ITM tries to describe.

Model description

A model is a technique or algorithm which describes the calculations required to produce the results. An implementation of a model is a representation as a procedure in some specific computer language that requires input data. The results are processed and showed in some output information.

This model is still in use and considers attenuation parameters which depend on variables related to climate, topography, and other features that added together contribute to attenuate the signal received at one point or area. However, these variables are different for each location, requiring a more careful assessment of each scenario and environment.

According to Longley-Rice, the signal received by a mobile station is the result of the signal transmitted properly attenuated in free space and the sum of the attenuation formed by random variables on their way.

Given the values for the input parameters, the ITM first computes several geometric parameters related to the propagation path. The model uses empirical relations involving the terrain irregularity parameter to estimate their position. Next, the model computes a reference attenuation, which is a certain median attenuation relative to free space, the median is to be taken over a variety of times and paths.

In the model, the LOS area is defined as the region where the earth's surface does not interrupt the propagation of radio waves.

Parameters

Table 8 lists all the input parameters required by the ITM model. Also indicate the allowable values or the limits for which the model was designed.

Description of some of these parameters can be found below:

- Terrain Irregularity Parameter — The terrain that separates the two terminals is treated as a random function of the distance between the terminals. To characterize this random function, the ITM model uses a single value Δh to represent simply the size of the irregularities. For an average terrain, it is used $\Delta h = 90\,\mathrm{m}$;

Table 8: Main parameters required by ITM model.

System Parameters	
Frequency	20 MHz to 20 GHz
Distance	1 km to 2000 km
Antenna heights	0.5 m to 3000 m
Polarization	vertical or horizontal
Environmental Parameters	
Terrain irregularity parameter, Δh	
Electrical ground constants	
Surface refractivity	250 to 400 N-units
Climate	
Deployment Parameters	
Siting criteria	random, careful, or very careful
Statistical Parameters	
Reliability and confidence level	0.1% to 99.9%

Source: Table from [45].

- Electrical Ground Constants — The relative permittivity (dielectric constant) and the conductivity of the ground;
- Surface Refractivity, Ns — The atmospheric constants, and in particular the atmospheric refractivity, must also be treated as a random function of position and, now, also of time. For most purposes, this random function can be characterized by the single value Ns, representing the normal value of refractivity near ground (or surface) levels. Usually measured in N-units (parts per million);
- Climate — Equatorial, Continental Subtropical, Maritime Subtropical, Desert, Continental Temperate, Maritime Temperate over land and over sea. For average atmospheric conditions, it is used a Continental Temperate climate and $Ns = 301\,\mathrm{N-units}$. Together with Ns, the climate serves to characterize the atmosphere and its variability in time;
- Siting Criteria — A qualitative description of the care which one takes to site each terminal on higher ground;
- Statistical Parameters — They describe the kind and variety of statistics that the user wishes to obtain. Very often such statistics are given in the form of quantiles of the attenuation.

APPENDIX B – ANTENNA PATTERN

Mathematical Modeling

One of the input parameters requested for the Radio Mobile software for elaboration of coverage maps is the antenna pattern used. For the study case, it was considered a LTE base station located at a coastal area of Jericoacoara city, therefore it was used a sector antenna, otherwise there would be a waste of signal power for the sea. The antenna horizontal radiation pattern used was the following :

$$A_h(\varphi) = -\min\left[12\left(\frac{\varphi}{\varphi_{3\mathrm{dB}}}\right)^2, A_m\right] \quad \text{where} -180 \leq \varphi \leq 180 \tag{9}$$

$\varphi_{3\mathrm{dB}}$ is the 3 dB beam width which is 65 degrees, and A_m is the maximum attenuation and has a value of 20 dB.

And the vertical radiation pattern used was:

$$A_v(\theta) = \max\left[-12\left(\frac{\theta - \theta_{etilt}}{\theta_{3\mathrm{dB}}}\right)^2, SLL_v\right] \quad \text{where} -90 \leq \theta \leq 90 \tag{10}$$

$\theta_{3\mathrm{dB}}$ is the 3 dB beam width which is 6.2 degrees, $SLL_v = -18\,\mathrm{dB}$ is the side lobe level relative to the maximum gain of the main beam, and θ_{etilt} is the electrical downtilt angle in degrees.

For the electrical downtilt angle, it was considered a value of 6 degrees, as values between 3.5 and 10.5 degrees appear to be the optimum values for a homogeneous traffic distribution.

