DISSERTAÇÃO DE MESTRADO ACADÊMICO

SPECTRUM AVAILABILITY IN THE VHF AND UHF BANDS FOR THE DEPLOYMENT OF SECOND-GENERATION DIGITAL TERRESTRIAL TELEVISION SYSTEMS IN BRAZIL

Thiago Aguiar Soares

Brasília, Dezembro de 2022

UNIVERSIDADE DE BRASÍLIA

FACULDADE DE TECNOLOGIA
DEPARTAMENTO DE ENGENHARIA ELÉTRICA

UNIVERSIDADE DE BRASÍLIA
Faculdade de Tecnologia

DISSERTAÇÃO DE MESTRADO ACADÊMICO

SPECTRUM AVAILABILITY IN THE VHF AND UHF BANDS FOR THE DEPLOYMENT OF SECOND-GENERATION DIGITAL TERRESTRIAL TELEVISION SYSTEMS IN BRAZIL

Thiago Aguiar Soares

Dissertação de Mestrado Acadêmico submetida ao Departamento de Engenharia Elétrica como requisito parcial para obtenção do grau de Mestre em Engenharia Elétrica

Banca Examinadora

Prof. Ugo da Silva Dias, Ph.D, ENE/Universidade de Brasília - UnB
Orientador

Prof. Hurgeles Sales Silva, Ph.D, ENE/Universidade de Brasília - UnB
Examinador Interno

Prof. Cristiano Akamine, Ph.D, Universidade Presbiteriana Mackenzie
Examinador Externo

FICHA CATALOGRÁFICA

SOARES, THIAGO AGUIAR
SPECTRUM AVAILABILITY IN THE VHF AND UHF BANDSFOR THE DEPLOYMENT OF SECOND-GENERATION DIGITAL TERRESTRIAL TELEVISION SYSTEMS IN BRAZIL [Distrito Federal] 2022.
xvi, 63 p., 210 x 297 mm (ENE/FT/UnB, Mestre, Engenharia Elétrica, 2022).
Dissertação de Mestrado Acadêmico - Universidade de Brasília, Faculdade de Tecnologia.
Departamento de Engenharia Elétrica

1. Digital Terrestrial Television (DTT)	2. Spectrum Policies
3. VHF/UHF Bands	4. Regulation
I. ENE/FT/UnB	II. Título (série)

REFERÊNCIA BIBLIOGRÁFICA

SOARES, T. A. (2022). *SPECTRUM AVAILABILITY IN THE VHF AND UHF BANDSFOR THE DEPLOYMENT OF SECOND-GENERATION DIGITAL TERRESTRIAL TELEVISION SYSTEMS IN BRAZIL* . Dissertação de Mestrado Acadêmico, Publicação PPGENE.DM-797/22, Departamento de Engenharia Elétrica, Universidade de Brasília, Brasília, DF, 63 p.

CESSÃO DE DIREITOS

Thiago Aguiar Soares
Depto. de Engenharia Elétrica (ENE) - FT
Universidade de Brasília (UnB)
Campus Darcy Ribeiro
CEP 70919-970 - Brasília - DF - Brasil

DEDICATION

To my Family.

ACKNOWLEDGMENTS

My sincere acknowledgment to my wife Polyanna Martins and my kids, Lívia Martins and Felipe Martins, who gave me endless love, kindness, tenderness, and mental support during my journey. Without them, nothing would be possible. Special thanks to my parents, who gave me an education and supported me in every moment. I would also like to thank my friends Alexandre Moraes, Paulo Cardoso, and Agostinho Linhares, who encouraged my return to academic studies since the beginning. The support of all my co-workers was also essential to conciliate my daily work routine with academic research, in particular, Roberto Colletti, Bônia Mota, Thiago Rizza, Dionízia Possati, Otavio Caixeta, and William Zambelli. I would also like to express my gratitude to my primary supervisor, Ugo Dias, who guided me throughout this project, and all the great professors from PPGEE. Last but not least, I would like to thank all my friends and family members who even without knowing it, psychologically contributed a lot to this accomplishment.

ABSTRACT

Digital Terrestrial Television (DTT) services still play an important role in Brazil in delivering media content to a large number of people. Although the growing penetration of broadband connectivity and the consumption of over-the-top services, television broadcasting is still the main platform for providing information, entertainment, and culture, especially in economically less favored regions. Furthermore, second-generation DTT systems are already internationally standardized and in operation in many countries. These new technologies provide essential enhancements such as Ultra High Definition Television (UHDTV) video transmissions with High Dynamic Range (HDR) and Wide Color Gamut (WCG) capabilities, immersive audio techniques, and new generations of middleware platforms, which will bring new converged broadcasting-broadband experiences to viewers. To allow the evolution of DTT services, spectrum availability should be deemed for deploying new technologies. Hence, in this work, we study the current and future spectrum availability of the 174-216 MHz Very High Frequency (VHF) band and 470-698 MHz Ultra High Frequency Band (UHF) band in Brazil for the deployment of second-generation Digital Terrestrial Television Systems, which are being studied under the "TV 3.0 Project" initiative, coordinated by The Brazilian Digital Terrestrial Television System Forum (SBTVD Forum). Coverage simulations using the Recommendation ITU-R P.1812 were computed for all expected operating television stations, in different scenarios, to estimate the spectrum usage over the Brazilian territory. Results indicate that even after the analog TV switch-off there will be no spectrum availability in the main metropolitan regions for simulcast transmissions between the current ISDB-Tb System and the future TV 3.0. Hence, hybrid approaches should be implemented to introduce a new digital television system in Brazil successfully.

RESUMO

Os serviços de televisão digital terrestre ainda desempenham papel importante no provimento de conteúdo de mídia para um grande número de pessoas. Apesar da crescente penetração da conectividade à banda larga e do consumo de serviços *over-the-top*, a transmissão televisiva ainda é a principal plataforma para fornecimento de informação, entretenimento e cultura, especialmente em regiões economicamente menos favorecidas. Além disso, os sistemas de televisão digital de segunda geração já estão padronizados internacionalmente e em operação em muitos países. Essas novas tecnologias proporcionam muitas melhorias, como transmissões de vídeo em *Ultra High Definition* (UHDTV), *High Dynamic Range* (HDR) e *Wide Color Gamut* (WCG), técnicas de transmissão áudio imersivo e novas plataformas de middleware, que trarão novas experiências convergentes entre radiodifusão e banda larga aos telespectadores. A disponibilidade de espectro, contudo, é fator essencial para a permitir a evolução dos serviços de televisão digital e a implantação novas tecnologias. Neste sentido, o presente trabalho avalia a disponibilidade de espectro atual e futuro no Brasil nas bandas de *Very High Frequency* (VHF), 174-216 MHz, e *Ultra High Frequency Band* (UHF), 470-698 MHz, para implantação de sistemas de televisão digital terrestre de segunda geração, que estão sendo avaliados no âmbito do "Projeto TV 3.0", coordenado pelo Fórum do Sistema Brasileiro de Televisão Digital Terrestre (Fórum SBTVD). Simulações de cobertura foram calculadas usando a Recomendação ITU-R P.1812 para todas as estações de televisão em operação, em diferentes cenários, para estimar o uso espectro no território brasileiro por serviços de televisão digital. Os resultados indicam que mesmo após o desligamento da TV analógica não haverá disponibilidade de espectro nas principais regiões metropolitanas do Brasil para transmissões simultâneas entre o sistema ISDB-Tb atual e a futura TV 3.0. Portanto, abordagens híbridas devem ser implementadas para que um novo sistema de televisão digital seja implementado com sucesso no Brasil.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF SYMBOLS

List of Acronyms and Abbreviations

3GPP	3rd Generation Partnership Project
5G NR	5G New Radio
ACLR	Adjacent Channel Leakage Ratio
Anatel	Brazilian National Telecommunications Agency
Ancine	Brazilian National Film Agency
APIs	Application Programme Interfaces
ATSC	Advanced Television Systems Committee
ASTC 3.0	Advanced Television Systems Committee 3.0
BI	Bussines Intelligence
BNE	Broadcast Network Europe
BST-OFDM	Band-Segmented Transition - Orthogonal Frequency Division Multiplexing
BICM	Bit-interleaved Coded Modulation
CfP	Call for Proposals
CITEL	Inter-American Telecommunication Commission
COFDM	Coded Orthogonal Frequency-Division Multiplexing
CPM	Conference Preparatory Meeting
DTMB	Digital Television Terrestrial Multimedia Broadcasting
DTMB-A	Digital Television Terrestrial Multimedia Broadcasting - Advanced
DTT	Digital Terrestrial Television
DVB-T	Digital Video Broadcasting - Terrestrial
DVB-T2	Digital Video Broadcasting - Terrestrial 2
EBU	European Broadcasting Union
ERP	Effective Radiated Power
ETSI	European Telecommunications Standards Institute
E-UTRA	Evolved UTRA
FCC	Federal Communications Commission
FEC	Foward Error Correction
FFT	Fast Fourier Transform
FTA	Free-to-air
GI	Guard interval
GIRED	*Grupo de Implantação do Processo de Redistribuição e Digitalização de Canais de TV e RTV*
HD	High Definition
HDR	High Dynamic Range
HLS	HTTP live streaming
IFFT	Inverse Fast Fourier Transform

