TV White Spaces for Digital Inclusion in Brazil

Matheus F. S. do Nascimento, Raphael B. Evangelista, Carlos F. M. e Silva, Francisco R. P. Cavalcanti,
André L. F. de Almeida and Yuri C. B. Silva.
Grupo de Pesquisa em Telecomunicações (GTEL)
Universidade Federal do Ceará (UFC), Fortaleza, Ceará, Brazil.
E-mails:{matheusfreire,raphael,cfms,rodrigo,andre,yuri}@gtel.ufc.br.

***Abstract*—This work presents a technological opportunity to improve the spectral efficiency 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 Spaces (TVWS) 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 TVWS as a way to soften part of the poor coverage services of 3G, 4G and provide Internet access around the rural regions in Ceará.**

***Index Terms*—TVWS, DSO, DTV, GLDB, WSD, SBTVD, NRA, Anatel, FCC, Ofcom.**

I. Introduction

"There is no more spectrum available", declared Herbert Hoover, the US Secretary of Commerce in 1925 [1]. 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 and more telecommunication services to be implemented.

The increasing demand for services such as mobile telephony does require changes in how the spectrum is managed, since 5G communication systems are foreseen to provide thousand to ten thousand times more capacity comparing to the legacy 4G ones [2]. 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, Global Positioning System (GPS), as well as for military and police communications.

Several measurements performed worldwide showed that spectrum occupancy rates range only from 5% to 15% [3]; this fact has been noticeably verified in the case of Television (TV) bands [4]. 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 Cognitive Radio (CR) has emerged [4], where the radio device is able to reuse underutilized spectrum chunks in a opportunistic manner.

With the appearance of TV White Spaces (TVWS), the CR may use this portion of TV bands that are unused by licensed services [5]. The white spaces has recently 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 Very High Frequency (VHF) and Ultra High Frequency (UHF) bands [6]. Nevertheless, this work focuses on the UHF band, since it is the only one used by the Brazilian Digital TV System [3].

At the same time, Internet access is 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].

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 rural area 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 countryside of this northeastern Brazilian state, which is quite common in such part of the country. Therefore, the case study of Ceará is representative of many others rural regions throughout Brazil.

The remainder of this work is organized as follows: The definition of TVWS and the opportunistic methods for its exploitation, as well as the main TVWS standards are described in Section II. Section III describes the current situation of TVWS in the world and presents the two main regulators' perspective. Section IV describes the SBTVD, the Brazilian Digital TV (DTV) System, the entities responsible for spectrum management and the situation of 450 MHz and 700 MHz bands. The case study of Ceará is presented in Section V, it shows a picture illustrating the coverage gain obtained by the use of TVWS in a specific city of the state, Jericoacoara. Finally, some concluding remarks are given in Section VI.

II. TV White Spaces and Digital Switchover

The Digital Switchover (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 is still in progress in some others. As an example, in Brazil, the Ministry of Communications established in 2014 a new DSO plan, starting in 2015 and gradually to be implemented until December 2018, instead of a "one shot" method, as planned before [8].

The advantage of DTV 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 International Telecommunication Union (ITU) calls "digital dividend" [3]; 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, Fig. 1 shows the regions using channel 21 in Europe [9], 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.

Fig. 1. Europe areas using DTV channel 21.

As such, TVWS are locally underutilized portions of the terrestrial TV bands and occurs as a by-product of the DSO. It is a spectrum in the range of VHF and UHF that is not in use at a particular time and location [10], and therefore, it represents a new opportunity for wireless networking in a frequency band that has good propagation characteristics.

TVWS can be used by an unlicensed White Space Device (WSD)[1],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 network implemented using white spaces was deployed in Wilmington, North Carolina, culminating in a regulatory process initiated by the Federal Communications Commission (FCC) in May, 2004.

A. 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 use, i.e., used by WSDs, are essential [9]. 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 Equivalent Isotropic Radiated Power (EIRP) 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 Geolocation Database (GLDB) [9].

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[2]. For the WSD to use a specific TV channel, this channel must be reported empty by the scanners [5]. Specific and sophisticated sensing algorithms 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 [9], 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.

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 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 [6]. 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 [6], the interference between WSDs depends on the architecture adopted, there are some mechanisms that allow WSDs to avoid such interference situations that are called

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

[2]Incumbent users are also known as the primary spectrum users, since they own the spectrum due to regulatory decisions. Secondary users are only able to use the spectrum when no primary users are using it, employing opportunistic methods [11].

