**UNIVERSIDADE FEDERAL DE ITAJUBÁ - UNIFEI**
**GRADUATE PROGRAM IN**
**ELECTRICAL ENGINEERING**

# Coexisting Analysis of 5G Waveforms with ISDB-T System in TV White Spaces.

**Samuel de Souza Lima Moreira**

Itajubá, August 19, 2020

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Thesis presented to the Programa de Pós-Graduação em Engenharia Elétrica in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering.

**Concentration Area: Microelectronics**

**Supervisor: Prof. Dr. Tales Cleber Pimenta**
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# Abstract

The efficient use of the electromagnetic spectrum becomes increasingly necessary due to the increase number of cellular devices. One possible solution is the opportunistic spectrum use in the VHF and UHF bands, allocated for television broadcasting. Therefore, it is necessary to evaluate the concurrent operation of broadcasting and mobile communication systems. This work aims to identify, analyze and measure the interoperability between those systems, by evaluating the feasibility of coexistence of different types of services. In this article, evaluations were made on two major candidates for the next cellular generation, the GFDM and the F-OFDM, operating along with the Integrated Services Digital Broadcasting Terrestrial – ISDB-T standard. The results show the flexibility of the GFDM and F-OFDM waveforms over the OFDM waveform, thus enabling opportunistic use of the spectrum over licensed and unlicensed users.

**Key-words**: 5G. Broadcasting. ISDB-T. F-OFDM. GFDM. Software Defined Radio. TV White Spaces.

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# List of abbreviations and acronyms

| | |
|---|---|
| *1st Generation Mobile Networks* | 1G |
| *2nd Generation Mobile Networks* | 2G |
| *3rd Generation Mobile Networks* | 3G |
| *4th Generation Mobile Networks* | 4G |
| *5th Generation Mobile Networks* | 5G |
| *Additive White Gaussian Noise* | AWGN |
| *Agência Nacional de Telecomunicações* | Anatel |
| *Asynchronous Serial Interface adapter* | ASI |
| *Bit Error Rate* | BER |
| *Centro de Referência de Radiocomunicações* | CRR |
| *Cognitive Radios* | CR |
| *Cyclic Prefix* | CP |
| *Cyclic Suffix* | CS |
| *Digital Television Receiver* | DTR |
| *Effective Isotropic Radiated Power* | EIRP |
| *Enhanced Mobile Broadband* | eMBB |
| *Field Programmable Gate Array* | FPGA |
| *Filtered Orthogonal Frequency Division Multiplexing* | FOFDM |
| *First In, First Out* | FIFO |
| *Generalized Frequency Division Multiplexing* | GFDM |
| *Global Positioning System* | GPS |
| *Industrial Scientific and Medical* | ISM |
| *Institute of Electrical and Electronics Engineers* | IEEE |
| *Integrated Services Digital Broadcasting Terrestrial* | ISDB-T |
| *Intermediate Frequency* | IF |
| *International Telecommunications Union* | ITU |
| *Internet of Things* | IoT |
| *Inverse Fast Fourier Transformation* | IFFT |
| *Long Term Evolution* | LTE |
| *Machine to Machine* | M2M |
| *Machine-Type Communication* | MTC |

| | |
|---|---|
| *Orthogonal Frequency Division Multiplexing* | OFDM |
| *Out-of-Band* | OOB |
| *Primary Users* | PU |
| *Radio Frequency* | RF |
| *Random Access Memory* | RAM |
| *Secondary Users* | SU |
| *Short Message Service* | SMS |
| *Software Defined Radio* | SDR |
| *Television White Spaces* | TVWS |
| *Transport Stream* | TS |
| *Ultra High Frequency* | UHF |
| *Ultra-Reliable and Low-Latency Communications* | URLLC |
| *Universal Serial Bus* | USB |
| *Very High Frequency* | VHF |
| *White Spaces* | WS |
| *Windowed Generalized Frequency Division Multiplexing* | W-GFDM |
| *Wireless Local Area Network* | WLAN |
| *Wireless Regional Area Network* | WRAN |
| *Zero-Forcing* | ZF |

# Summary

# 1 Introduction

According to the *International Telecommunications Union* (ITU) by the end of 2016, 53% of the world's population still did not have access to the Internet. Despite public and private efforts to expand services and customers numbers, world population growth outpaces the increase rate of connection points [1, 2]. In Brazil *Agência Nacional de Telecomunicações* (Anatel) estimates that there are approximately 27 million broadband access points. This number is equivalent to only 46,7% of households. In the North and Northeast regions, this percentage is more critical, with only 16,96% and 24,42% of households respectively, connected by broadband cables [3]. This situation can be seen in Figure 1, where the density of the distribution of access points in Brazil is presented.

The increase in the number of connections in those areas, given the country's large territorial extension, is linked to technical and economical challenges imposed by the expansion of an optical back haul. The adverse conditions of the Northern region, such as low population density, large distances between localities, climatic conditions, among others, make it difficult to implement terrestrial networks [2].

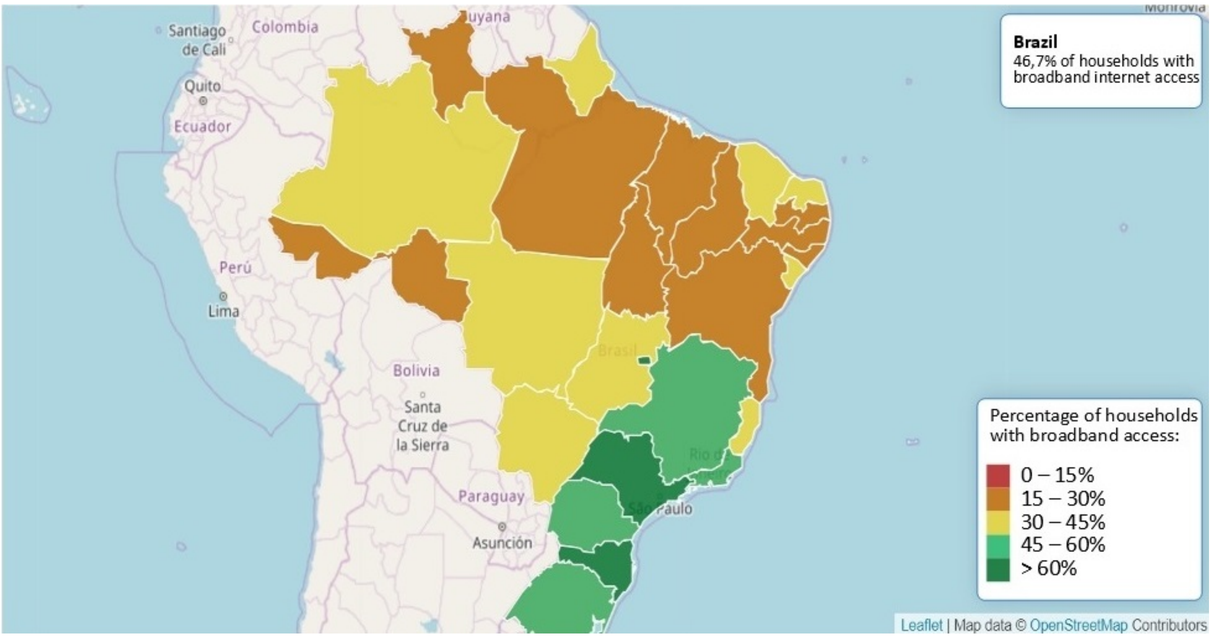



Figure 1 – Broadband access in Brazil.

On the other hand, in the coming years, there will be more than 10 billion connected devices worldwide, generating five exabytes of mobile data per month, and more than three exabytes of video streaming [4]. Transforming these estimates into real business opportunities for operators requires addressing the following crucial issues: how to solve the challenges of providing broadband access to regions that lack adequate coverage, and how to meet growing traffic demand when access to electromagnetic spectrum is limited.

Currently, the *5th Generation Mobile Networks* (5G) is being discussed by the scientific community and industry, with some initial trials being deployed worldwide. One of the critical challenges for fifth generation is to provide broadband access to regions that lack adequate coverage. The other is to meet the growing demand for traffic on locations of limited band. One of the proposed goals is to make viable the wireless broadband internet access for rural areas, the *Wireless Regional Area Network* (WRAN) [5]. The *Institute of Electrical and Electronics Engineers* (IEEE) 802.22 standard addresses this challenge by proposing the exploration of idle channels by means of *Cognitive Radios* (CR) networks [6].

Although most of the electromagnetic spectrum has already been licensed by regulatory agencies, several measurements show that the rate of electromagnetic spectrum occupancy is in the range of 5% to 15% [4, 7]. Due to the analogue TV shutdown process, a significant part of the spectrum in the *Very High Frequency* (VHF) and *Ultra High Frequency* (UHF) bands is becoming unoccupied [7, 8]. Bands that were previously reserved for primary users (holders of the spectrum usage), are now available to secondary users. Those gaps in the frequency spectrum are called *White Spaces* (WS) [9].

In this context, the adoption of *Cognitive Radios* (CR) to use the spectrum gaps is a solution to allow secondary users to operate in the unused bands, thus optimizing the available resources. Nevertheless, it must be assured that they do not cause interference to the primary users of the spectrum [6].

In [10, 11], the authors present a modulation technique of multiple non-orthogonal carriers suitable for CR because it allows the fragmented use of the spectrum and controls the out of range emission. This modulation technique is known as *Generalized Frequency Division Multiplexing* (GFDM), which can be considered a generalization of the *Orthogonal Frequency Division Multiplexing* (OFDM) [12]. The main feature that makes GFDM a promising transmission pattern for 5G is its flexibility [11]. Another technique, proposed to reduce the *Out-of-Band* (OOB) emissions and to reduce spurious emissions, is the *Filtered Orthogonal Frequency Division Multiplexing* (FOFDM) [13], which is a strong candidate to be adopted for the 5G.

In order to address the lack of a broadband coverage in Brazil, and the increasing number of connected devices, this thesis proposes a study for enabling the secondary use of the electromagnetic spectrum. Two test procedures were proposed, to evaluate three technologies that are candidates for the *5th Generation Mobile Networks* (5G) and the standard Brazilian *Integrated Services Digital Broadcasting Terrestrial* (ISDB-T) digital TV standard. A waveform signal generator system was developed on a software defined radio platform to evaluate the coexistence between primary systems and some proposed technologies for the next generation of mobile communications.