IMSC1	Internet Media Subtitles and Captions
IMT	International Mobile Telecommunications
IP	Internet Protocol
ISDB-T	Integrated Services Digital Broadcasting - Terrestrial
ITU	International Telecommunications Union
LDM	Layered Division Multiplexing
LLch	Low-latency Channel
LPDC	Low-Density Parity Check
MIFR	Master International Frequency Register
MIMO	Multiple-Input Multiple-Output
MISO	Multiple Input Single Output
MTS	Multichannel Transmission System
NHK	Science & Technology Research Laboratories of Japan Broadcasting Corporation
NPR	Notice of Proposed Rulemaking
OECD	Organisation for Economic Cooperation and Development
OFDM	Orthogonal Frequency-Division Multiplexing
OTA	Over-the-air
OTT	Over-the-top
PCC.II	CITEL Permanent Consultative Committee II
PN-MC	Pseudo-random noise
PLP	Physical Layer Pipe
RAN	Radio Access Network
RF	Radio frequency
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
SBTVD	*Sistema Brasileiro de Televisão Digital*
SBTVD Forum	Brazilian Digital Terrestrial Television System Forum
SFN	Single frequency Network
SISO	Single-input and Single-output
TMCC	Transmission and Multiplexing Configuration Control
TVWS	TV White Spaces
UHDTV	Ultra High Definition Television
UHF	Ultra High Frequency
VHF	Very High Frequency
VVC	Versatile Video Coding
WCG	Wide Color Gamut
WebVTT	Web Video Text Tracks Format
WSD	White Spaces Devices

1 INTRODUCTION

1.1 BACKGROUND

Free-to-air (FTA) broadcasting services still play an important role in Brazil in delivering media content to a large number of people. Besides the growing penetration of broadband connectivity and over-the-top (OTT) media services, FTA television and sound broadcasting are still the main platforms for providing information, entertainment, and culture, especially in economically less favored regions. Linear television, in particular, is the audiovisual platform with the most significant consumption in Brazil [1]. In addition, the Digital Terrestrial Television switch-over brings enormous benefits to the population by offering better picture and audio quality, interactivity, and integration with broadband services. After fifteen years since the beginning of the transition in 2007, digital terrestrial television already reaches about 96% of the Brazilian municipalities [2]. Until the end of the transition, to be completed in December 2023, more digital TV channels will increase content diversity in various cities.

Driven by the rapid improvement of TV sets definition and the necessity of higher quality and connectivity, digital television systems continue their technological evolution. Second-generation DTT broadcasting systems are already internationally standardized and in operation in many countries. These systems are meant to offer higher bit rate capacity per Hz and better power efficiency in comparison to first-generation systems. The technical improvements allow video transmissions in UHDTV and the inclusion of other technologies such as HDR, WCG, immersive audio techniques, and new generations of middleware, which will bring new disruptive experiences to the viewers. In Brazil, an ambitious initiative aims to define state-of-the-art technologies for a second-generation DTT system: the TV 3.0 Project.

Nonetheless, over the past years, broadcasting services have been suffering from increasing competition with telecommunications services, such as streaming and pay-TV services via cable or satellite. The consumer profile is also changing – there is an increasing search for services that provide access to non-linear and on-demand content – which raises frequent questions about the survival of traditional linear FTA broadcasting.

The availability of spectrum resources for digital television services is also declining worldwide, especially in the UHF Band, following a worldwide tendency to allocate more frequencies to mobile communications services. The 700 MHz band is already globally harmonized for the deployment of International Mobile Telecommunications (IMT) Services and the 600 MHz band is also being considered in many countries for services rather than DTT. Furthermore, there is an intense debate for the next World Radiocommunication Conference (WRC-2023) of the Radiocommunication Sector of the International Telecommunications Union (UIT-R) over the full review of the frequency band 470-694 MHz in some regions of the world. So optimizing the usage of the bands allocated for DTT transmissions is crucial for the success of the deployment of second-generation DTT networks.

[1] 79% from the total daily video consumption according to Kantar Ibope Media, Inside Video 2022. Available at <https://www.kantaribopemedia.com/inside-video-2022-download/>

[2] Based in the coverage predictions using the methodology detailed in Chapter 3.

1.2 OBJECTIVE

This work analyzes the current and future spectrum usage of the 174-216 MHz VHF band and 470-698 MHz UHF band in Brazil for the deployment of second-generation DTT systems and discusses new approaches to optimize the usage of these bands. Specifically, the work intends to:

- Analyze the available DTT database to estimate operative stations;
- Generate coverage predictions with appropriate spectrum management software;
- Develop a quantitative assessment of DTT coverage in Brazil by using Python libraries with data science tools;
- Develop realistic transition models for second-generation DTT systems based on the spectrum availability in the Brazilian territory;
- Propose regulatory actions to help government bodies to drive the implementation of second-generation DTT systems and promote spectrum efficiency policies in the VHF and UHF Bands.

1.3 ORGANIZATION

The current Chapter 1 contains a brief introduction about the research topic.

Chapter 2 presents the status of the development, implementation, and standardization of second-generation DTT systems, and also some key technical parameters to help understand the transition challenges from first-generation DTT. It also contains details about the TV 3.0 project that is being developed in Brazil.

Chapter 3 contains coverage simulations using Recommendation ITU-R P. 1812, whose results quantify the spectrum usage of the 174-216 MHz VHF band and the 470-698 MHz UHF band. It also summarizes the history of DTT implementation in Brazil and presents some spectrum challenges for the deployment of second-generation DTT networks.

Chapter 4 analyses the spectrum availability after the analog TV switch-off and discusses possible uses of the VHF and UHF bands. It also includes some technical and regulatory proposals for the deployment of second-generation DTT systems in Brazil.

Finally, Chapter 5 summarizes the main findings and draws some conclusions.

1.4 PUBLICATIONS

The following papers were published during the research:

- Soares, Thiago Aguiar and Dias, Ugo Silva. "Quantitative Assessment of VHF and UHF Bands in Brazil After the Analog TV Switch-off." XL Simpósio Brasileiro de Telecomunicações e Processamento de Sinais (SBrT2022), <http://dx.doi.org/10.14209/sbrt.2022.1570824940>.;
- Soares, Thiago Aguiar; Cardoso, Paulo E. R and Dias, Ugo Silva ; 2022. "Spectrum Availability for the Deployment of TV 3.0". SET EXPO PROCEEDINGS. ISSN Print: 2447-0481. ISSN Online: 2447-049X. v.8. doi:10.18580/setep.2022.44.5. <https://dx.doi.org/10.18580/setep.2022.44.5>.

2 SECOND-GENERATION OF DIGITAL TERRESTRIAL TELEVISION

DTT plays an important role worldwide in providing FTA audiovisual content with better picture and sound quality. DTT is being introduced in the VHF/UHF bands by administrations from 1997 [1]. In 2010, the International Telecommunications Union (ITU) started standardizing second-generation systems, which are meant to offer many technical improvements. The current chapter presents the status of the development, implementation, and standardization of second-generation DTT systems, and also some key technical parameters to help understand the transition challenges from first-generation systems. It also contains details about the TV 3.0 Project, an initiative that aims to define a second-generation DTT system to be implemented in Brazil.

2.1 DTT SYSTEMS

The first-generation DTT systems are standardized by ITU in Recommendation ITU-R BT.1306 - Error correction, data framing, modulation, and emission methods for digital terrestrial television broadcasting. Four systems are currently standardized in the above-mentioned recommendation:

- ATSC - Advanced Television Systems Committee;
- DVB-T - Digital Video Broadcasting - Terrestrial;
- ISDB-T - Integrated Services Digital Broadcasting - Terrestrial;
- DTMB - Digital Television Terrestrial Multimedia Broadcasting

Since their standardization, DTT Systems have been widely implemented worldwide and several countries have started switching-off analog TV services. In many countries, this process has still been completed, mainly in developed countries in North America, Europe, and Asia [2]. Driven by the rapid improvement of TV sets definition and the necessity of higher quality and connectivity, DTT systems continue their technological evolution. In November 2010, ITU started standardizing second-generation systems with the approval of Recommendation BT.1877: Error-correction, data framing, modulation, and emission methods and selection guidance for second-generation digital terrestrial television broadcasting system [3]. In its recent version, there are three standardized systems:

- DVB-T2 - Digital Video Broadcasting - Terrestrial 2;
- ASTC 3.0 - Advanced Television Systems Committee 3.0;
- DTMB-A - Digital Television Terrestrial Multimedia Broadcasting

These recommended systems have already been implemented around the world and new systems are also being developed for future operation. Advanced ISDB-T, an evolution of ISDB-T System [4] and 5G Broadcast System, based on a set of 3rd Generation Partnership Project (3GPP) specifications [5], are well-known candidates for the next standardized second-generation DTT Systems. Moreover, in September 2022, the 5G Broadcast took the first step to becoming a fully standardized second-generation standard. It was included as new terrestrial multimedia broadcasting for mobile reception using handheld receivers, named "System L", in Recommendation ITU-R BT. 2016-2 - Error-correction, data framing, modulation and emission methods for terrestrial multimedia broadcasting for mobile reception using handheld receivers in VHF/UHF bands [6].