"coexistence mechanisms" [4]. The GLDB takes inputs from the regulators and incumbents to form the basis of the channel occupancy map. Fig. 2 illustrates the GLDB approach.

Additionally, the work in [12] describes an experimental testbed that combines the Digital Video Broadcasting - Terrestrial (DVB-T) 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.

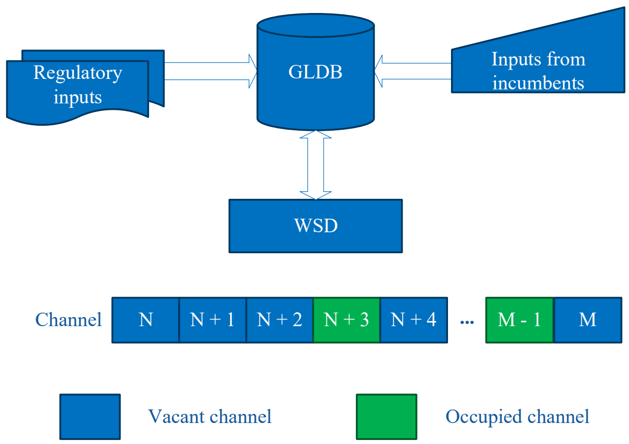

Fig. 2. GLDB schematic approach and vacant/occupied DTV channels. The regulatory and incumbents inputs specifies the channel and the maximum allowed EIRP that should be used to do not interfere with the primary users.

B. Main TVWS Standards

The following summarizes the main standards for TVWS [3], [13]:

- ECMA-392
  First TVWS standard published and mainly designed for communication between personal device. 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 wireless 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 Long Term Evolution (LTE), to a possible operation in white space bands.

III. 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 National Regulatory Authority (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, so there remains uncertainties about what sort of TVWS availability is realistic [14]. The amount of TVWS spectrum available can change significantly from one to another countries [3]. In this work we consider the specificities of the Brazilian regulatory scenario and how DSO will play out in Brazil.

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 [10]. 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.

A. 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 United States of America (USA) and the United Kingdom (UK).

The FCC is an independent regulatory agency of the United States of America, which is in charge with regulating interstate and international communications by radio, television, wire, satellite, and cable [15].

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 Notice of Inquiry (NOI) 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 Notice of Proposed Rulemaking (NPRM) 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 [5], allowing unlicensed secondary operations to develop new communication opportunities for broadband wireless users.

The Office of Communications (Ofcom) 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 470–790 MHz band. The Ofcom seems to undertake the same approach as the FCC [5]. 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 [14]. Most of the effort is devoted to assess the appropriateness of the sensing and geolocation techniques to provide protection to the incumbent radio services.

IV. 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 [16]. 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 [3]. 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 that 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 [9].

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 [3].

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 Agência Nacional de Telecomunicações (Anatel) considers the technology not consolidated [17]. 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.

A. SBTVD

Digital TV is regulated in Brazil by decrees 4901/2003 and 5820/2006, with the creation of the Brazilian Digital TV System (Sistema Brasileiro de Televisão Digital (SBTVD)). It is a modified version of the Japanese platform (ISDB-T) called Integrated Services Digital Broadcasting, Terrestrial, Brazilian version (ISDB-Tb) and several other countries in Latin America have also adopted or are considering the adoption of the Brazilian system [3].

The ISDB-Tb is a Single Frequency Network (SFN), 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+ [18].

The ISDB-Tb uses the concept of Based Segmented Transmission (BST), which allows this system to provide three kinds of services: fixed, mobile, and portable. The ISDB-Tb is also based on Orthogonal Frequency Division Multiplexing (OFDM), 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 [18].

The Brazilian digital TV channels are in the range of 14 to 69 (470–806 MHz); they are all in the UHF frequency band and each channel occupies a bandwidth of 6 MHz [3]. However, the 700 MHz band (698–806 MHz) will be used for 4G/LTE mobile broadband after the DSO process is completed, so this frequency is not considered in this case study as TVWS.

B. Entities Responsible for Spectrum Management in Brazil

Brazil has two federal entities responsible for the spectrum management: Anatel and Ministério das Comunicações (MiniCom) [17]. 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).