This work intends to assist in the survey of protection relationships, to determine the emission masks that allow 5G systems to coexist with legacy systems. The results obtained show that the next generation technologies cause less interference and might be a suitable solution for areas at poor broadband coverage.

## 1.1 Structure of this Dissertation

The work is organized as follows: Chapter 2 presents the topics that motivated this thesis. Chapter 3 presents a brief description of the evaluated waveforms and Chapter 4 describes how the system used to conduct the experiments was developed. In Chapter 5 the procedures for carrying out the tests are shown and in Chapter 6 the results for the interoperability of and coexistence of the different tests are presented. Finally, Chapter 7 the presents the conclusions.

# 2 Rationale

This chapter describes the fundamentals of the thesis, and describes some applications that might be suitable for the Brazilian broadband scenarios.

## 2.1 A Brief History of Mobile Communications

Mobile phones and smart phones are an essential part of our currently life and have revolutionized the way society communicates [14]. Since the deployment of the first mobile communication systems, cellular networks have evolved in terms of coverage and increasing user capacity. The *1st Generation Mobile Networks* (1G) system basically offered voice traffic employing analog modulation. The *2nd Generation Mobile Networks* (2G) standard has increased system capacity through the use of digital communication techniques and, in addition, introduced a new communication service by text message, called *Short Message Service* (SMS). Next came the *3rd Generation Mobile Networks* (3G) and *4th Generation Mobile Networks* (4G) systems, developed to meet the growing demand for mobile broadband internet access, which was effectively met with the consolidation of the 4G [14].

Currently, the next generation of mobile networks is being discussed by the scientific community. A major difference between 5G and previous generations is the diversity of requirements that must be addressed for different applications due to several distinct scenarios [15, 16, 17].

## 2.2 5G Scenarios

According to [18] there are four scenarios for 5G, namely: *Enhanced Mobile Broadband* (eMBB), characterized by the high transmission rate; WRAN, including long-range networks; *Ultra-Reliable and Low-Latency Communications* (URLLC), covering low latency and high robustness networks and, finally, the *Internet of Things* (IoT), that encompasses a massive number of devices connected to a single cell [15, 18]. Figure 2 illustrates these proposed scenarios. Each of those scenarios presents a set of specific and sometimes conflicting requirements. Therefore, the waveform used in the physical layer of 5G networks should be flexible enough to meet all the challenges predicted for this new standard [17, 18, 19].

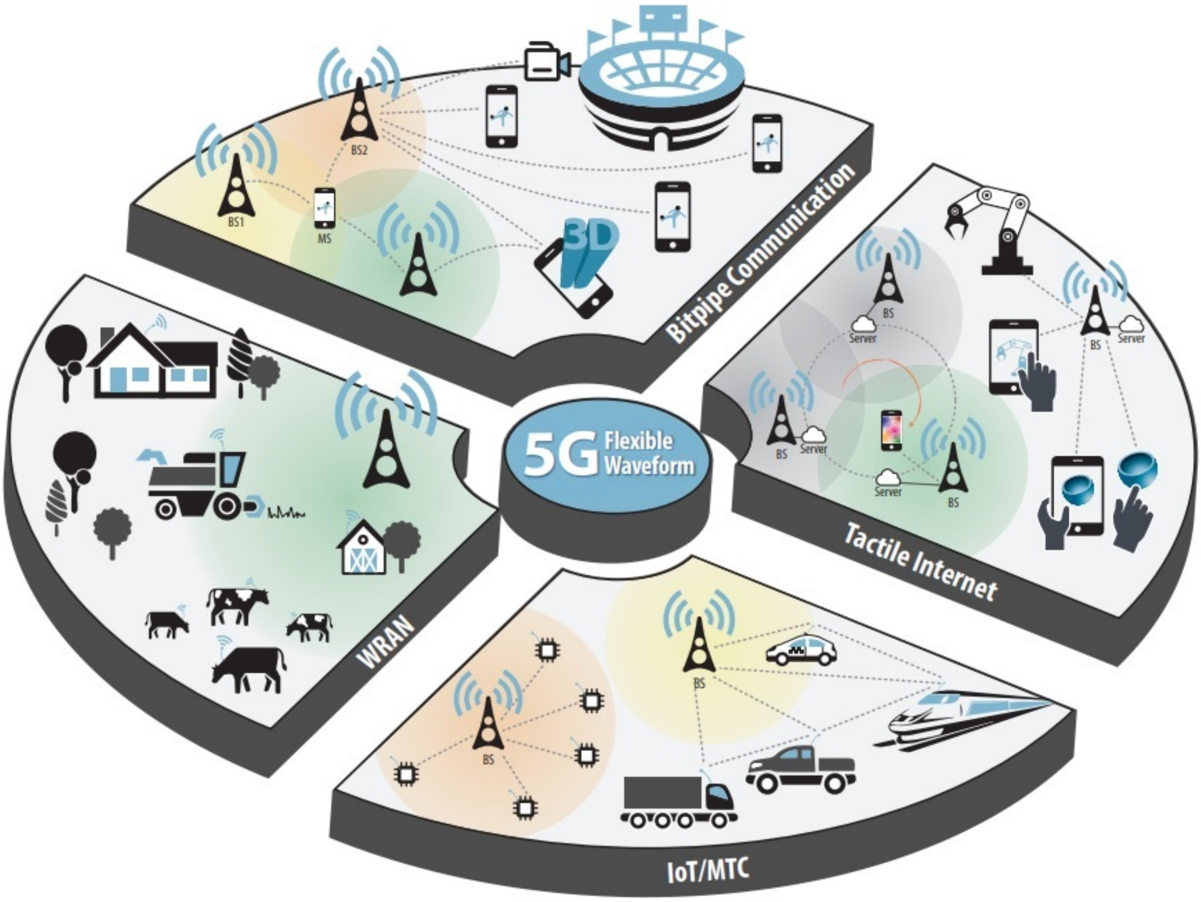



Figure 2 – Scenarios Proposed for the 5G [15].

### 2.2.1 Bitpipe Communication

In the eMBB scenario, identified as bitpipe communication in Figure 2, it is estimated that on-demand video consumption and instant sharing of high-resolution content will require transmission rates 100 times higher than currently available rates, reaching connections up to 20 Gbps [15, 18]. Sporting events and artistic presentations are examples of a great concentration of users eager to share their experiences, recorded in high-resolution photos and videos. Thus, dynamic spectral allocation of wide frequency ranges, low spurious emission, opportunistic reuse of channels, and the use of spatial multiplexing techniques are essential in this scenario [18].

### 2.2.2 Internet of Things

This scenario aims to promote efficient management of numerous network-connected autonomous devices to meet a wide range of applications that have distinct communication requirements. Smart grids and smart cities are examples of trends that will be present all over the world, connecting countless new autonomous devices to the Internet. Communications *Machine to Machine* (M2M), or *Machine-Type Communication* (MTC), such as sensor and actuator networks, will lead to countless number of devices per cell. The main challenge is to deal with a multitude of devices connected simultaneously, a number that can reach hundreds of thousands per cell, at least an order of magnitude above the capacity of 4G networks [18].

### 2.2.3 Tactile Internet

This scenario is considered as super real time and, it is aimed at low latency applications. Strict specification of this requirement is necessary to provide solutions that involve security and also to meet the growing use of applications running in the cloud [18].

### 2.2.4 Rural Area Networks

Low population density and low revenue areas are not profitable enough to justify the implementation and operation maintenance of the network infrastructures [18].

It is expected the 5G will offer Internet access in those areas under the restriction of low cost of deployment. Therefore, 5G must be able to operate at a range of more than 50 km, in order to reach a sufficient number of potential subscribers in a single cell. The IEEE 802.22 standard, which defines WRAN, establishes the use of cognitive radios operating in spectral gaps in TV range. These unoccupied gaps are defined as TV White Spaces, and is an attractive solution to this demand.

## 2.3 Television White Spaces

Television White Spaces (TVWS) are the unused TV broadcast channels which can be available for wireless communication systems. More available spectrum is freed up after the transition from analog to digital television [8]. They are located in the VHF and UHF bands and offer several important properties that make them highly desirable for wireless communications: ability to penetrate buildings and foliage, non-line of sight connectivity, and broadband payload capacity. Therefore, TVWS channels can be used in certain locations by devices such as *Long Term Evolution* (LTE) gadgets, wireless mobile interoperability for microwave access, wireless microphone, etc [4, 9].

The prospect of having a large availability of spectrum reuse combined with appropriate free space channel characteristics in this frequency range has triggered the development of several standards and protocols for operation in unoccupied channels. The protocols have the function of specifying the set of methods and technologies that will enable the operation in *White Spaces* (WS). The 802.11af and 802.22 protocols, whose main objective is to provide Internet access through the use of unoccupied channels in the TV band are presented in the next section [7].

### 2.3.1 The IEEE 802.11af Protocol

The IEEE 802.11 standard establishes a set of standards that specify wireless communication systems for operation under *Wireless Local Area Network* (WLAN) mode. This protocol is a modification of the 802.11 standard that allows operation on White Spaces [20]. Thus, this set incorporates a series of cognitive functionalities, geolocation and access to databases. There are two possible scenarios for implementing the 802.11af standard: indoor use, for coverage of regions within a radius of less than 100m, as in the existing 802.11 WLAN networks; and external use (outdoor), for access points covering up to 5 kilometers, depending on the link conditions.

Wireless Local Area Networks systems generally operate in the GHz range of the electromagnetic spectrum, more specifically 2.4 GHz, 3.6 GHz and 5 GHz. In this way, the physical and link layers are optimized for this frequency range. In order to migrate to the TV band, the IEEE 802.11af protocol is set to be flexible enough to accommodate this frequency range and meet the requirements of different regulatory agencies in each country [7]. In the IEEE 802.11af protocol, the access points send their own geolocation information, obtained through satellites, via *Global Positioning System* (GPS), in order to request the list of TV channels available in the WS databases. The device can load information from unoccupied channels to several selected points in the vicinity in relation to its current position. Based on data of an operating region, the device can define at which channel this devices are able to operate. These groupings are called overlapping channel lists. This list can then be used without consulting a database within a period of up to 24 hours [20]. At the end of this period, a new consultation needs to be made. The access point must check its position every 60 seconds and if a new location is detected, outside the stored limits of its operating area, the device needs to contact the database to obtain a new list of valid channels.