A key technical characteristic of second-generation DTT systems is that they are meant as systems offering higher bit rate capacity per Hz and better power efficiency in comparison to the systems described in Recommendation ITU-R BT.1306 and there is no general requirement for backward compatibility with first-generation systems [3]. So, countries willing to transition from first to second-generation DTT systems will need to make efforts to make spectrum available.

UHDTV is one of the major applications of second-generation digital terrestrial broadcasting. Some countries have already carried out UHDTV field experiments on digital terrestrial broadcasting to demonstrate the feasibility of these systems (see the compilation of some performed tests in [7]). Other improvements provided by second-generation DTT systems are further detailed in this Chapter.

The next subsections contain information about the status of implementation of each above-mentioned second-generation DTT systems and also some key technical transmission specifications that make these new systems improve video and audio quality, as well as new possibilities of integration with broadband applications and other features.

2.1.1 DVB-T2

The DVB-T2 is the extension of the television standard DVB-T, issued by the consortium DVB and standardized by the European Telecommunications Standards Institute (ETSI) in 2019 [8] (latest version available in [9]). It was the first considered second-generation DTT System and was harmonized in ITU-R in the first version of ITU-R Recommendation BT.1877.

Since its standardization, the DVB-T2 System has already been implemented in 116 countries [3], mainly in Europe and Africa. Being the first second-generation DTT System to be standardized and globally harmonized in ITU-R has brought the benefit of being adopted in countries where no first-generation DTT System had been implemented. So, in these countries, no transition from first to second-generation DTT systems was required. On the other hand, it was inevitable that newly harmonized second-generation DTT systems, like ATSC 3.0 and DTMB-A, have improved performance due the intrinsic technological evolution on various broadcasting fields over the time.

DVB-T2 technology provides increased flexibility in the choice of system parameters such as the Coded Orthogonal Frequency-Division Multiplexing (COFDM) parameters (Fast Fourier Transform - FFT sizes, guard interval durations, number of carriers - normal and extended), the new Foward Error Correction

[3] A summary of the deployment of DVB Systems can be found in <https://dvb.org/solutions/dtt-deployment-data/>

(FEC) schemes and code rates, modulations for digital terrestrial broadcasting, channel bandwidths, etc [10]. This flexibility gives greater choice in the trade-off between network planning, information rates, and robustness of the digital terrestrial television reception [10].

The main reason for launching DVB-T2 was the use of new ways of modulating and error-protecting the broadcast stream to increase the efficiency in the use of radio spectrum [8]. It was important to have this new technology ready when many countries had to perform the analog TV switch off and some others were adopting MPEG-4 as video coding technology to broadcast High Definition (HD) services [8].

The top-level model of the DVB-T2 system is shown in Figure 2.1. The DVB-T2 system process can be divided into input processing, bit-interleaved coding, modulation, framing, and Orthogonal Frequency-Division Multiplexing (OFDM) symbol generation modules [11]. The whole system input can be one or more MPEG transport stream(s) and (or) generic stream(s). Each logical data stream is carried by a physical layer pipe (PLP). If there are multiple physical layer pipes (PLPs), data transmission will be flexibly time divided in the physical layer. The multi-PLPs and time division technique of the DVB-T2 allow the different levels of coding, modulation, and time-domain interleaving depth to be applied to different PLPs, providing different robustness for each service. In the single-input and single-output (SISO) transmission mode (single transmit antenna), the DVB-T2 physical layer output is the RF signal modulated on one RF channel, like DVB-T. In the Multiple Input Single Output (MISO) transmission mode (dual antennas), DVB-T2 uses the modified Alamouti coding, where the physical layer output can separate out the second output signal, which is transmitted by the second antenna [11].

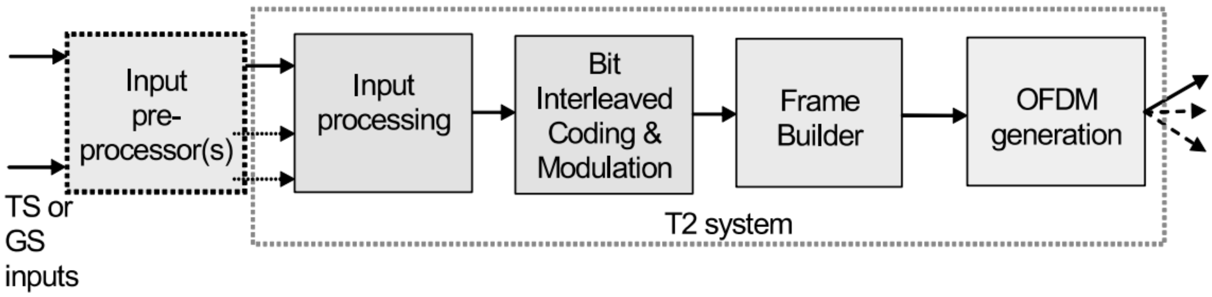

Figure 2.1: Block diagram of DVB-T2 chain. Source: reproduced from [9].

2.1.2 ATSC 3.0

The ATSC 3.0 is a second-generation DTT System that is defined in a suite of more than 30 Standards and companion Recommended Practices. In 2017, the United States Federal Communications Commission (FCC) adopted the ATSC 3.0 broadcast standard that permits voluntary use to enable market-driven innovation and the efficient use of broadcast spectrum [12]. ATSC 3.0 is fundamentally different from predecessor ATSC systems and is therefore largely incompatible with them. This divergence from earlier design is intended to allow substantial improvements in performance, functionality, and efficiency sufficient to warrant implementation of a non-backward-compatible system [13]. With higher capacity to deliver Ultra High-Definition services, robust reception on a wide range of devices, improved efficiency, IP transport, advanced emergency messaging, personalization features, and interactive capability, the ATSC

3.0 Standard provides much more capability than previous generations of terrestrial broadcasting [13].

Since its standardization ATSC 3.0 have reached 57 cities in the U.S.[4], targeting markets that will reach more than 85% of the public [14]. South Korea adopted very early the technology, even before the technology being formally adopted by the FCC, launching 4K ATSC 3.0 broadcasts in May 2017 that now reaches more than 70% of the South Korean population. In 2022, Jamaica launched ATSC 3.0 services and are now reaching more than half of the 14 parishes on the island. India is exploring ATSC 3.0 for direct-to-mobile services and broadcast traffic [14].

An interesting movement is taking place in the United States. American viewers are rediscovering the benefits of over-the-air (OTA) television. With the increase of "cord-cutters", which refers to viewers that cancel their subscriptions to cable or satellite TV services to maintain only streaming and internet media services, DTT is advancing over the country and complementing video consumption with the "old" broadcasting technology [5]. Furthermore, many spontaneous initiatives to promote the NextGenTV (commercial name of the ATSC 3.0 technology) and help new OTA television viewers are being developed in the U.S. [6].

Technically speaking, ATSC 3.0 physical-layer in essence provides a broad range of improvement over throughput, reliability, flexibility, and future extensibility by using state-of-the-art bit-interleaved coded modulation (BICM) and OFDM framing technologies [15]. It ensures 30% enhanced capacity over ATSC 1.0 for the same coverage [15] , [16].

The ATSC 3.0 physical layer is built on the foundation of OFDM modulation with powerful Low-Density Parity Check (LPDC) forward error correction codes, with two code lengths (16,200 and 64,800 bits) and twelve code rates (from 2/15 up to 13/15) [16]. There is support for six modulation orders from Quadrature Phase Shift Keying (QPSK) up to 4096 Quadrature Amplitude Modulation (QAM) and for three multiplexing modes for data PLP: time, frequency and power (with two layers, known as Layered Division Multiplexing - LDM), which can be combined, along with three frame types of SISO, MISO and MIMO (Multiple-Input Multiple-Output) [16]. The physical layer supports twelve selectable guard interval (GI) lengths (cyclic prefixes) from $27\mu s$ up to $700\mu s$, and 3 FFT sizes of 8K, 16K and 32K, which offer strong echo protection in a 6 MHz channel [16].