C. *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 698–806 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 I shows the result of the first Brazilian auction process of the 700 MHz band [19].

TABLE I
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 451–458 MHz and 461–468 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.

V. CEARÁ CASE STUDY

There is some shift from wired to mobile wire-free communications, but this is a gradual trend rather than a sudden change [14]. 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 [16]. 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.

Fig. 3 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 worsen. 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. Fig. 4 shows the number of already licensed DTV unused channels in each city of Ceará in 2013. 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 Fig. 4 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, at Fortaleza, the capital 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. The work in [20] shows that 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 Fig. 4 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.

A. *Case Study Considerations*

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

- Programme Making and Special Events (PMSE) equipment such as microphones may not be considered, since PMSE are likely to be rare in hard-to-reach locations [10];
- The regulations must be based on the models of FCC and Ofcom, as these approaches provide the most straightforward TVWS regulatory system [14], [15];
- It must be considered suitable propagation models during the development of the GLDB to enhance the system's performance. Works in [21], [22] present appropriate models to work with UHF band.

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

(a) 3G coverage.

(b) 4G coverage.

Fig. 3. 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.

requiring a license, but following a strict set of rules to avoid

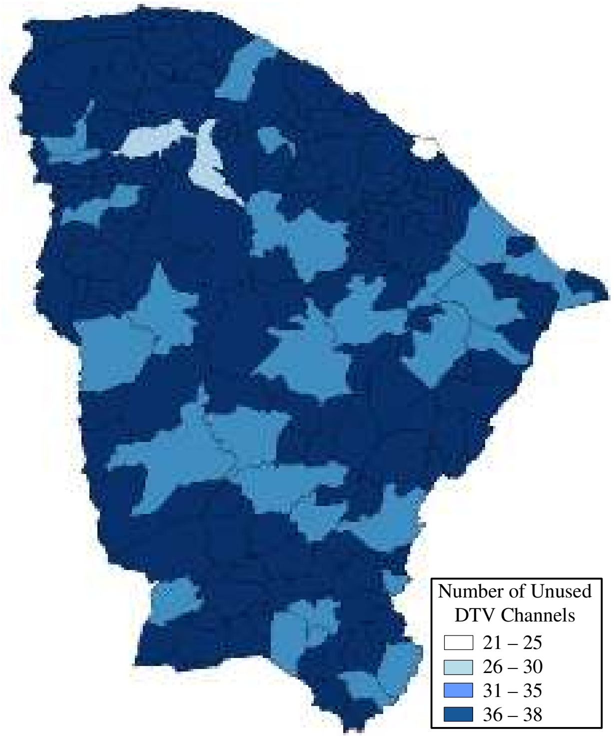

Fig. 4. DTV unused channels per city in Ceará State.

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 function that negotiates with a central resource management entity to obtain short-term grants to use spectrum resources [23].

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]; Fig. 5 elucidates the described process.

B. 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 [11], [24], [13] and are aligned with the European Telecommunications Standards Institute (ETSI) Reconfigurable Radio Systems (RRS) TR 102907 document [25].

1) Spectrum of Commons: Deploying a fiber network structure to provide some telecommunication service may not be profitable in rural areas [11]. 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

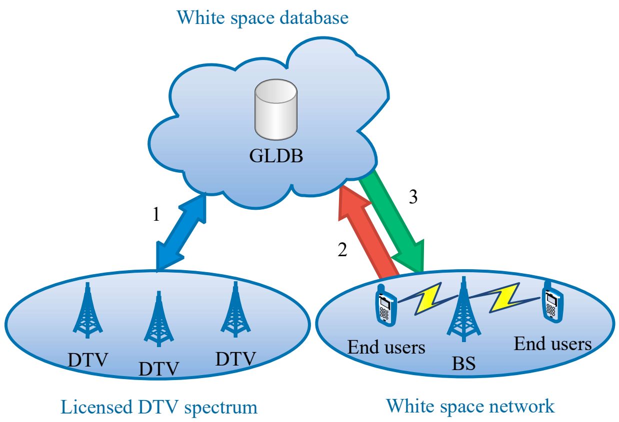

Fig. 5. GLDB approach for a white space network. The request and grant of TVWS channels are as follows: a map of TVWS (location and maximum EIRP allowed) is built and stored in the GLDB based on the free DTV channels (1); the BS requests TVWS channel to the GLDB (2); the GLDB grants TVWS channels, if available, to a set of BS to be then attributed to the end users (3).

extending a fixed network. It allows the sharing, but does not provide a proper Quality of Service (QoS) 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 [11].