Matlab Code

```
%horizontal antenna pattern parameters
angle_h = [0:180 -179:-1]';
HPBW_h = 70;
FRB_h = 20; %dB

%vertical antenna pattern parameters
angle_v = (90:-1:-90)';
angle_tilt = [0 6 12];
SSL_v = -18; %dB
HPBW_v = 6.2;
```

```
%horizontal pattern
g_h = -min(12*(angle_h/HPBW_h).^2, FRB_h);

%vertical pattern
g_v = zeros(181, 3);

for i=1:length(angle_tilt)
g_v(:,i) = max(-12*((angle_v - angle_tilt(i)*
ones(length
(angle_v),1))/HPBW_v).^2, SSL_v);
end

%exporting to files

ant_file_0tilt = [g_h; g_v(:,1)];
fileout1 = 'lte_bs_0tilt.ant';
fid1 = fopen(fileout1, 'w');
for i= 1:length(ant_file_0tilt)
fprintf(fid1, '%.2f\n', ant_file_0tilt(i,1) );
end

ant_file_6tilt = [g_h; g_v(:,2)];
fileout2 = 'lte_bs_6tilt.ant';
fid2 = fopen(fileout2, 'w');
for i= 1:length(ant_file_6tilt)
fprintf(fid2, '%.2f\n', ant_file_6tilt(i,1) );
end


ant_file_12tilt = [g_h; g_v(:,3)];
fileout3 = 'lte_bs_12tilt.ant';
fid3 = fopen(fileout3, 'w');
for i= 1:length(ant_file_12tilt)
fprintf(fid3, '%.2f\n', ant_file_12tilt(i,1) );
end
```

Antenna Pattern Results

The graphics of the horizontal and vertical antenna pattern can be found in the Fig. 24 and 25, respectively.

Figure 24: Horizontal antenna radiation pattern used in the case study.

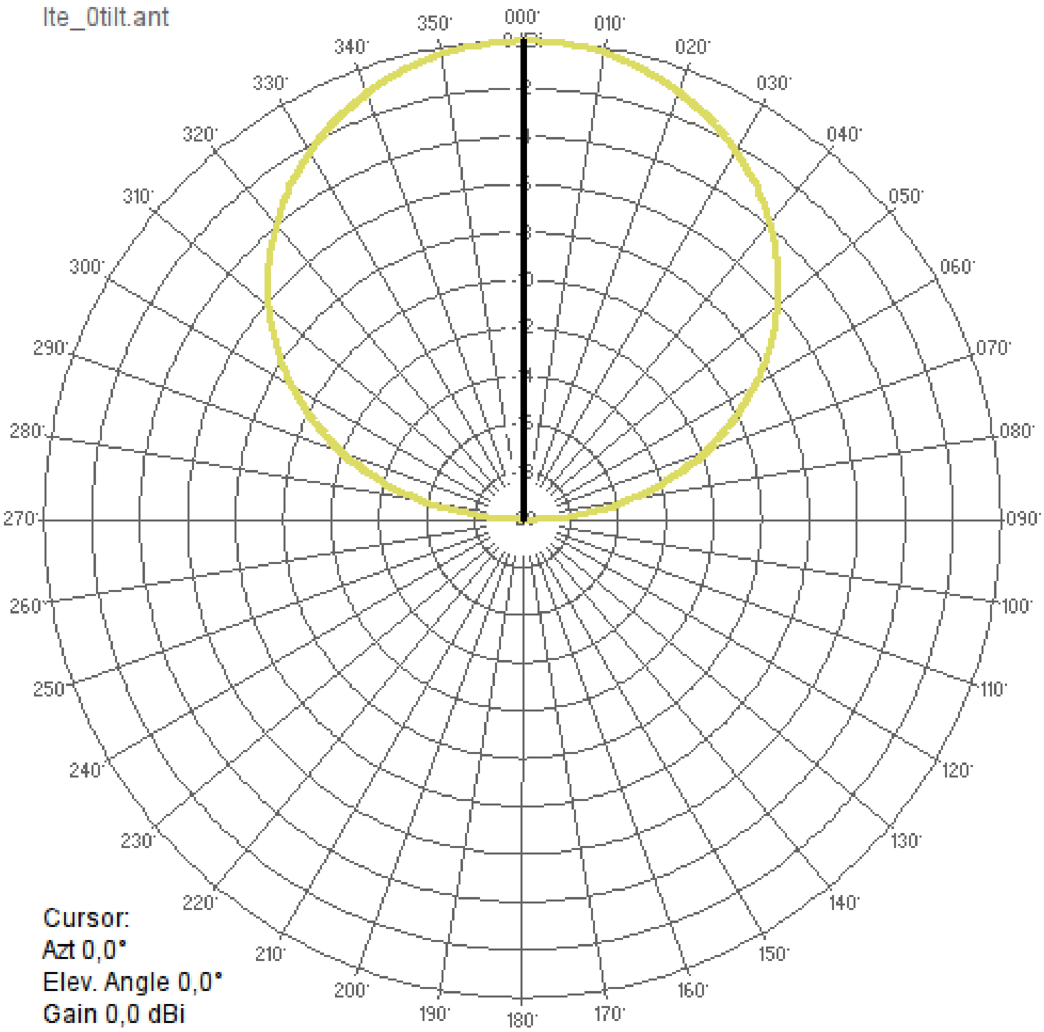
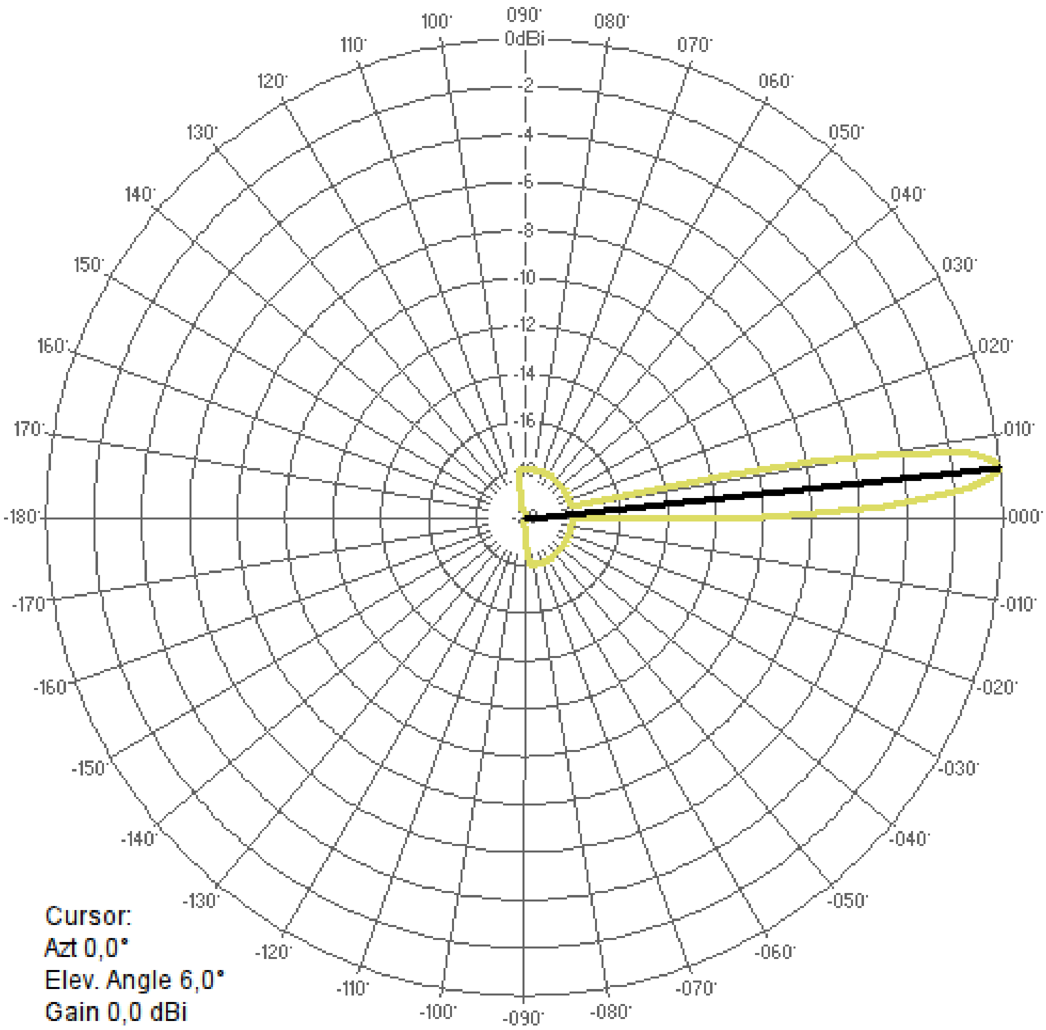