Figure 2.2 illustrates the block diagram of the ATSC 3.0 system architecture for one RF channel. The system architecture consists of four main parts: Input Formatting, BICM, Framing and Interleaving, and Waveform Generation [17]. The solid lines show blocks common to all configurations, dotted lines show blocks specific to LDM (MIMO blocks are not used), and dashed lines show blocks specific to MIMO (LDM blocks are not used) [17].

[4] Updated status can be found on <https://www.atsc.org/nextgen-tv/deployments>

[5] Reports about getting back to the "old" broadcasting reception can be found in renowned tech websites like in <https://www.tomsguide.com/opinion/this-dollar12-tv-antenna-helped-me-finally-cut-the-cord>

[6] More information about some initiatives can be found in <https://www.watchnextgentv.com/>,<https://www.antennaweb.org/>,<https://www.rabbitears.info/market.php?request=atsc3> and <https://www.thefreetvproject.org/>

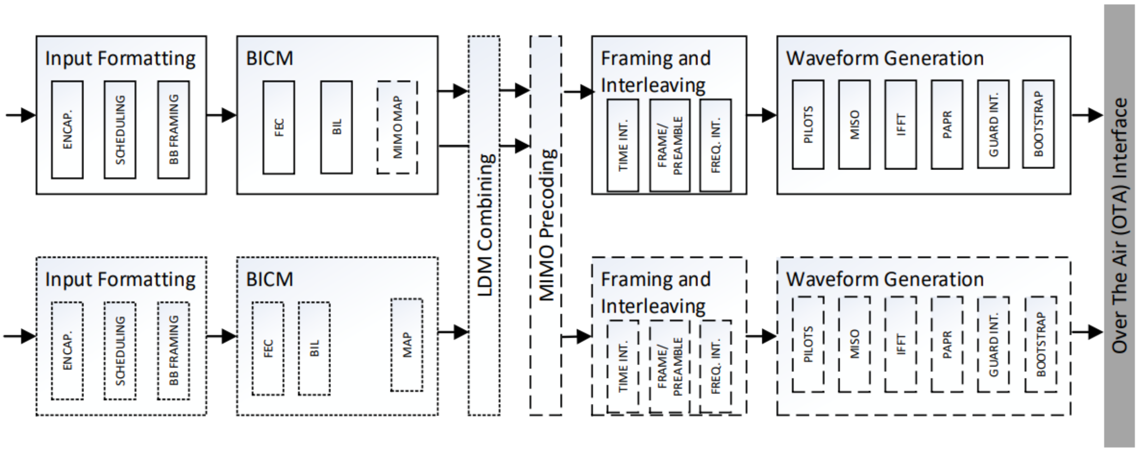

Figure 2.2: Block diagram of the ATSC 3.0 system architecture for one RF channel. Source: reproduced from [17].

2.1.3 DTMB-A

Digital Terrestrial Television Multimedia Broadcasting - Advanced (DTMB-A) is a DTT broadcasting standard proposed by China, which has been accepted by ITU as the international second-generation DTT standard in July 2015 [18]. China initiated its efforts for the research and development on the next generation DTT systems to further improve the spectrum efficiency to support the services such as 4K ultra-high definition TV and 3DTV, offer more flexibility and robustness for the fixed and mobile receptions, provide multi-service broadcast capability, and facilitate the buildup of the single frequency network (SFN) [19], [18]. At present, DTMB/DTMB-A standards have successfully deployed and put into operation in mainland China, Hongkong, Macao as well as other countries and regions, such as Laos, Cuba, Cambodia, East Timor, and Pakistan [7].

The functional block diagram of the DTMB-A transmitter is presented in Figure 2.3. The control frames within the control channel are generated by the following baseband processing: FEC channel coding at low code rates, bit interleaving, QPSK constellation mapping, symbol interleaving, inverse fast Fourier transform (IFFT), and frame header insertion [18]. The data frames are produced by the following baseband processing: FEC channel coding, bit interleaving, constellation mapping, symbol interleaving, IFFT, and frame header insertion [18]. Either identical or different lengths of the frame header and frame body could be adopted by control frames and data frames, wherein the frame header is composed of multicarrier pseudo-random noise (PN-MC) binary sequence in the frequency domain [18]. The control frames and the data frames corresponding to different service types are combined to generate the super-frame, and then the baseband post-processing and up-conversion are used to generate the radio frequency (RF) signal for transmission [18].

2.1.4 Advanced ISDB-T

Since 2016, the Science & Technology Research Laboratories of Japan Broadcasting Corporation (NHK) has been researching and developing transmission systems for a next-generation DTT as a part

[7] <http://www.dtnel.org/2020/dtvnews_0106/1947.html>

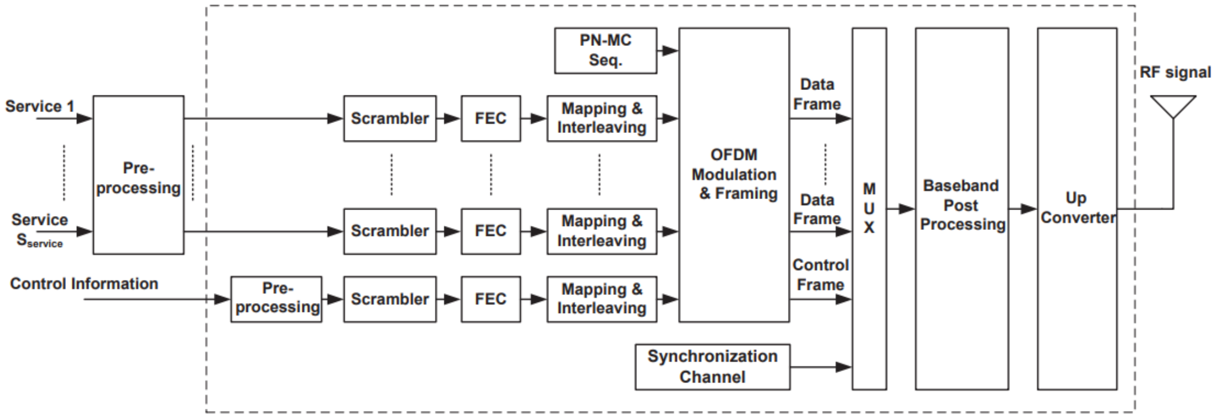

Figure 2.3: Block diagram of the DTMB-A transmitter. Source: reproduced from [18].

of the research program "Research and Development for Advanced Digital Terrestrial TV Broadcasting System" under the auspices of the Ministry of Internal Affairs and Communications, Japan [20]. Despite the standardization process has not been completed, the system has already been tested and is being considered as a new second-generation DTT system as an evolution of the current standardized ISDB-T System.

The Advanced ISDB-T inherits the features of the current DTT system, the ISDB-T [20]. One of the capabilities of the Advanced ISDB-T is to provide 4K/8K UHDTV services for fixed reception and HDTV services for mobile reception in one channel. Therefore, the Advanced ISDB-T can transmit up to three layers (layers A, B, and C) with different transmission capacities and robustness [20].

The Advanced ISDB-T uses a similar frame structure of ISDB-T, but innovates with a new parity-check matrix for the LDPC code, dual transmit/receive polarization with 2x2 MIMO configuration, and modulation up to 4096 QAM. The modulation used is Band-Segmented Transition - Orthogonal Frequency Division Multiplexing (BST-OFDM) with 35 segments and IDDT up to 32K [21], [22]. It is worth comparing the technical transmission parameters of the Advanced ISDB-T and the ISDB-T systems to have a better understanding of the improvements of new second-generation DTT Systems over the current DTT transmissions in Brazil. Table 2.1 shows the main transmission parameters of the systems, summarized in [23].

Table 2.1 shows that Advanced ISDB-T also uses OFDM multiplexing technique and a segmented transmission structure. The bandwidth per segment, however, was reduced to increase the number of segments from 13 (in ISDB-T) to 35, allowing for a flexible bitrate distribution between layers, such as the mobile and the fixed reception layer [23]. The Table 2.1 also shows that more options were added for carrier modulation, coding rates, and other transmission parameters. Additionally, more options regarding the carrier modulation and code rates of LDPC codes have been provided to allow for finer adjustments of the transmission capacity and robustness [23].

The block diagram of the modulator of the Advanced ISDB-T system is shown in Figure 2.4 [24]. The main data is divided into three hierarchical-frame signals (on layers A, B, and C) according to the service and the transmission and multiplexing configuration control (TMCC) information, and LLch signals are output from the input interface (Input I/F) [24]. The data signals are subjected to error-correction coding

Table 2.1: Transmission Parameters of Advanced ISDB-T and ISDB-T. Source: reproduced from [23].