### 2.3.2 The IEEE 802.22 Standard

The IEEE 802.22 standard is the first standardization initiative for WRAN. The main protocol difference is the mechanism that allows coexistence of the *Primary Users* (PU), which are the owners of licensed channel and the *Secondary Users* (SU), in the TV frequency range [5, 6].

The main objective of the 802.22 standard is to provide wireless broadband access in rural or sparsely populated areas. It is intended to achieve this by using concepts of cognitive radios. The expected coverage area is typically 17–30 km, possibly up to 100 km, depending on link conditions, *Effective Isotropic Radiated Power* (EIRP) and antenna height [5].

The protocol covers two types of devices: the base stations and the client terminals.

Client devices support connections from up to 512 devices. The maximum data rate is 18 Mbps for channels of 6 MHz bandwidth. The minimum data rate determined is 1,5 Mbps for the downlink and 384 kbps for the uplink when the client is located at the edge of the cell. During the transmission of the payload, the system uses adaptive modulation, based on the characteristics of the channel, thus allowing greater flexibility and quality of service. The link layer provides a set of cognitive features to protect primary users and supports spectral sensing. The protocol supports point to point and multipoint connections [5].

In addition, a channel selection and spectrum sensing algorithm is specified to provide guidelines to allow, or not, to broadcast on a TV channel. IEEE 802.22 devices use systems and hardware that are relatively more sophisticated to achieve the detection and protection of primary users and to ensure quality of service.

According to the IEEE, there are two modes of geographic positioning that can be used by protocol 802.22: one mandatory made by satellites and one optional made by terrestrial geolocation. The technology should detect whether any device on the network moves over a distance of more than 50 meters. In this case the base stations and client devices must follow local standards, determined by the regulatory agency, and obtain a new list of channels available from the database services [5, 6].

## 2.4 TV White Spaces Applications

This section describes some possible applications for white space communication, that might be suitable for the broadband demands currently required for the Brazilian scenario [1, 2, 3].

### 2.4.1 Broadband Access in Rural Areas

Broadband access for rural areas is one of the most appealing scenarios when considering the prospect of communication systems using TVWS in Brazil. This scenario aims to provide internet access to regions where this type of service is either very expensive, or not yet available. This scenario intends to use WS both to provide Internet access for the end user and to connect it to the backbone of existing networks. Wireless networks operating in the 2.4 GHz and 5 GHz bands are not suitable when assessing infrastructure, installation and maintenance costs [21]. Due to the small coverage area that devices offer in this frequency range, the number of devices required discourages the deployment of networks operating in these frequency bands [21]. The use of lower frequencies allows providers in rural areas the possibility to extend the reach of the links, using fewer access points for both fixed and mobile terminals [21].

### 2.4.2 Machine to Machine Communication

In this context, Internet of Things application targets sensors, meters and intelligent electronic devices. Public utility networks such as electricity, gas and water are currently migrating to wireless technologies [21]. The smart meters that make up these networks are simple battery-powered devices that perform end-user data monitoring and communicate through access points or network coordinators within a radius of several dozen meters to a few kilometers. The required data rate is relatively low due to the nature of the data exchanged. With the growing adhesion of unlicensed use of the electromagnetic spectrum, an expansion of bandwidth is expected for use of smart utility networks [4, 21].

### 2.4.3 Industrial, Municipal and Smart Campus Networks

Industrial, municipal and smart campus networks can be expanded both in bandwidth and in distance with the use of free channels in the TV range. While cities and universities can provide internet access, industrial networks focus on building control, security and remote automation of industrial processes [4, 21].

The favorable characteristics of this frequency and penetration range should provide the best performance with fewer access points, thus reducing infrastructure cost when compared to the congested *Industrial Scientific and Medical* (ISM) [21].

### 2.4.4 Indoor White Space

Wireless networks are recently going through a transition process, where customers demand multiple simultaneous streams of data within the same environment. The emergence of services such as video streaming, cloud data sharing, and video games elevate further the needs of bandwidth increase. According to [4], the availability of the electromagnetic spectrum is different between outdoor and indoor environments, and there may be divergences between floors and even between rooms. Therefore, many frequencies marked as unavailable by a database could potentially be exploited using low-power devices operating on free channels. The indoors use of white space devices can be an elegant solution for relieving the 2.4 GHz range [21].

### 2.4.5 Public Security

Most wireless public safety networks, such as police and the fire department, currently have voice-only support and, in some countries, transfers of small data packets that require only a few tens of kilo bits per second. Deployments in critical situations such as medical emergencies, natural catastrophes, and crisis management are some examples that require an emergency network with high reliability. The long range and penetration capacity without line-of-sight signals in this frequency range are attractive in this scenario [21].

### 2.4.6 Broadband in Public Transportation

According to the National Industry Association, approximately one in four Brazilians use public transport as their main source of transportation [1]. The growing demand for communication access has become more accentuated in municipal and long-distance public transport, such as interstate buses and trains, to provide multimedia entertainment and Internet access. The use of WS can provide a larger coverage area when compared to current cell topology [21].

## 2.5 Summary

This chapter presented the fundamentals that motivated the elaboration of this thesis. In the next chapter the basic of the waveforms which were evaluated in this work are presented.

# 3 Waveforms

Communication systems usually are designed to achieve the maximum possible data transmission capacity. On the other hand, the 5G systems consider other goals, usually of conflicting characteristics [18]. Thus, as it is more complex [22], it needs greater flexibility in its waveform standardization.

This chapter briefly describes the fundamentals required to achieve a valid signal transmission for some of the proposed next generation waveform candidates.

## 3.1 Orthogonal Frequency Division Multiplexing - OFDM

The *Orthogonal Frequency Division Multiplexing* (OFDM) has been used as the default interface for the fourth cellular generation and the current terrestrial broadcasting standard [12]. However, its use hinders dynamic access to the spectrum due to its highly spurious emission outside the range of interest, which requires the use of filters, and pre-correction techniques to meet the standards imposed by regulatory agencies [12]. Therefore, for a feasible fragment use of the spectrum, the transmitting radio must reduce the out-of-range emissions to minimize the interference on adjacent channels.

## 3.2 Generalized Frequency Division Multiplexing - GFDM

The GFDM waveform [10] can be described by its flexibility in frequency and time. It is organized into $K$ sub-carriers in frequency and $M$ sub-symbols in time. Thus, it results in $N = KM$ different versions of a prototype pulse $g[n]$, where each one is circularly shifted both time and frequency domains, and modulated by the corresponding data symbol [10, 11] given by:

$$x[n] = \sum_{k=0}^{K-1} \sum_{m=0}^{M-1} d_{k,m} g\left[\langle n - mK \rangle_N\right] e^{j2\pi \frac{k}{K} n}, \tag{3.1}$$

where $d_{k,m}$ is the data symbol carried by the $k$-sub-carrier in the $m$ sub-symbol, $g[n]$ is the prototype pulse, $(< \cdot >_N)$ is the modulo $N$ operator of $n = 0, 1, \ldots, N - 1$.

Figure 3 illustrates the diagram of a GFDM block example, with valid data, sub carriers and sub symbols representation. The reference transmitter diagram block is given by Figure 4.

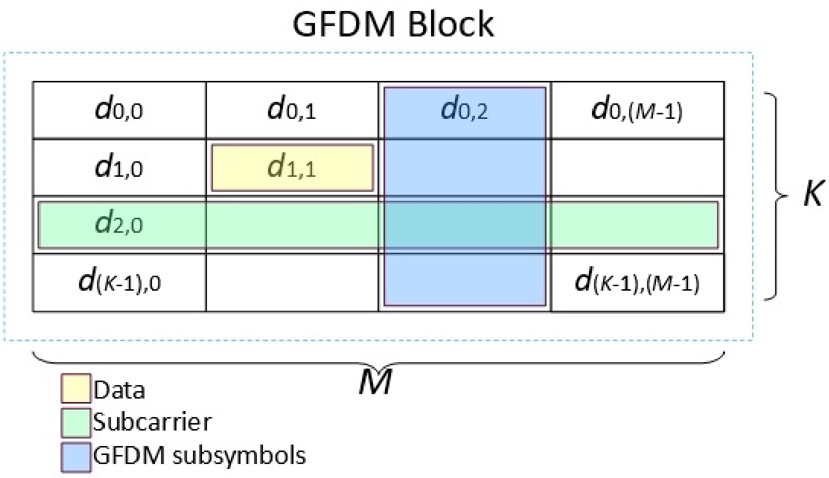



Figure 3 – GFDM symbol block.

In the receiver, assuming perfect synchronization, and considering the *Cyclic Prefix* (CP) is removed, the signal will be equalized in the frequency domain, and then can be demodulated as

$$\hat{d} = \mathbf{B}_{\mathrm{ZF}}\mathbf{y}_{\mathrm{eq}} \tag{3.2}$$

where $\mathbf{y}_{\mathrm{eq}}$ is the received and equalized signal, and $\mathbf{B}_{\mathrm{ZF}}$ is the process of demodulation by the *Zero-Forcing* (ZF) technique.

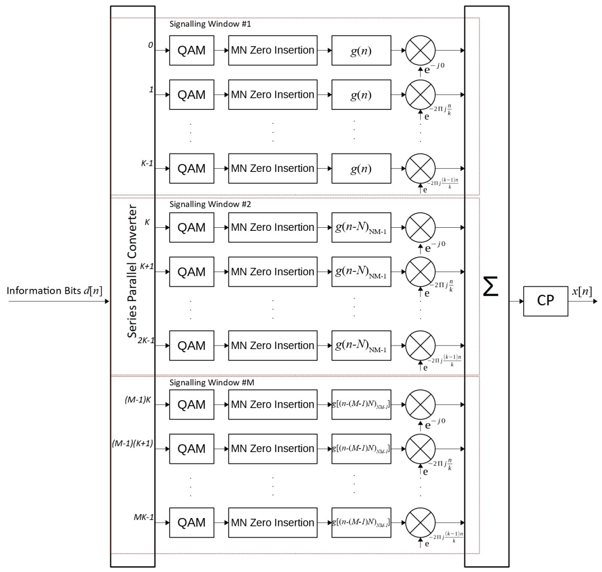



Figure 4 – GFDM Transmitter block diagram.