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 [26].

2) Secondary Spectrum Market: The 4G/LTE supports flexible carrier bandwidths, from 1.4 MHz up to 20 MHz. The one used in the simulation in Section V-C 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 [9].

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 [11]. This scenario is used as the basis to illustrate the case study, LTE over TVWS.

C. Case Study Discussion

As seen in Figure 3, 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.

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 [27].

The Table II shows the main parameters used in the simulation following 3GPP recommendations [28]. 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 II
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

The Fig. 6 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 Fig. 3, 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 (692–698 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[3]. The average capacity calculated from the coverage area in Fig. 6 is 2 Mbps, following the Channel Quality Indicator (CQI) table, which indicates the suitable downlink transmission data rate according to a modulation and coding scheme value, given a Signal to Interference plus Noise Ratio (SINR) [29]. This average capacity is calculated in the downlink direction and assuming that the user gets all the 25 resource blocks.

In this manner, the Fig. 6 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 Fig. 6, the coverage area gain using the TVWS is expressive. Fig. 7 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 (470–476 MHz); and channel 51 (692–698 MHz), the same used in the radio mobile simulation. This figure shows a normalized comparison for these three bands, overlapping each coverage 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

[3]The resource block has a total size of 180 kHz in the frequency domain and 0.5 ms in the time domain [29].

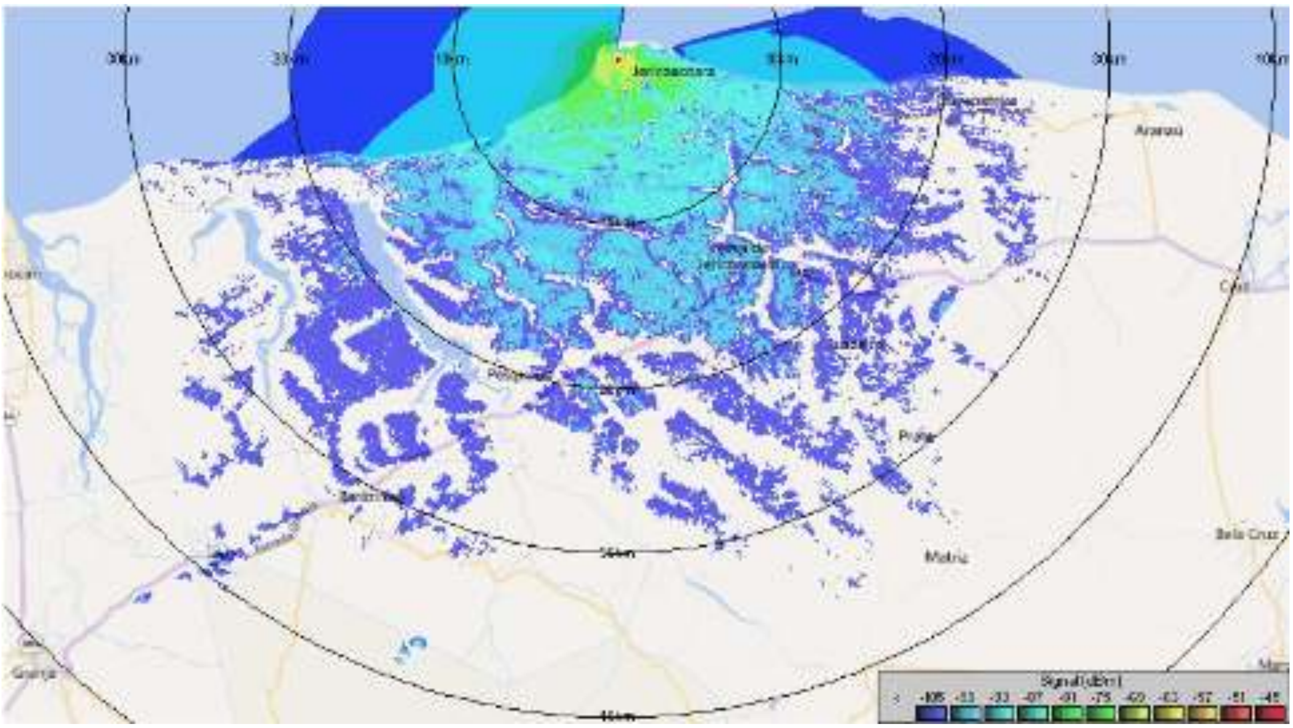

Fig. 6. Coverage map generated using the Radio Mobile software, illustrating the LTE over TVWS scenario at 51 DTV channel at Jericoacoara city.