	Advanced ISDB-T (for an FFT size of 16k)	**ISDB-T (for an FFT size of 8K)**
Modulation method	OFDM	OFDM
Channel bandwidth	6 MHz	6 MHz
Occupied bandwidth	5.83 MHz	5.57 MHz
Number of segments	35	13
FFT size	16,384 (16k)	8,192 (8k)
Number of carriers	15,121	5,617
Scattered pilot ratio	1/3; 1/6; 1/12; 1/24; 1/48	1/12
Carrier modulation	QPSK, 16QAM, 64QAM, 256QAM, 1024QAM, 4096QAM 16QAM through 4096QAM are non-uniform constellation)	QPSK, 16QAM, 64QAM, DPQSK (uniform constellation)
Effective OFDM symbol length	2,592 μs	1,008 μs
Guard interval ratio	1/4, 1/8, 1/16, 800/16,384	1/4, 1/8, 1/16, 1/32
Inner code	LDPC	Convolutional
Outer code	BCH	RS
System	SISO, MIMO	SISO

and mapping in the bit-interleaved coded modulation (BICM) blocks. After that, the layer-combining block combines the data subcarriers for hierarchical layers [24]. Then, time interleaving and frequency interleaving are performed to form data segments. In the other data flow, LDPC encoding and DBPSK modulation are applied to the low-latency channel (LLch) signals. The OFDM frame is constructed from the data segments, pilot signals, TMCC signals, and LLch signals. Finally, an IFFT is performed and the GI is inserted [24].

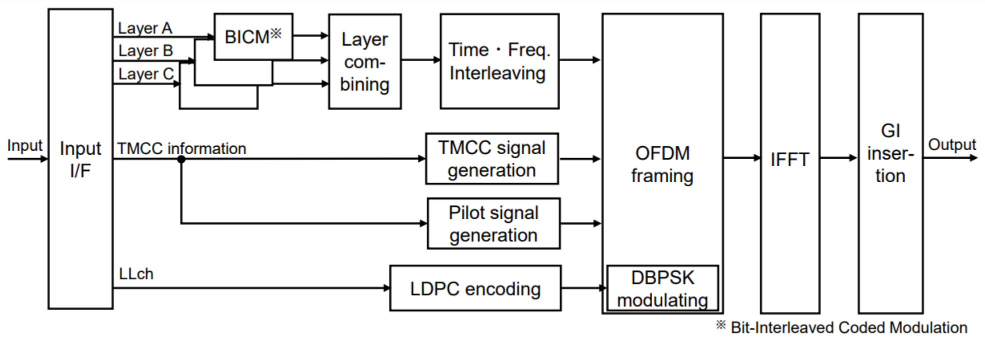

Figure 2.4: Block diagram of the Advanced ISDB-T. Source: reproduced from [24].

2.1.5 5G Broadcast

The LTE-based 5G Terrestrial Broadcast (5G Broadcast) is a standalone broadcasting system offering a downlink-only service intended for direct reception by all members of the general public across the service area, including the capability of free-to-air reception. Several 3GPP specifications have been extended or newly developed over several releases to address the use cases and requirements for 5G dedicated broadcast networks. With the completion of Release 16, a comprehensive set of 3GPP specifications is available that fulfills the use cases and requirements for a 5G Broadcast System [5]. The 5G Broadcast specifications have been published by ETSI on the 22nd of December 2020 in TS 103 720 “5G Broadcast System for linear TV and radio services; LTE-based 5G terrestrial broadcast system” [25].

In September 2022, the 5G Broadcast was also included as new terrestrial multimedia broadcasting for mobile reception using handheld receivers, named "System L", in Recommendation ITU-R BT. 2016-2 - Error-correction, data framing, modulation and emission methods for terrestrial multimedia broadcasting for mobile reception using handheld receivers in VHF/UHF bands [6]. This is the first step to standardizing the system within the scope of ITU-R. A number of other ITU Reports and Recommendations are under review to complete the standardization framework.

The international harmonization of the 5G Broadcast as a new second-generation DTT standard is being coordinated by the European Broadcasting Union (EBU). This is a clear movement from Europe to focus on 3GPP-based technology for broadcasting services instead of evolving DVB-T2 System. The bet is that consumer habits for video consumption will increasingly demand requirements for mobile communication, which explains a system designed in a 3GPP common core that would facilitate the reception on handheld receivers.

Figure 2.5 shows the reference architecture of the 5G Broadcast System. The 5G Broadcast Service consists of a Bearer Service and a User Service. The latter provides the announcement of 5G Broadcast User Services and also provides information about how to discover and access them. The former provides the distribution means for 5G Broadcast User Services, including a radio bearer. A radio access network (RAN) interface is defined, including a NodeB in the 5G Broadcast Transmitter and an Access Stratum modem in the 5G Broadcast Receiver [5].

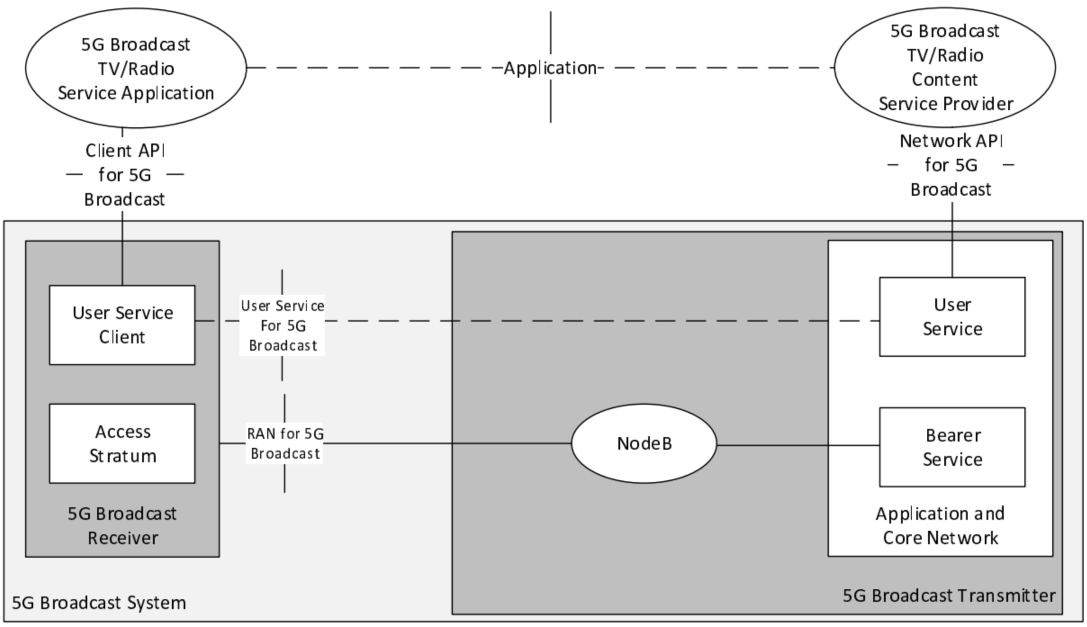

Figure 2.5: Reference architecture for 5G Broadcast System. Source: reproduced from [5].

2.2 THE BRAZILIAN TV 3.0 PROJECT

In Brazil, studies for second-generation DTT Systems have already been initiated. In July 2020, The Brazilian Digital Terrestrial Television System Forum (SBTVD Forum) released a Call for Proposals (CfP) seeking input from interested organizations for Brazil's next-generation Digital Television system components and sub-components [26]. The initiative is called "TV 3.0 Project". The CfP received 36 responses from 21 different organizations worldwide, considering its six system components (Over-the-air Physical Layer, Transport Layer, Video Coding, Audio Coding, Captions, and Application Coding)[8].

The TV 3.0 Project Phase 2 "Testing and Evaluation of the candidate technologies" was carried out from July 2021 to December 2021. Considering the test results, as well as the market and intellectual property aspects of the candidate technologies, some components have already been defined. Figure 2.6 shows the technologies that were selected after extensive laboratory and field test evaluation, which were coordinated by the Technical Module of the Forum SBTVD and involved about 70 researchers from 7 different Brazilian Universities. The testing and evaluation reports are available on the SBTVD Forum website [2].

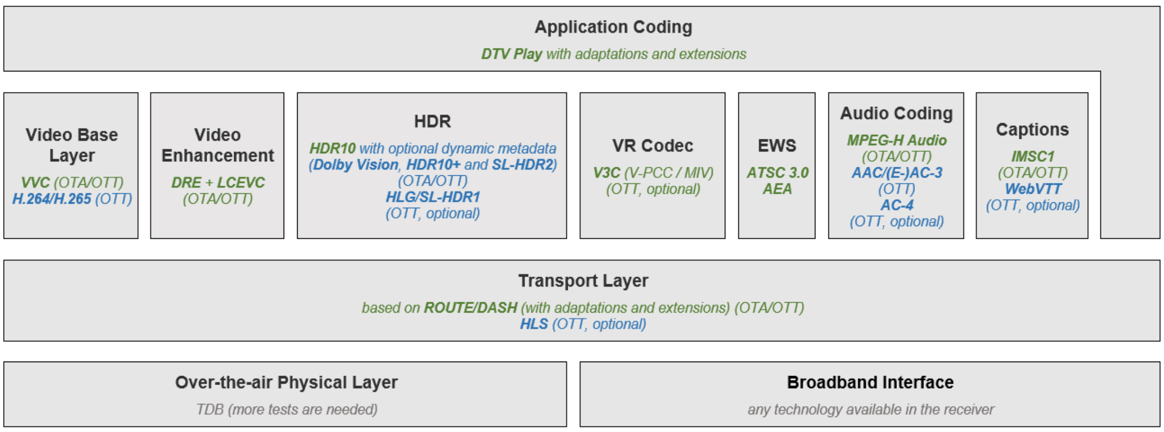

Figure 2.6: Selected technologies for the TV 3.0 Project [2]. Source: reproduced from [27].