### 3.2.1 Windowed Generalized Frequency Division Multiplexing - W-GFDM

The *Windowed Generalized Frequency Division Multiplexing* (W-GFDM) is one variation of GFDM technique that applies a signal windowing GFDM in time domain to smooth the transitions between the signal blocks.

In this technique, the cyclic prefix, of length $NPC = NCH + NW$ (where $NCH$ is the number of samples of the channel response to the impulse and $NW$ is the size of the transition window), and the CS of $NCS = NW$, are used only once per block.

## 3.3 Filtered Orthogonal Frequency Division Multiplexing - FOFDM

The *Filtered Orthogonal Frequency Division Multiplexing* (FOFDM) technique has been developed as a promise of being a simple solution to the out of band emission problem [13]. In this approach, data destined for each user are treated independently, corresponding to the signal that will be transmitted in each of the L sub bands. For the signal of each sub band, the bits are mapped to data symbols and grouped into $K_l$ symbols, where $K$ is the number of sub-carriers on the $lth$ sub band, in which, each of the $L$ *Inverse Fast Fourier Transformation* (IFFT) will be computed. It is then added a CP of size $N_{\mathrm{PC}_l}$ and the resulting signal is filtered, by sub band, by a $g_l[n]$ filter. The theoretical transmitter block diagram is presented by Figure 5.

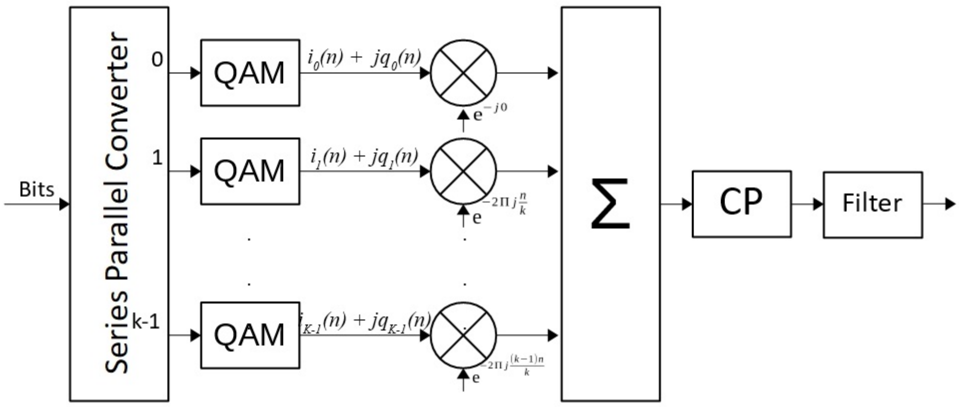



Figure 5 – F-OFDM transmitter block diagram [23].

In [13] an FOFDM system is proposed wherein the transmitter generates its OFDM signal by employing a group of $K_l$ consecutive sub-carriers over $M$ consecutive OFDM symbols. The signal transmitted by each mobile terminal is given by

$$x_{\mathrm{f}}[n] = \sum_{m=0}^{M-1} x_m(n - m(K_l + N_{\mathrm{PC}_l})) \tag{3.3}$$

where,

$$x_m[n] = \sum_{k=k'}^{k'+K_l-1} d_{m,k} \exp\left(j2\pi \frac{k}{K_l} n\right) \quad \text{para} \quad -N_{\mathrm{PC}_l} \le n \le N. \tag{3.4}$$

The FOFDM signal is then obtained by filtering the signal $x_f[n]$ through the appropriate prototype filter $g_l[n]$, which can be described by the convolution process as,

$$\bar{x}_{\mathrm{f}}[n] = x_{\mathrm{f}}[n] * g_l[n] \tag{3.5}$$

where $\bar{x}_{\mathrm{f}}[n]$ is the *lh* sub band signal.

The prototype filter must be properly designed to mitigate out-of-range emissions. At the receiver input, at the base station, the signal received from the *uth* - users is given by [13],

$$y[n] = \sum_{u=0}^{U} \bar{x}_{\mathrm{u}}[n] * h_u[n] + w[n] \tag{3.6}$$

where $U$ is the number of mobile terminals, $\bar{x}_{\mathrm{u}}[n]$ is the signal of the *uth* user, $h_u[n]$ is the impulsive response of the *uth* channel and $w[n]$ is *Additive White Gaussian Noise* (AWGN). After reception, the signal is first passed through a matched filter $g_l[n]$, where the cyclic prefix is removed, and then transformed from time to frequency domain. Equalization is performed and finally the signal is demodulated.

## 3.4 Summary

This chapter presented the equations for enabling the development of the waveform generator system. These signals will operate as a secondary user, and thus the receivers will not be implemented for the purpose of this study. The next chapter describes the process of setting up the environment for the coexistence test procedure.

# 4 System Setup and Waveform Generator

To perform the experiments (described in Chapter 5), a waveform generator system was developed using the National Instruments software defined radio [24]. This chapter describes the process of setting up the environment required to measure the coexistence scenario between the technologies. The arranged setup is described in the block diagram presented in Figure 6.

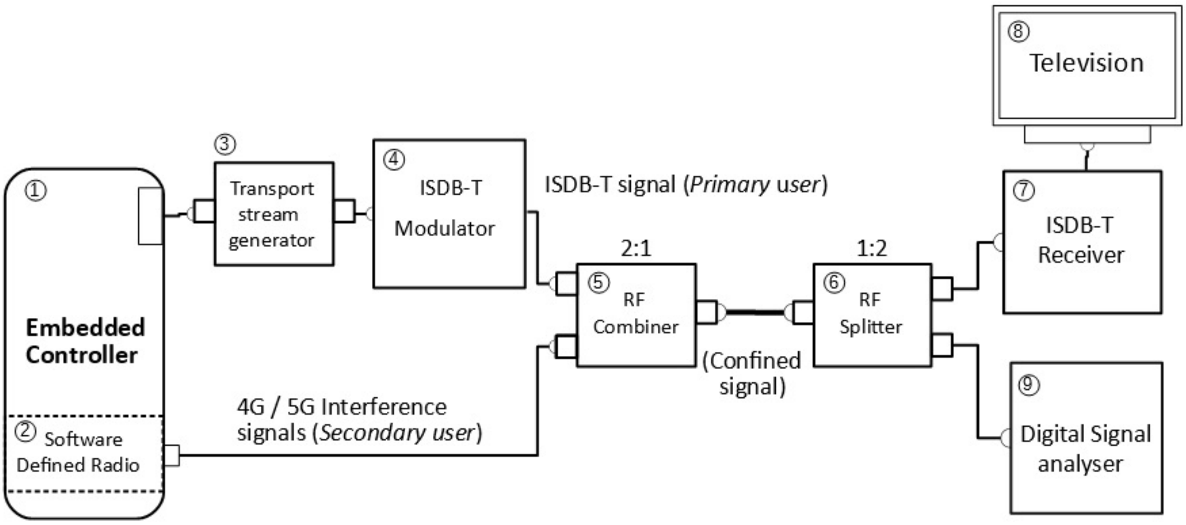



Figure 6 – Proposed measurement setup for coexistence evaluation.

## 4.1 Measurement Setup

The system is operated by a modular embedded controller, responsible for running and managing the application. An *Universal Serial Bus* (USB) *Asynchronous Serial Interface adapter* (ASI) is used to generate the *Transport Stream* (TS) [25]. Its output bit stream is connected to an *Integrated Services Digital Broadcasting Terrestrial* (ISDB-T) standard *Digital Television Receiver* (DTR) encoder [26]. An OFDM modulated DTR radio frequency signal, tuned to the desired TV channel is then generated. The output power levels are controlled on the main panel, so it is possible to configure the desired reference signal.

The reference OFDM and 5G signals are transmitted by a FLEX-Rio *Software Defined Radio* (SDR). Interfering and interfered signals are grouped in a confined medium using a *Radio Frequency* (RF) combiner. Finally, the set is connected to a domestic DTR receiver. Video images are observed on a standard home television set. The same reference video stream is looped thought the entire process, to ensure a proper evaluation [27, 28].

Observation of the electromagnetic spectrum and the measurements of channel power are performed with digital signal analyzers.

Figure 7 shows the laboratory setup and the list of used equipments and RF devices are presented in Table 1.


Figure 7 – Laboratory setup environment.

## 4.2 User Application Development

The application uses Labview Communications Suite platform. The developed system consists of one host session, used for high level user interface and another low level application for hardware interface, as it can be seen in Figure 8.

The host software consists of a user panel where the operator configures the parameters of the interfering signals. The code is implemented in graphical language (called "G" language) [24], and the generated diagram is compiled into a machine bit-file code. This way, its performance can be comparable to that displayed by the high-level programming languages [24].

Table 1 – Devices for setting up the test environment.

| Device | Manufacturer | Model |
|---|---|---|
| PXI express with 4 slots - 3 GB/s | National Instruments | NI PXIe-1071 |
| PXI express controller | National Instruments | NI PXIe-8880 |
| Flex RIO FPGA board for PXI Express | National Instruments | PXIe-7976R |
| Flex RIO RF adapter | National Instruments | NI-5791 |
| ISDB-T digital modulator | Hitachi | XYZ |
| ASI/SD-SDI USB 2.0 Adapter | DekTec | DTU-245 |
| RF combiner | Hewlett Packard | 11667A |
| RF attenuator (20dB) | JBM | J2001-20-AB |
| RF attenuator (30dB) | JBM | J2001-30-AB |
| Impedance matching circuit 50-75R | JBM | J2042-BI |
| Digital signal analyser | Keysight | DSAZ632A |
| Mixed digital signal analyser | Agilent/Keysight | N9020A |