propagation model used for generating Figure 7 was the "Cost-231 Extension to Hata Model" [30] 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 [31].

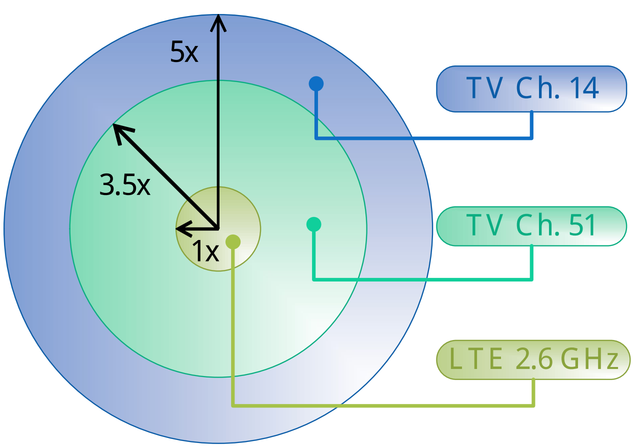

Fig. 7. Coverage area comparison for channel 14 (470–476 MHz), channel 51 (692–698 MHz), and LTE 2.6 GHz.

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 receive the TVWS frequency, 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.

D. Business Model

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 the USA, the FCC has certificated some IT companies, including Google, Microsoft, and SpectrumBridge, as GLDB operators [6].

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 V-B, it is important to highlight that the TVWS opens an opportunity for new players to get into the market.

Fig. 8 illustrates a possible cash flow process that could be adapted to the Brazilian case. The regulator (Anatel) is responsible to manage the spectrum and the GLDB management can be outsourced to a company, thus aiming new business opportunities. The same reasoning applies to the broker. Anatel promotes the primary spectrum market and the resource is sold. The spectrum slices are fixed which follows a long-term licensing schema, 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 enters in the short-term licensing schema, where it could be used by the secondary systems to implement the scenarios described in Section V-B [11]. The work in [6] presents a more detailed and diversified business model.

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.

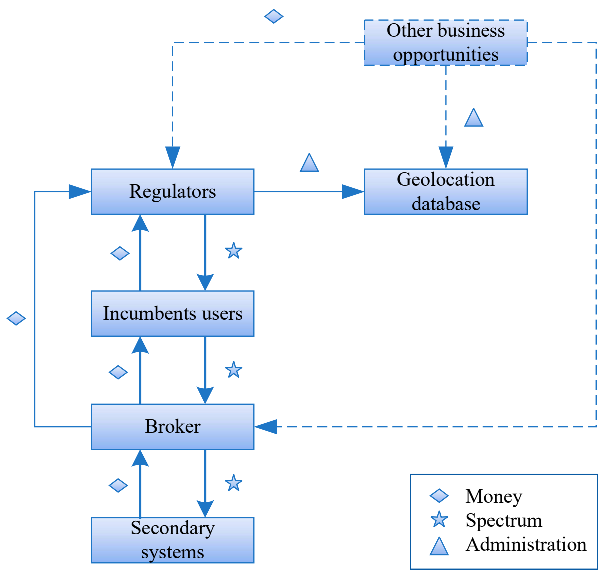

Fig. 8. Example of cash flow process. Other business models could be adopted.

VI. Conclusion

In this work, we 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 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. 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 Mbps for downlink inside the coverage area. 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 rural regions.

As a continuation of this work, it will be considered the development of some trials of GLDB generation and access using the testbeds of the Federated Union of Telecommunications Research Facilities for an EU-Brazil Open Laboratory (FUTEBOL) Project, a partnership consortium among European and Brazilian institutions that seek the convergence point between optical and wireless networks. In this work, the feasibility of the GLDB approach can be assessed for the Brazilian rural scenarios.

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