The Phase 3 of the project will include complementary tests for selection of the physical layer technology, development of the necessary adaptations and extensions to the transport layer specification, subjective assessment of the video coding quality (determination of the necessary bitrate), development of adaptations and extensions of the Application Coding, and other activities are expected to be developed until 2024 [28]. TV 3.0 is expected to launch in 2025.

2.3 TV 3.0 MAIN USE CASES

The TV 3.0 Project contains technical elements that will define the main use cases of the next-generation DTT System that will be introduced in Brazil. The general requirements were organized by each system component in the Call for Proposals released by the SBTVD Forum. Altogether, sixty three main use cases

[8]Updated information about the status of the project can be found at <https://forumsbtvd.org.br/tv3_0/>

were defined. Each one is divided in minimum technical specifications, which are detailed in Section 4 of the CfP [26].

The **Physical Layer** specifications are based on the frequency reuse-1, i.e., the use of the same RF channel by independent stations covering adjacent service areas. This is a disruptive specification, that would provide great flexibility for the transmission network, which could be freely expanded and subdivided using the same channel. This approach has already been proposed by EBU in a technical report that describes a new wideband reuse-1 based DTT concept, called WiB [29]. It would allow an optimized implementation of DVB-T2, indicating a possible capacity increase in the range of 37 - 60%, assuming the DVB-T2 reference can carry about 200 Mbit/s per site within the 470 - 694 MHz band [29]. The practical implementation, however, was not further carried out.

The reuse-1 technique would reduce the demand for additional spectrum for the technological transition because all channels could be used simultaneously and independently in all locations, significantly increasing the capacity available for DTT, especially in locations that currently have few channels. On the other hand, reuse-1 broadcast requires C/N ≤ 0 dB in a Rayleigh channel, which implies a limited channel capacity. To compensate that, the CfP requires MIMO 2x2 and channel bonding to be used in conjunction with scalable video coding [26]. The technology to be adopted for the Physical Layer will be defined in Phase 3 of the TV 3.0 Project.

The **Transport Layer** main requirement is to be Internet Protocol (IP) based. With this capability, seamless connectivity between broadcast and broadband could be achieved. The fully IP-compliant design of the ATSC 3.0, for instance, becomes possible a convergence service of broadcast and broadband in various system layers, more than a simple data bonding in the application/presentation layer, even being possible to coordinate compatible numerologies with 5G enhanced mobile broadband (eMBB) [30].

The IP-based also facilitates the redistribution of content to other linear platforms (cable, satellite, IPTV) or not linear services (fixed or mobile 4G/5G broadband), in addition to redistribution to mobile devices on the network home (home gateway). It would also allow targeted advertising between linear content and non-linear content (via fixed broadband or mobile 4G/5G) and the implementation of an enhancement layer over the internet. The ROUTE/DASH technology was already adopted for the TV 3.0 Transport Layer, as can be seen in Figure 2.6. Furthermore, the system will maintain optional support for HTTP live streaming (HLS) streaming.

The **Video Coding** enhancements have a greater impact on the end-user experience. In 2019, more than half of worldwide TV sales were of UHDTV 4K displays (3,840 x 2,160 pixels)[9]. The minimum requirements of TV 3.0 include the support of improved video resolution, adequate to consumer electronics display evolution, of at least UHDTV 4K resolution from the over-the-air delivery. However, even more resolution, up to 7,680 x 4,320 (UHDTV 8K), is required with enhancements provided by internet delivery.

The Video Coding Layer also should provide improved video dynamic range and color space, which includes HDR capability and WCG. An important aspect is also to provide state-of-the-art coding efficiency, to allow better quality video in limited capacity channels. Finally, the video coding shall be interoperable with different distribution platforms and shall support scalability and extensibility as specified. The Versa-

[9]Statista -Worldwide market share of TV sales from 2017 to 2019, by screen resolution, available at <https://www.statista.com/statistics/818419/world-tv-market-share-by-type/>

tile Video Coding (VVC), also known as H.266, has already been defined in the TV 3.0 Phase 2 (see Figure 2.6). The system will also maintain support for H.264 and H.265 for the distribution of alternative content over the internet. Furthermore, for HDR transmissions, the HDR10 technology was adopted with optional support for Dolby Vision, HDR10+, and SL-HDR2 dynamic metadata.

In terms of audio quality, the **Audio Coding Layer** shall support immersive and interactive audio (including, for example, 2.0, 5.1, 5.1+4H channel-based formats and object-based capability) and also provide state-of-the-art coding efficiency and support live (real-time) encoding with minimum end-to-end latency. It shall also support audio description delivery in the same stream as the main audio, as an alternative full mix, or as an additional audio object with associated metadata [26]. Technical requirements will also allow the development of a single delivery format for multiple playback configurations, like TV, soundbar, home theater, binaural, and others. The MPEG-H Audio was adopted in Phase 2 for over-the-air and internet distribution, and other audio formats currently supported, like AC-4, will be maintained.

It is expected that accessibility applications will be improved with new **Captions** technologies. The use cases of the TV 3.0 captions shall enable frame-accurate synchronization with video, support the complete character set currently used for closed captioning in Brazil, enable live and offline closed-captioning, enable text styling control, enable sending sign language gloss as a separate caption stream to be synthesized as sign language video by an appropriate app and support emergency warning information captions [26]. For the Captions, Internet Media Subtitles and Captions 1.0 (IMSC1) was adopted in Phase 2 for over-the-air and internet distribution, maintaining the optional support for Web Video Text Tracks Format (WebVTT). The ATSC 3.0 Advanced Emergency Alert was also adopted for the Emergency Warning System.

Last but not the least, interactivity and other applications are part of the possibilities provided by the **Application Coding Layer**. Recently, the SBTVD Forum has developed the DTV Play (Ginga receiver profile FSD 09 as defined in ABNT NBR 15606-1), which is part of the "TV 2.5" project. The "TV 2.5" project comprised two aspects: broadcast-broadband integration and audiovisual quality. The first aspect involved the development of the DTV Play, addressing use cases such as on-demand video, synchronized companion devices, an audiovisual enhancement over the Internet, and targeted content. The second aspect was addressed through the introduction of three new optional immersive audio codecs, and through the introduction of two new optional HDR video formats [26].

As a result of the TV 3.0 Phase 2, it was decided to adapt and extend DTV Play to enable all existing use cases and to evolve it with new possibilities provided by the proponents. The envisaged experience for TV 3.0 with the new application coding is an application-oriented user experience including, besides the interactivity functions and broadcast-broadband integration, the presentation of all audiovisual content. So, the user experience will be app oriented, where each broadcaster can deliver an app to the viewers that could manage all the received content, either over-the-air or over the internet connection, providing seamless integration between broadcast and broadband.

3 SPECTRUM USAGE OF DIGITAL TELEVISION SERVICES IN BRAZIL

Spectrum resources are crucial for the implementation of new DTT systems. However, the availability of spectrum for DTT is declining worldwide, especially in the UHF Band, following a worldwide tendency to allocate more frequencies to mobile communications services. The current chapter describes how spectrum is allocated for DTT services and how it is being used over the past years in Brazil. It also contains coverage simulations results that quantify the current spectrum usage of the 174-216 MHz VHF band and the 470-698 MHz UHF band.

3.1 SPECTRUM ALLOCATION FOR DIGITAL TELEVISION SERVICES

The International Telecommunications Union (ITU), through its Radiocommunication Sector (ITU-R), and its executive arm, the Radiocommunication Bureau (BR), is the global agency responsible for management of the radio frequency spectrum and satellite orbit resources. The foundation of international frequency management is the Radio Regulations (RR), the binding international treaty that determines how the radio frequency spectrum is shared between different services, including space services [10]. The cornerstone of the RR is the International Table of Frequency Allocations to be found in Article 5 [31] , [32]. The World Radiocommunication Conferences (WRCs) establish and revise the texts of the Radio Regulations, including the Table of Frequency Allocations. WRCs are normally convened every three/four-year cycle. The agenda is set by the Council on the basis of the draft agenda as agreed by the previous WRC [33].