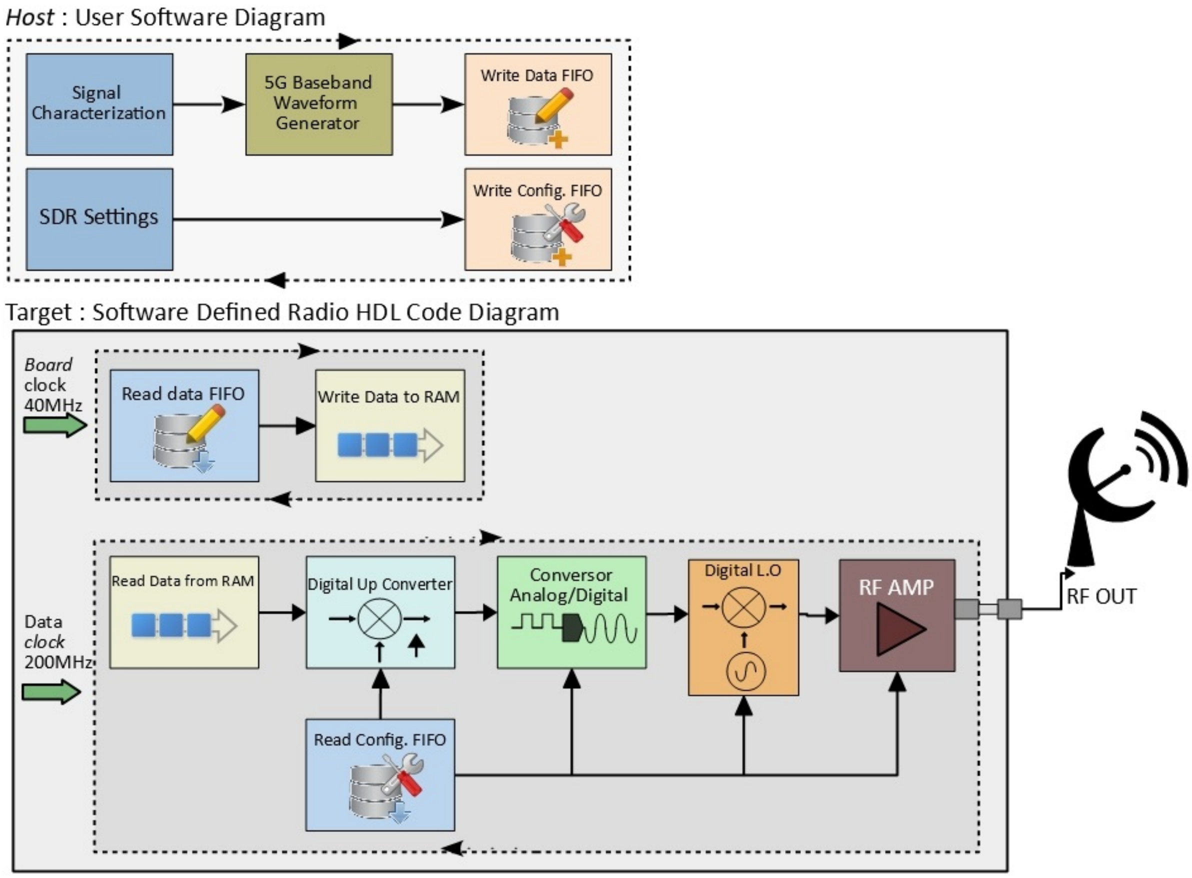



Figure 8 – 5G Waveform generator system block diagram.

### 4.2.1 Generation of baseband vectors

The interfering signals were initially generated through *scripts* coded by the Matlab®. These codes made use of the libraries developed by the *Centro de Referência de Radiocomunicações* (CRR) team and the University of Dresden, in Germany. These functions were adapted to be compatible with the Labview Communications compiler. A sample vector of 5G waveforms symbols is generated in baseband based on the input parameters. The samples are then transferred to the SDR *Field Programmable Gate Array* (FPGA) via a *First In, First Out* (FIFO) memory.

The system generates the vector of baseband samples, according to the user selection. This input is modulated in one of the selected 5G waveforms. User defined parameters, used for setting up the measurements, are shown in Table 2. Once the configuration is done, the samples are then transferred to the software defined radio embedded system.

Table 2 – User input configuration parameters for baseband signals.

| **Parameters** | **Function** |
|---|---|
| Modulation Selector | Selects modulation type |
| #Symbols | Number of generated baseband symbols |
| $M$ | Number of sub symbols (for OFDM, M=1) |
| $K$ | Total number of carriers |
| $K$offs | Number of side carriers switched off |
| $K$offc | Number of center carriers switched off |
| $nCp$ | Number of cyclic prefix samples |
| $nCs$ | Number of cyclic suffix samples |
| $nW$ | Signal window samples |

### 4.2.2 Software Defined Radio programming

During system initialization on the host, the generated bit-file is loaded into the Flex-Rio FPGA. The system starts operating only when the user generates a signal arrangement through the main panel. The process starts with the target reading a FIFO containing the binary vector. This data corresponds to the secondary user signal generated on the host application. These are then written into a *Random Access Memory* (RAM).

Once the RAM has data recorded, the stream is delivered to the digital up-converter block. According to the configuration parameters, as previously shown in Table 2, the generated symbols are converted to an *Intermediate Frequency* (IF). In the next step, the *Intermediate Frequency* (IF) signal is delivered to an analog-to-digital converter. Finally, it is converted to the user-adjusted frequency in the local oscillator block, and the RF transmission is performed. The generated symbols are repeated until the user provides a new valid input vector of samples. During the measurement procedures, some parameters must be adjusted to meet the desired targets. The parameters are described in Table 3.

The developed platform is a modular test system designed to allow the update of other 5G waveforms candidates and to allow coexistence the test with other legacy technologies.

Table 3 – Software defined radio main configuration parameters.

| **Parameters** | **Description** |
|---|---|
| Sample Rate | Specifies the rate of user generated signal vectors. In this project, this parameter is used to determine the signal bandwidth, and it is adjusted according to ISDB-T standard [27, 29]. |
| Power | Adjust the output power, expressed in dBm on Flex-RIO RF port. |
| Local Oscillator Frequency | Tunes the oscillator to desired frequency |
| Frequency Shift | Digitally applies on I/Q vectors, a frequency shifts around the center values, tuned by the local oscillator |

## 4.3 Summary

This chapter described the fundamentals for enabling the software defined radio vector waveform generator. This setup is designed to evaluate coexistence scenario of next generation technologies and the standard Brazilian broadcast system. The proposed test procedures will be shown in the next chapter.

# 5 Test procedures and signal characterization

This chapter presents the proposal for two experiment procedures for the identification, measurement and initial setup of interferences between systems based on FOFDM, GFDM and W-GFDM physical layer modulation techniques, operating in 700 MHz frequency range of the standard ISDB-T. The term interference should be interpreted as harmful, that is, one that degrades, obstructs or interrupts a radio communication service [27].

## 5.1 Scenario

The following experiments simulates a hypothetical WRAN scenario, where the primary system operates on standard DTR channels, and the secondary system on idle adjacent channels. The main objective is to demonstrate the advantages of the new generation of waveforms to coexist with primary services without causing any harmful interferences.

Even though the IEEE 802.22 standard have defined the use of OFDM as the physical layer modulation, the procedures demonstrate the advantages of using the 5G transmission techniques. The signals, interfered and interfering, simulate static conditions in a controlled environment. The multi-path fading is disregarded in this analysis.

## 5.2 Point of Failure

In domestic ISDB-T receivers, it is usually not possible to perform BER measurements, thus new methods have been proposed by the ITU to establish the protection relationship and guarantee the quality of service. The criterion chosen in this study to determine the point of failure was based on the recommendation ITU-R BT.1368-12 [30], where the protection ratio is subjectively determined through the image quality assessment, based on the user experience [28, 31].

The evaluation method was performed by varying the level of the interfering signal, while observing the received image. The primary service level is kept constant at a predetermined value while the interfering signal level is increased until constant errors or image freezing became noticeable, regardless of the observer's visual acuity. As recommended, the limits corresponds to the condition of no image errors during the first 20 seconds of observation [30].

The conducted tests consider that the channels are spaced by 428.571 KHz, as shown in Figure 9 [27, 29]. In order to measure the channel power, it was adopted 6 MHz and 18 MHz integration bandwidth, with a 100 KHz resolution and average signal sampling of 10 .

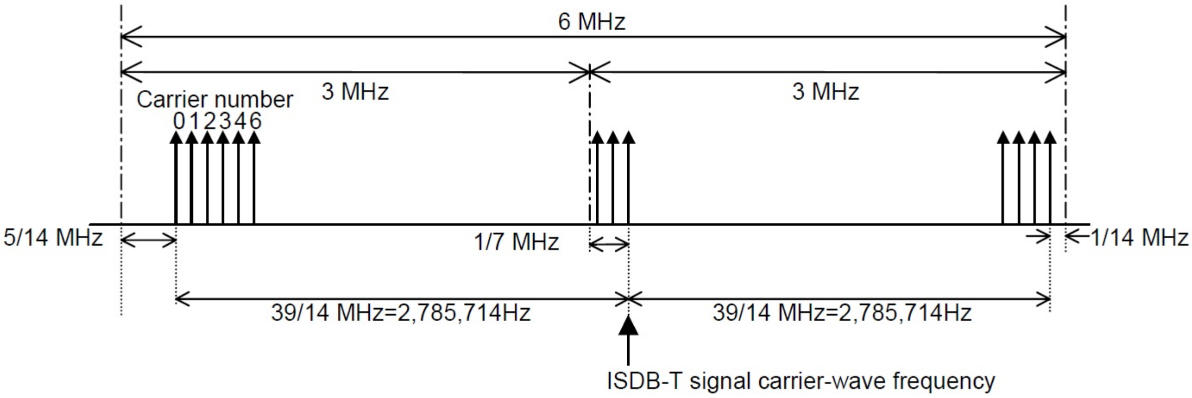



Figure 9 – ISDB-T channel spacing [27].

## 5.3 ISDB-T Signal Characterization

The characterization of the digital TV signal show in Figure 10 was performed according to the parameters presented in Table 4 [27, 29].

Table 4 – Characterization of ISDB-T Signal.

| **Layer** | **A** | **B** | **C** |
|---|---|---|---|
| Number of segments | 13 | - | - |
| Modulation | 64-QAM | - | - |
| FEC | 3/4 | - | - |
| Time Interleave | 2 | - | - |
| Bandwidth | 5.572421MHz | | |
| Partial Reception | No | | |
| Mode | *Mode* 3 | | |
| Guard Interval | 1/8 | | |

### 5.3.1 Operational Frequencies

In Brazil, the television broadcast frequency range consists of 6MHz channels designated from 2 to 51. This set of channels is separated into four bands in the VHF and UHF bands of the electromagnetic spectrum; 54-72MHz, 76-88 MHz, 174-216 MHz and 470-698 MHz. Annex **??** and C show the channeling ranges.