Figure 25: Vertical antenna radiation pattern used in the case study.



APPENDIX C – PARAMETERS USED IN THE RADIO MOBILE

The Table 9 shows all the parameters used in the Radio Mobile simulation of the Ceará case study.

Table 9: Main parameters used in the Simulation.

System Parameters	
Propagation Model (Non LOS)	ITM Model
Propagation Model (LOS)	Two Rays Model
Link Direction	Downlink
Unit Properties	
BS Latitide	$02^o47'43.30"S$
BS Longitude	$40^o30'42.96"W$
End user location	Anywhere
Network Properties	
Minimum Frequency	698 MHz
Maximum Frequency	704 MHz
Polarization	Any
Mode of Variability	Spot – 90%
Surface Refractivity	360 N − units
Relative Ground Conductivity	0.005
Relative Ground Permittivity	15
Climate	Equatorial
Topology	Data net, star topology
Transmission mode	SISO
System Properties	
BS Transmit Power	43 dBm
BS Sensitivity	−112 dBm
BS Minimum SNR	−10 dB
BS Noise Figure	5 dB
BS Transmitted Bandwidth	5 MHz
BS Line Loss	3 dB
BS Antenna Type	Sector Antenna (Appendix C)
BS Antenna Gain	14 dBi
BS Antenna Height	30 m
BS Antenna Azimuth	170^o
BS Antenna Elevation Angle	6^o
BS Additional Cable Loss	0 dB
End user Transmit Power	24 dBm
End user Sensitivity	−105 dBm
End user Minimum SNR	−7 dB
End user Noise Figure	9 dB
End user Received BW	5 MHz
End user Line Loss	0 dB
End user Antenna Type	Omnidirectional Antenna
End user Antenna Gain	0 dBi
End user Antenna Height	1.5 m
End user Additional Cable Loss	0 dB