The International Table of Frequency Allocations is the basis for an effective national spectrum management process [33]. Based on this international regulatory framework, countries establish a national table of frequency allocations, which determines the frequency bands that each radiocommunication service can use and the respective technical conditions. In Brazil, the National Telecommunications Agency (Anatel) is responsible for managing the radio frequency spectrum and defines which telecommunications services or applications can use each frequency band [34]. The Table of Frequency Allocations allocates frequency bands to services and is agreed for all three ITU Regions:

- Region 1: Europe and Africa including Russia;
- Region 2: Americas;
- Region 3: Asia including Iran and China;

[10]<https://www.itu.int/en/mediacentre/backgrounders/Pages/itu-r-managing-the-radio-frequency-spectrum-for-the-world.aspx>, visited on 09/10/2022.

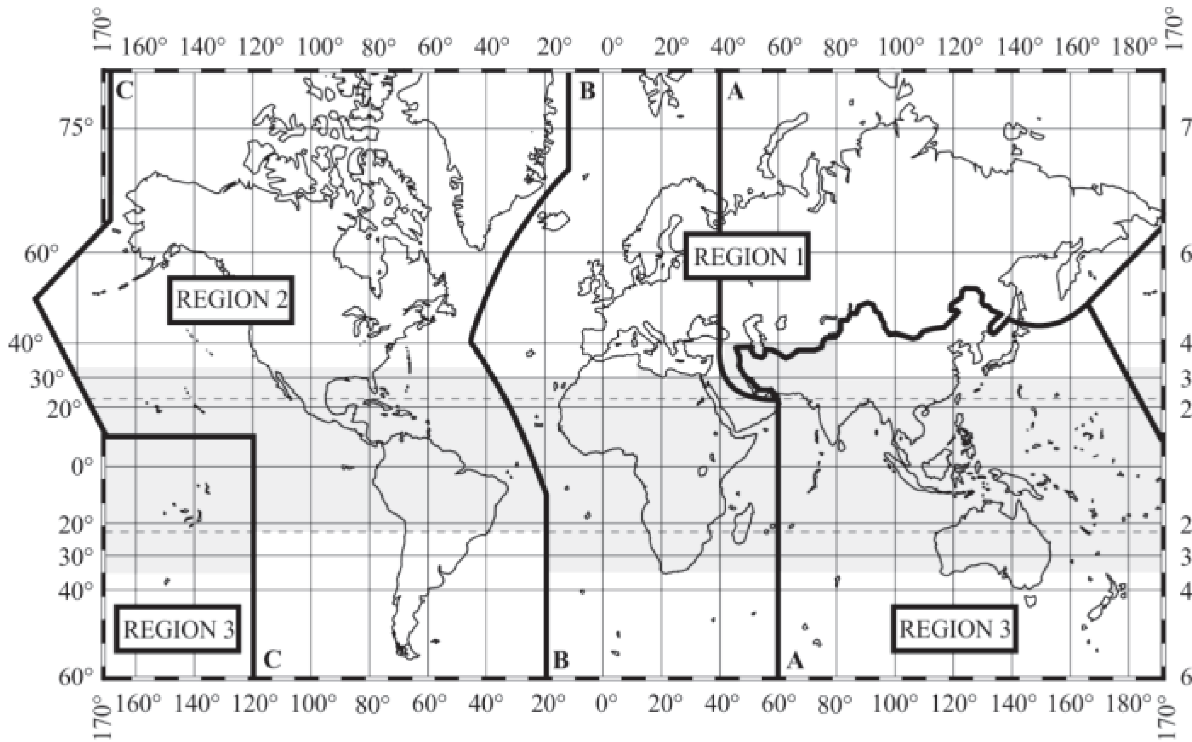

Figure 3.1: ITU Regions defined by ITU Radio Regulations. Source: reproduced from [31].

Services are allocated in the RR with one of at least two different priorities: "PRIMARY", services identified in capital letters have higher priority, and "Secondary", services identified in lowercase have lower priority and hence should not cause harmful interference into primary services and would have to accept interference from them [31] , [32]. Figure 3.1 contains an example of frequency allocation on the UHF Band in the ITU Radio Regulations.

The Table of Frequency Allocations divides the frequency band into smaller bands, which in the 2020 version of the RR [31] are allocated to more than 40 different radiocommunication services [35]. Each spectrum band could be allocated to one or more radio services with equal or different rights (primary and secondary). However, a notable feature is that the providers of a secondary service cannot cause harmful interference to a primary service and cannot claim protection from the harmful interference caused by primary services [35].

In some cases, countries have uses in frequency bands that are allocated on a global or regional basis at a conference for a different radio service they wish to keep in place for a domestic reason [36]. In these cases, the Table of Frequency Allocations can also contains country-specific allocations defined via footnotes. Footnotes are included during the conferences for several situations, including to show the different status of services (on a primary or secondary basis), as well as whether additional or alternative allocations are to occur [35].

However, a country footnote still means that the country taking the footnote cannot cause harmful interference in the operations of the country operating in a manner consistent with the allocation [36]. In many cases, however, footnotes are seen as a step back to a worldwide or regional harmonization of particular frequency bands. So, a specific agenda item is kept every WRC to promote the revision of

Table 3.1: Example of a table of frequency allocations of the ITU Radio Regulations. Source: reproduced from [31].

460-890 MHz

Allocation to services		
Region 1	**Region 2**	**Region 3**
460-470	FIXED MOBILE 5.286AA Meteorological-satellite (space-to-Earth) 5.287 5.288 5.289 5.290	
470-694 BROADCASTING 5.149 5.291A 5.294 5.296 5.300 5.304 5.306 5.312	**470-512** BROADCASTING Fixed Mobile 5.292 5.293 5.295	**470-585** FIXED MOBILE 5.296A BROADCASTING 5.291 5.298
	512-608 BROADCASTING 5.295 5.297	**585-610** FIXED MOBILE 5.296A BROADCASTING RADIONAVIGATION 5.149 5.305 5.306 5.307
	608-614 RADIO ASTRONOMY Mobile-satellite except aeronautical mobile-satellite (Earth-to-space)	**610-890** FIXED MOBILE 5.296A 5.313A 5.317A BROADCASTING 5.149 5.305 5.306 5.307 5.320
694-790 MOBILE except aeronautical mobile 5.312A 5.317A BROADCASTING 5.300 5.312	**614-698** BROADCASTING Fixed Mobile 5.293 5.308 5.308A 5.309	
790-862 FIXED MOBILE except aeronautical mobile 5.316B 5.317A BROADCASTING 5.312 5.319	**698-806** MOBILE 5.317A BROADCASTING Fixed 5.293 5.309	
862-890 FIXED MOBILE except aeronautical mobile 5.317A BROADCASTING 5.322 5.319 5.323	**806-890** FIXED MOBILE 5.317A BROADCASTING 5.317 5.318	

country footnotes [11].

Broadcasting services are defined in a general way in the RR. It establishes that the broadcasting service is "a radiocommunication service in which the transmissions are intended for direct reception by the general public. This service may include sound transmissions, television transmissions, or other types of transmission (CS)." (see article 1.38 of [31]). So, the International Table of Frequency Allocations does not specify if a determined frequency band is allocated for sound or television broadcasting - it only states the allocation for broadcasting according to its priority. Each country is free to establish its own rules for the assignment of broadcasting services on the allocated frequency bands, i.e., analog television, digital television, and sound broadcasting, among others.

It is interesting to remark that broadcasting services operate on a primary basis in all bands on which it is allocated in the RR. It shows the priority of broadcasting services in the assessment of harmful interference scenarios with other services that share the same frequency band. This is an important characteristic, especially in discussions about sharing studies with IMT services in the UHF Band.

In Brazil, television broadcasting services are allocated by both VHF and UHF Bands, as defined by Anatel technical rules [37]. Specifically, digital terrestrial television broadcasting occupies the High VHF Band and the UHF Band, as detailed in Table 3.2. Like most of the countries in Region 2, Brazil uses 6 MHz of bandwidth for each channel. So, there are currently 44 available channels in the allocated frequency band for DTT Services in Brazil.

Table 3.2: Frequency Allocation for DTT Services in Brazil.

	Frequency Band	**Channels**
High VHF	174 – 216 MHz	7 – 13
UHF	470 – 608 MHz	14 – 36
	614 – 698 MHz	38 – 51
TOTAL	**264 MHz**	**44**

Besides there is currently available 264 MHz for the introduction of DTT services, the implementation in Brazil started with 108 MHz more from the 700 MHz band (698 – 806 MHz, channels 52 to 69). In 2013, based on established public policies by the Ministry of Communications [38], this sub-band was allocated by Anatel for the introduction of forth generation mobile service [39]. Next section contains more information about how DTT services were implemented in Brazil.