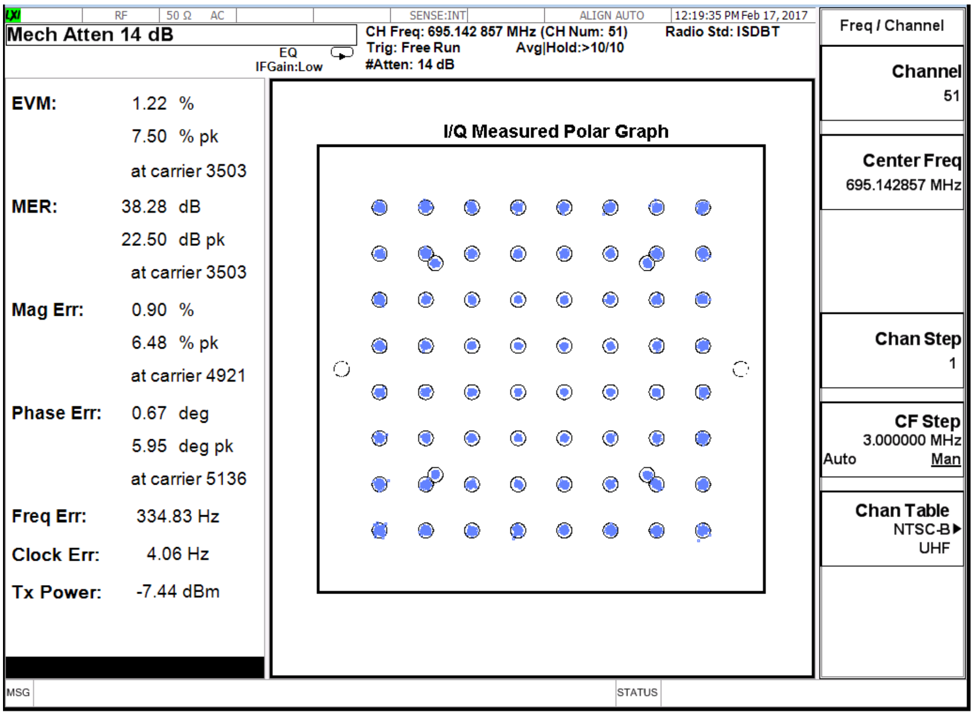



Figure 10 – 64-QAM ISDB-T reference signal setup.

## 5.4 ISDB-T Receiver Receiving Threshold Adjustment

The reception threshold level is the operational level of the receiver expressed in dBm. The following procedures were adopted to determine the reception threshold [28, 30]:

(a) A reference transport stream video was applied to the digital modulator input. The same reference video, played in a loop, was used for the entire test.

(b) The digital television signal was tuned to channel 32 on UHF band, initially at -70dBm level and 64-QAM modulation, as described in Table 4. It was checked whether the video was being displayed flawlessly by the receiver under test.

(c) The reference DTV signal level was reduced until there was visible and constant image failures, regardless of the observer's visual acuity. It was observed image quality stabilization for at least 20s [28, 30].

(d) The signal level was verified using digital signal analyzer in the channel power measurement mode. Starting from the visible threshold, the signal level was increased by 3 dB.

(e) Steps (a) thought (d) were then repeated for all receivers used in the following experiments.

## 5.5 Adjacent Channel Interference

The objective of this experiment is to establish the harmful interference point for operation on adjacent channels by determining the saturation threshold ($O_{th}$). This parameter expresses the power in dBm, when the DTR receiver loses its ability to discriminate the interfering signal from the desired one.

The following steps were conducted to perform the test:

(a) The previously characterized ISDB-T signal was connected to the measurement setup.

(b) It was initially applied an interfering OFDM modulated signal, operating on the lower adjacent channel ($N$-1).

(c) The power of the interfering signal was increased in 0.5 dB steps until the image showed visible and constant image errors.

(d) Upon reaching the limit condition, the adjacent channel power was measured, using the digital signal analyser.

(e) Steps (a) through (d) were repeated varying for GFDM, W-GFDM and FOFDM technologies.

(f) Finally, steps (a) to (e) were repeated for the upper adjacent channel ($N$+1).

The signals characterization are listed in Table 5. Proper channel spacing is considered according to [27].

Table 5 – Signals settings for adjacent channel interference test.

| | **OFDM** | **GFDM** | **W-GFDM** | **F-OFDM** |
|---|---|---|---|---|
| $M$ | 1 | 3 | 3 | 1 |
| $K$ | 512 | | | |
| $KoffS$ | 128 | | | |
| $KoffC$ | 0 | | | |
| $nCP$ | 64 | | | |
| $nCS$ | 0 | 0 | 50 | 0 |
| $nW$ | 0 | 0 | 50 | 0 |

The reference ISDB-T signal is displayed on the center bin, while the interference signal is shown on the side channel as shown in Figure 11.

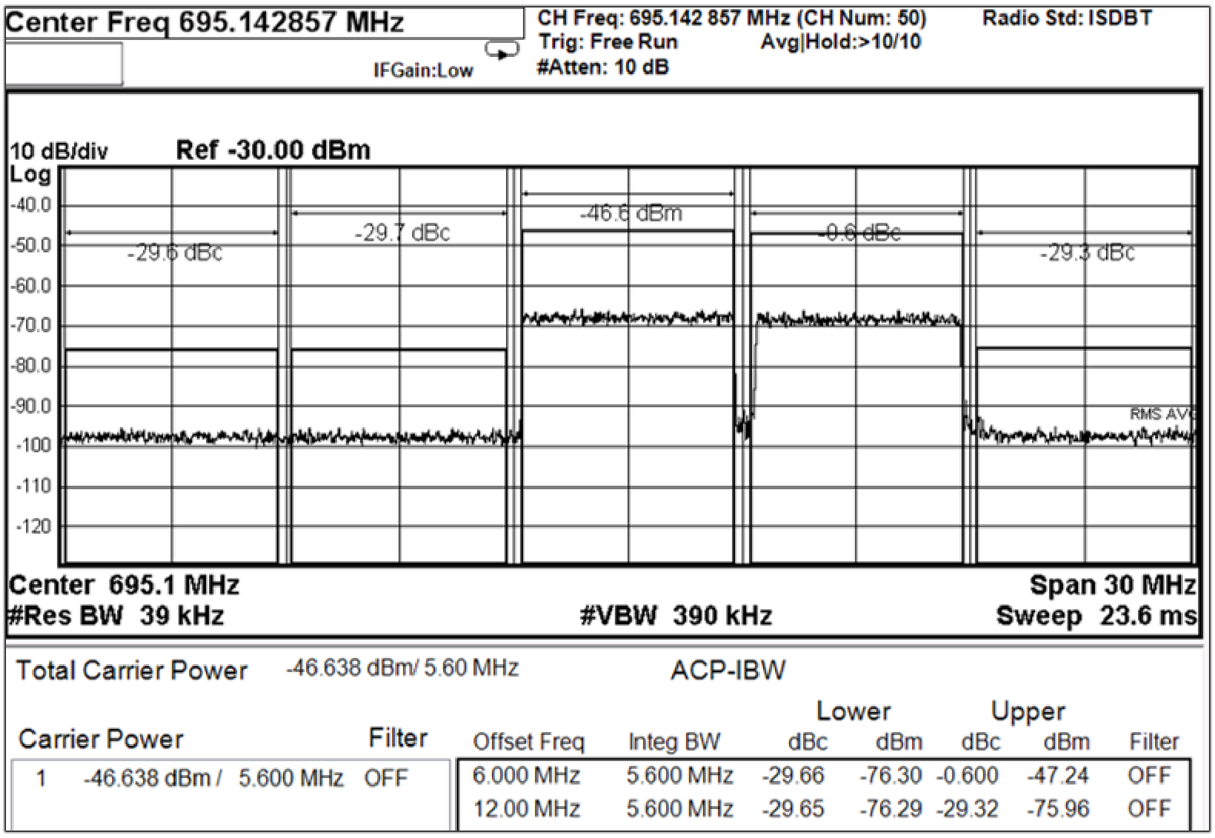



Figure 11 – Adjacent test method channel spacing signal verification.

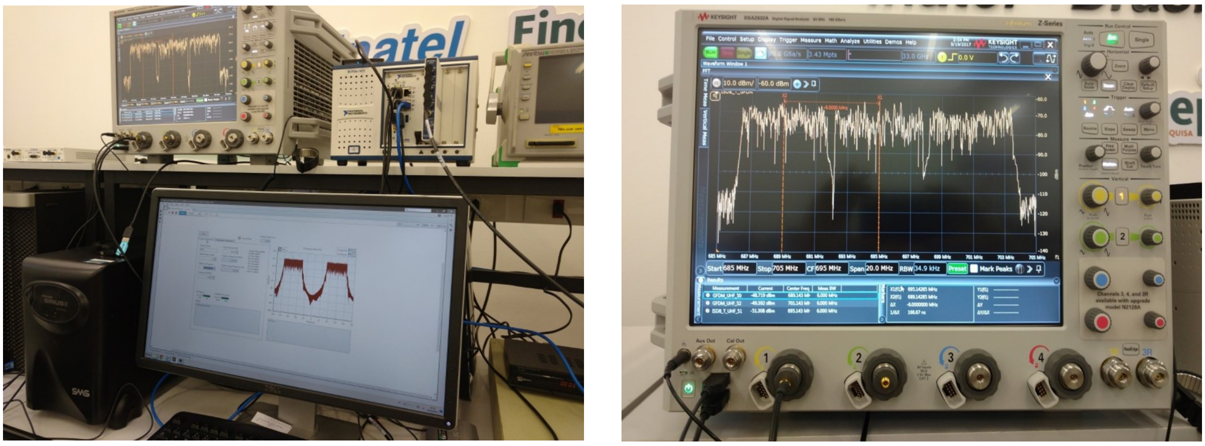
## 5.6 Interference from multiple associated channels

One of the characteristics of 5G waveforms designed for this test is the ability to shut down the center carriers, thus allowing the association of multiple idle channels. The proposed experiment aims to evaluate the ability of 5G waveforms to occupy multiple channels without interfering into the existing primary services. An example of this scenario is shown in Figure 12.

The same procedures of the previous experiment were adopted, but in order to perform the power measurements, the ISDB-T signal was initially turned off. The characterization of this procedure is presented in Table 6.

Table 6 – Signals settings for multiple adjacent channel test.

| | **OFDM** | **GFDM** | **W-GFDM** | **F-OFDM** |
|---|---|---|---|---|
| $M$ | 1 | 3 | 3 | 1 |
| $K$ | 512 | | | |
| $KoffS$ | 104 | | | |
| $KoffC$ | 152 | | | |
| $nCP$ | 64 | 50 | 50 | 64 |
| $nCS$ | 0 | 0 | 50 | 0 |
| $nW$ | 0 | 0 | 50 | 0 |



(a) Signal being generated on host software with parameters presented on Table 6.

(b) Multiple channel interference displayed on mixed signal analyser.

Figure 12 – Interference from associated channels and carriers switched off.

## 5.7 Summary

Since the measurement of BER is not a common option in domestic DTR reception devices, this chapter presented two test procedures based on user experience [27]. The experiment is based on quality of image, regarding the observer visual ability, in order to assure the primary systems do not suffer harmful interference by the secondary system. In the next chapter the obtained results are shown and evaluated.

# 6 Measurement Results

This chapters describes the results obtained by the realization of the two proposed tests described in Chapter 5.

## 6.1 Receivers Operational Level

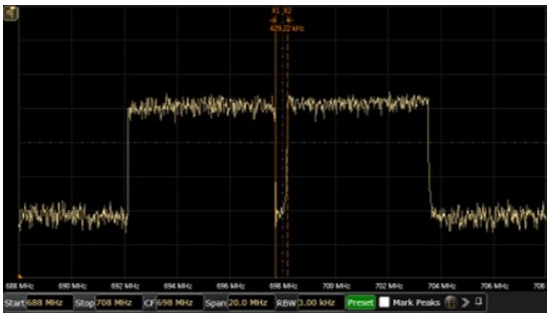
Initially, the operational levels of each evaluated DTR receiver were obtained, according to the procedure described in Section 5.2. Four different tuner ISDB-T receivers were used. By comparing the obtained results, which are shown in Table 7, is it first possible to realize that there is a significant difference in reference levels between each of the used receivers.

Table 7 – ISDB-T Receivers Operational Level.

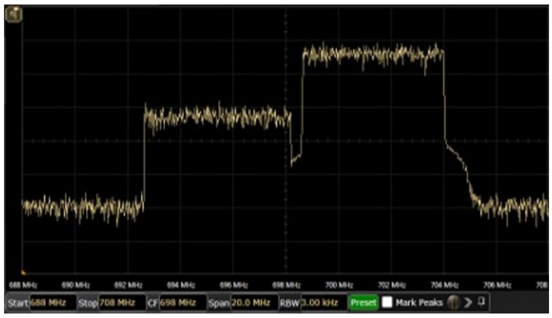
| **Receiver** | **RX1** | **RX2** | **RX3** | **RX4** |
|---|---|---|---|---|
| Power Level (dBm/6MHz) | -75.7 | -75.2 | -79.7 | -75.1 |
| Power Level (dBm/18MHz) | -75.2 | -73.7 | -77.9 | -73.8 |

## 6.2 Interference Evaluation

The saturation threshold ($O_{th}$) expresses the value in which the receiver loses its ability to discriminate the interfering signal from original source. By increasing the secondary service reference power, and maintaining the primary service with the reference level, the point of failure is used to determine the safe operational level, which could be used as an reference for a regulatory agency when determining the out-of-band emissions mask. An example of point of failure event is shown in Figure 13. The effects of the out of band emissions are displayed by the digital signal analyzer.



(a) Secondary signal with [27] signal channel spacing.



(b) Secondary signal causing a harmful interference on primary DTV service.

Figure 13 – GFDM signal, operating on N+1 adjacent channel.

## 6.3 Adjacent Channel Interference Test Results

This sections presents for the proposed experiments as shown in section 5.5. By comparing the $O_{th}$ measurements of the interference test on adjacent channels, as presented in Table 8, it can be seen that both the FOFDM and W-GFDM transmission techniques caused harmful interference in all tested equipments when operating at higher power levels. It indicates that the two techniques would have less out of band spurious emission on adjacent channels, when operating as secondary services. It is observed that the variation between these two techniques is in the range of 1dB. Therefore these two technologies would be a more suitable solution as a modulation technique.

Table 8 – Measured $O_{th}$ level for adjacent channel interference test.

| **Receivers** | **RX1** | | **RX2** | | **RX3** | | **RX4** | |
|---|---|---|---|---|---|---|---|---|
| **UHF Channel** | **31** | **33** | **31** | **33** | **31** | **33** | **31** | **33** |
| **OFDM (dBm/6MHz)** | -53.4 | -53.1 | -54.4 | -53.6 | -53.2 | -53.6 | -53.6 | -53.4 |
| **GFDM (dBm/6MHz)** | -47.3 | -47.4 | -50.1 | -50.2 | -49.3 | -49.2 | -49.2 | -49.3 |
| **W-GFDM (dBm/6MHz)** | -38.0 | -39.8 | -41.2 | -41.2 | -42.8 | -39.7 | -41.2 | -41.1 |
| **F-OFDM (dBm/6MHz)** | -38.5 | -38.6 | -41.7 | -40.3 | -43.5 | -39.7 | -41.2 | -40.2 |

The Interference to signal ratio of the measured $O_{th}$ interference levels with the DTR operational levels is given by:

$$O_{th}(dBm) - DTRLevel(dBm) = InterferencetoSignalRatio(dBc) \tag{6.1}$$

These results are presented by Figure 14, where 31, is the N-1 adjacent channel, 33 is the N+1 channel. This values indicates the difference from the interference levels from the reference from the reference digital receiver. The reference ISDB-T signal was on channel 32, operating with the reference level measured at 6 MHz resolution bandwidth, as displayed on the first row of Table 7.

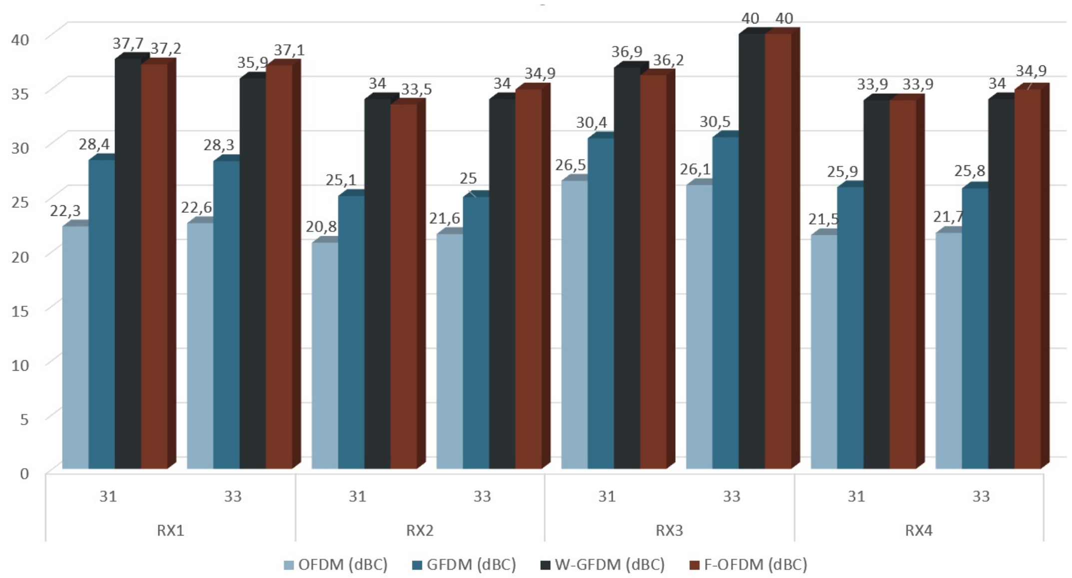



Figure 14 – Comparison with ISDB-T operational level for adjacent channel test (dBc).

## 6.4 Results for Adjacent Channel Interference Test on Multiple Channels

In the experiment of signals operating on multiple channels, and carriers switched off, the secondary signals occupies both the N+1 (31) and N-1 (33) channels, forming a 18 MHz bandwidth signal, with 12 MHz of useful band. The center carries is turned off so the ISDB-T signal operates on the center channel (32). Proper channel spacing is assured according to [27]. These design is intended to increase the signal bandwidth, thus resulting in higher transmission rates.

The $O_{th}$ measurements is shown in Table 9. It can be observed that the W-GFDM transmission technique interfered on the primary service, at the highest level. In this experiment, the FOFDM technique offered no noticeable advantage over the OFDM. The equation 6.1 was applied to this scenario and can be seen in Figure 15. Maybe that this problem is due to the implementation of the prototype filter used in generation of the baseband signal, and further studies should be conducted to evaluate this result.

The relation of used receivers thresholds is now compared with the 18MHz reference, as shown in the second row of Table 7. $O_{th}$ interference levels is illustrated by Figure

Table 9 – Measured $O_{th}$ for interference signals occupying multiple channels test.

| | **RX1** | **RX2** | **RX3** | **RX4** |
|---|---|---|---|---|
| OFDM (dBm/18MHz) | -65.25 | -65.2 | -68.2 | -66.8 |
| GFDM (dBm/18MHz) | -59.2 | -60.7 | -63.7 | -63.0 |
| W-GFDM (dBm/18MHz) | -42.2 | -41.9 | -43.9 | -43.2 |
| F-OFDM (dBm/18MHz) | -65.3 | -65.2 | -68.3 | -66.9 |

15. In this figure the operational level of primary service to interference ratio of secondary services in W-GFDM can be seen.

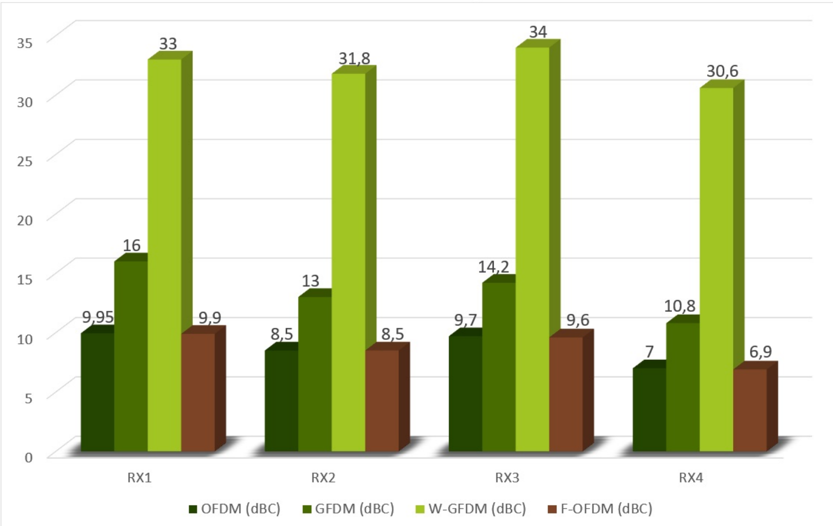



Figure 15 – $O_{th}$ Comparison with ISDB-T Operational Level for multiple channel test (dBc)

## 6.5 Technologies Comparison

Initially, it is noticed that there is great variation between the operational level of the receivers. It is important to point out that a more detailed quality assessment in the receptors tends to reduce these differences and enable the use of the frequency spectrum in this application. For both tests, the results indicate that out of range emissions for the proposed 5G modulations are lower when compared to the traditional OFDM technology. Figure 16 illustrates this situation, where it is possible to see the difference between technologies through measurements of power spectral densities.

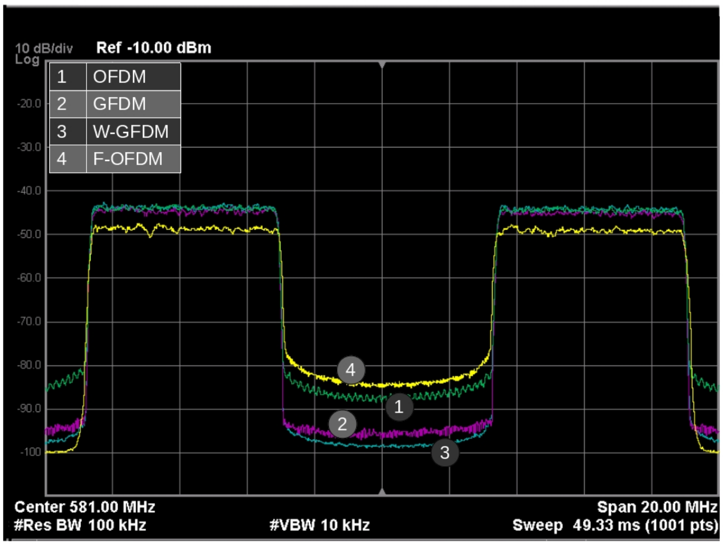



Figure 16 – Out of band emission waveform Comparison.

Figure 17 offers a better comparison between OFDM and W-GFDM (best scenario) where the the visualisation of the out-of-band emission becomes more evident.

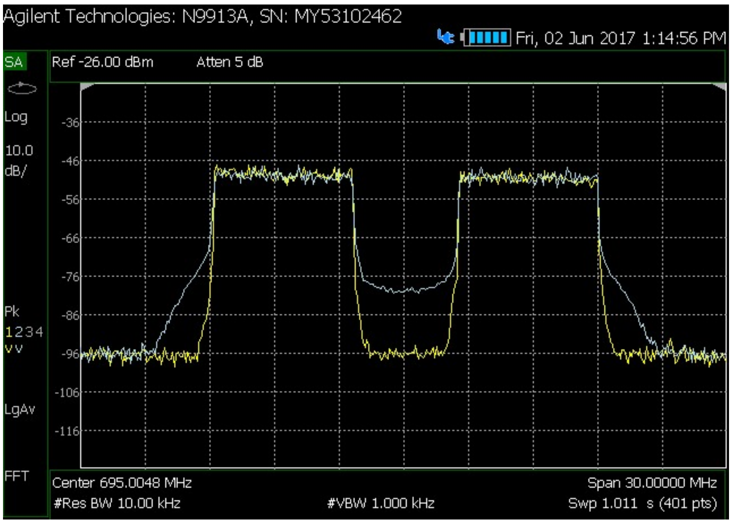



Figure 17 – OFDM vs W-GFDM mask emission comparison.

## 6.6 Summary

The more efficient use of the CP used by the W-GFDM technique enables greater spectral efficiency and energy savings is achieved when compared to the other modulations [32]. This feature is important in the WRAN scenario, where long channel path delays require long cyclic prefixes [5]. Therefore, it is a very promising solution for white space communications.

# 7 Conclusions

TVWS are unoccupied channels at any given time or location in the VHF and UHF bands that became available due to shutdown of analog terrestrial TV transmitters. The use of TVWS is a possible solution to achieve digital inclusion in Brazil since it allows to optimize the resources of the electromagnetic spectrum. Characteristics such as cells with radius of up to 30 km and opportunistic use of idle channels, among others, endorse the use of White Spaces in rural areas, peripheries of large cities, isolated or difficult to access and low population density areas, since the Internet service otherwise would not exist or the service is of poor quality.

Allowing secondary users to use available media "unlocks" the existing traditional frequency allocation and maximizes its use. At the same time, estimations based on white spaces spectrum databases indicate that the availability of TVWS is often very limited in dense urban areas where spectrum resources are more needed [7]. Therefore, the benefits provided by the utilization of TVWS have yet to be fully assessed.

Although TVWS bands offer additional frequency bands for different applications, a lot of coordination efforts are required in order to achieve efficient usage of the frequency bands to avoid interference. Since each service operator uses their own security systems and firewalls, there will be many coordination systems between the approved databases and the individual commercial base stations.

Scenarios that must be met by 5G networks in Brazil were presented and it is possible to realize that they have conflicting requirements [18]. Therefore the 5G standards must be flexible enough to meet these different conditions. Thus, the transmission techniques used must enable the reconfiguration of their parameters so that they are able to meet these different requirements. Without the necessary flexibility to meet future applications, business models can be rendered unfeasible, reducing the social and economic impact of future networks. Thus, the design of a flexible physical layer, which adapts to the different demands of the applications is essential for the establishment of a new mobile communication network.

This thesis evaluated the coexistence of three technologies proposed for the next generation of mobile communications, and the Brazilian ISDB-T digital TV standard. A waveform generator system was developed in Labview Communications, in order to evaluate the coexistence between primary and interfering signals. It was also demonstrated a feature of one of the 5G wave-forms to associate multiple channels for increased bandwidth, and the ability to turn on or off the central carriers, thus enabling the secondary operation.

IEEE 802.22 determines the use of OFDM transmission technique as physical layer modulation for the WRAN scenario. Although a small sample of receptors was used, it can be observed considerable variations of reception thresholds. However, the tests presented in this report show that GFDM as a transmission technique has advantages when considering out-of-band emission and fragmented use of the spectrum.

The tests results show that the transmission techniques proposed for 5G such as windowed-GFDM and FOFDM have advantages when considering the out-of-band emission and fragmented use of the spectrum. By operating in multiple channels, new possibilities for increasing the spectral efficiency are enabled. Based on those values, it may be possible to estimate the limitations on the characteristics of operation or installation of systems transmitting as a secondary service.

This work intends to assist in the survey of protective relationships, to help determine the emission masks that allow 5G systems to coexist with primary systems.

# Appendix

# Annex

# ANNEX A – Publications

- S. S. L. Moreira, T. C. Pimenta, F. M. Portelinha and R. M. Volpato, "Coexisting Analysis of 5G Networks with ISDB-T System in TV White Spaces", 2020 IEEE 11th Latin American Symposium on Circuits and Systems (LASCAS), San Jose, Costa Rica, 2020, pp. 1-4, doi: 10.1109/LASCAS45839.2020.9068960.
- S. S. L. Moreira, T. C. Pimenta, F. M. Portelinha and R. M. Volpato, (2018). "Análise do Acesso Oportunista ao Espectro nas Faixas de UHF para Futuras Redes de Comunicações Móveis - 5G.", Conference: MOMAG 2018, At Santa Rita do Sapucaí – MG

# ANNEX B – Frequency of TV channels in VHF Range

Table 10 – VHF channels in Brazil [3].

| VHF Channel | Range (MHz) | Center (MHz) |
|---|---|---|
| 2 | 54 - 60 | 57 |
| 3 | 60 - 66 | 63 |
| 4 | 66 - 72 | 69 |
| 5 | 76 - 82 | 79 |
| 6 | 82 - 88 | 85 |
| 7 | 174 - 180 | 177 |
| 8 | 180 - 186 | 183 |
| 9 | 186 - 192 | 189 |
| 10 | 192 - 198 | 195 |
| 11 | 198 - 204 | 201 |
| 12 | 204 - 210 | 207 |
| 13 | 210 - 216 | 213 |

# ANNEX C – Frequency of TV channels in UHF Range

Table 11 – UHF channels in Brazil [3].

| UHF Channel | Range (MHz) | Center (MHz) |
|---|---|---|
| 14 | 470 - 476 | 473 |
| 15 | 476 - 482 | 479 |
| 16 | 482 - 488 | 485 |
| 17 | 488 - 494 | 491 |
| 18 | 494 - 500 | 497 |
| 19 | 500 - 506 | 503 |
| 20 | 506 - 512 | 509 |
| 21 | 512 - 518 | 515 |
| 22 | 518 - 524 | 521 |
| 23 | 524 - 530 | 527 |
| 24 | 530 - 536 | 533 |
| 25 | 536 - 542 | 539 |
| 26 | 542 - 548 | 545 |
| 27 | 548 - 554 | 551 |
| 28 | 554 - 560 | 557 |
| 29 | 560 - 566 | 563 |
| 30 | 566 - 572 | 569 |
| 31 | 572 - 578 | 575 |
| 32 | 578 - 584 | 581 |
| 33 | 584 - 590 | 587 |
| 34 | 590 - 596 | 593 |
| 35 | 596 - 602 | 599 |
| 36 | 602 - 608 | 605 |
| 37 | 608 - 614 | 611 |
| 38 | 614 - 620 | 617 |
| 39 | 620 - 626 | 623 |
| 40 | 626 - 632 | 629 |
| 41 | 632 - 638 | 635 |
| 42 | 638 - 644 | 641 |
| 43 | 644 - 650 | 647 |
| 44 | 650 - 656 | 653 |
| 45 | 656 - 662 | 659 |
| 46 | 662 - 668 | 665 |
| 47 | 668 - 674 | 671 |
| 48 | 674 - 680 | 677 |
| 49 | 680 - 686 | 683 |
| 50 | 686 - 692 | 689 |
| 51 | 692 - 698 | 695 |

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