3.2 SPECTRUM CHALLENGES

The second-generation DTT broadcasting transmission systems are meant as systems offering higher bit rate capacity per Hz and better power efficiency in comparison to the systems described in Recommendation ITU-R BT.1306 and there is no general requirement for backward compatibility with first-generation systems [3]. So, transitioning from first to second-generation DTT systems will require spectrum availabil-

[11] Agenda item 8 of the World Radiocommunication Conference (WRC-23): "to consider and take appropriate action on requests from administrations to delete their country footnotes or to have their country name deleted from footnotes, if no longer required, taking into account Resolution 26 (Rev.WRC-19);".

ity.

Nonetheless, the availability of spectrum resources for DTT Services is declining worldwide, especially in the UHF Band. The 700 MHz band is already globally harmonized for the deployment of IMT Services and the 600 MHz band is also being considered in many countries for services rather than DTT. Furthermore, there is an intense debate for the 2023 ITU-R World Radiocommunication Conference over the full review of the frequency band 470-694 MHz in ITU Region 1 [40], which includes Europe, Africa, the northern part of Asia, and part of the Middle East.

The movement to reallocate spectrum resources to IMT services started in 2007. In the ITU-R WRC 2007, IMT services were identified to use the 800 MHz Band (790-862MHz) in Region 1 and Region 3 and the 700 MHz Band (698-806 MHz) in Region 2 [41]. At that time, Brazil included a footnote to have a different category of service in the 700 MHz band to preserve the usage of TV services in the band[12]. This footnote was further removed in WRC 2015 [42], when public policies had been established in Brazil to repurpose the band for 4G deployment (more information about the process is described in the next section). In the meantime, in ITU-R WRC 2012, another part of the UHF Band, the 700 MHz (694-790 MHz) was identified for IMT in Region 1 [43].

The WRC 2015 included a specific item for IMT identification in the remaining UHF Band (470-694/698 MHz). As a result of this conference, Regions 2 a 3 decided to not modify the table of frequency allocations but identify as a special basis via footnote the IMT identification of the 600 MHz in some countries[13]. Some of these countries also identified the 500 MHz (470 - 608/610 MHz) for IMT. This identification, however, was made in a condition to not cause harmful interference to, or claim protection from, the broadcasting service of neighboring countries.

The negotiations held in WRC 2015 concluded by re-discussing the identification of the role UHF Band in Region 1 for IMT in the WRC 2023. So, in the WRC 2019, it was included agenda item 1.5 [14] to review the spectrum use and spectrum needs of existing services in the frequency band 470-960 MHz in Region 1 [44]. Despite this agenda item being just for discussion between countries in Region 1, a debate is being held amongst Region 2 countries within the Permanent Consultative Committee II (PCC II) of the Inter-American Telecommunication Commission (CITEL). The regional agreement is that any changes made to the Radio Regulations under WRC-2023 agenda item 1.5 must not impact the existing allocations and identifications for Region 2, nor subject Region 2 to any changed procedural or regulatory provisions. However, even with a clear position, discussions on WRC-2023 to include the revision of the UHF Band in Region 2 on future WRCs are not discarded.

[12] Footnote 5.313B - Different category of service: in Brazil, the allocation of the band 698-806 MHz to the mobile service is on a secondary basis (see No. 5.32). (WRC-07).

[13] Bahamas, Barbados, Belize, Canada, Colombia, the United States and Mexico from Region 2 (see Footnote 5.308A in [42]) and Micronesia, the Solomon Islands, Tuvalu, Vanuatu, Bangladesh, Maldives, and New Zealand from Region 3 (see Footnote 5.296A in [42]).

[14] Agenda item 1.5 - to review the spectrum use and spectrum needs of existing services in the frequency band 470-960 MHz in Region 1 and consider possible regulatory actions in the frequency band 470-694 MHz in Region 1 on the basis of the review, in accordance with Resolution 235 (WRC-15)

3.3 DTT IMPLEMENTATION IN BRAZIL

DTT started to be implemented in Brazil in December 2007, in the city of São Paulo. Before this, a huge process was implemented to test the various available DTT Systems, conducted by the Brazilian Research and Development Center in Telecommunications [45]. The whole process resulted in the adoption, by means of the Decree No. 5820/2006 [46], of the ISDB-T digital television standard (Recommendation ITU-R BT.1306 System C) as a base for the terrestrial transmission [1], [47]. The video coding adopted was the ITU-T Recommendation H.264 (MPEG-4/AVC) and the data coding was an innovative system harmonizing international Application Programme Interfaces – APIs with local middleware development, the GINGA. These features together should facilitate the implementation of high-definition digital transmission and standard-definition digital transmission; simultaneous digital transmission for fixed, mobile, and portable reception; and, interactivity. Considering these technological innovations proposed by Brazil, the new Japanese-Brazilian system was further called ISDB-Tb.

In principle, the transition to digital television in Brazil was expected to be completed in 2016. However, considering the high diversity of economic distribution and different stages of DTT implementation in Brazilian territory, the deadline for the analog switch-off was reviewed successively. First, the Ministry of Communications, after discussions with Anatel and experts of the broadcasting sector, established in 2014 a new switch-off plan, starting in 2015 and gradually being implemented until November 2018, instead of a "one shot" method, as planned before [47]. Secondly, considering the lessons learned from the implementation of the analog switch-off in the first cities that underwent that process, the schedule was further revised, in order to complete the process from 2016 to 2019 in all state capitals, metropolitan areas, and other areas where the analog switch-off was required to clear the 698 - 806 MHz band (the 700 MHz band) and up to 2023 in the rest of the country [47].

The clearance of the 700 MHz was an important milestone for the deployment of DTT services in Brazil. It may sound counter-intuitive, but losing a considerable amount of frequency band (108 MHz) was a key factor for the success of the analog switch-off project. The process began in 2013 when public policies were established in Brazil to meet the objectives of the National Broadband Plan and also to expand DTT reception in Brazil [38]. The directives for Anatel were very clear:

- To initiate studies for the assignment of the 700 MHz band for mobile services;
- To evaluate the viability of re-plan analog and digital TV channels that occupied the band;
- To guarantee the protection of the broadcasting services from possible harmful interference from mobile services in adjacent bands;
- To guarantee the same coverage between analog and digital television;
- To consider regional and international harmonization, in order to adopt a frequency arrangement that favors coexistence in border regions and scale gain.

Besides policies were expressly set up to clear 700 MHz Band, the access and protection of TV broadcasting services became priority. Considering this scenario, Anatel allocated the 608 - 806 MHz band for mobile services, on a primary basis [39]. Further, it was included a number of obligations for the mobile network operators on the 700 MHz band auction [48] in order to facilitate the digital switchover and the implementation of the digital dividend [47]. The obligations included:

- Distribution of a DTT readiness kit (STB, antenna, and accessories) for low-income families;
- Provision of mass-media campaigns;
- Provision of a website and a 24/7 toll-free call-center to support the affected population in the process;
- Execution of household surveys to verify the fulfillment of the analog switch-off condition;
- Repack of TV channels to release the 700 MHz band;
- Mitigation of possible interference from IMT into TV receiving systems [47].

So, a unique worldwide policy was initiated in Brazil after the 700 MHz auction: the development of parallel and dependent actions to introduce fourth generation mobile services and promote the analog TV switch-off. To ensure the implementation of all changes necessary for releasing the 700 MHz band, the auction included the obligation that winning bidders defrays the migration of TV channels down to band between TV channels 7 to 51. It was established that 36% of the amount collected would be used to reimburse all broadcasters that were operating in 700 MHz band. Four companies won spectrum licenses in the auction, raising about R$ 10 billion Brazilian reais in revenue (about $3,8 billion American dollars at that time) [47].

Furthermore, a specific entity was established by the auction winners to manage the amount raised by the auction for restacking digital TV services, the GIRED (*Grupo de Implantação do Processo de Redistribuição e Digitalização de Canais de TV e RTV* - Redistribution and Digitizalition of TV Main and Relay Channels Implementation Group). The GIRED also carried out actions to ensure the completion of the switchover to digital TV and apply methodologies to avoid interference between the IMT services and broadcasting services in the UHF band.

The regulatory framework adopted in Brazil has brought impressive results. The first phase of the transition from analog to digital terrestrial television broadcasting in Brazil was successfully completed in January 2019. It has included 1,379 municipalities (129.6 million inhabitants, 62.6% of the Brazilian population), including all state capitals, metropolitan areas, and other areas where the analog switch-off was required to clear the 700 MHz band. The second phase includes the rest of the country (77.3 million inhabitants, 37.4% of the population, distributed in 4,191 municipalities) is expected to be concluded in December 2023 [47], [49]. Figure 3.2 shows the DTT implementation timeline in Brazil with the major milestones.

The next section contains a quantitative assessment of the VHF and UHF Bands, based on the current DTT channel distribution in Brazil.

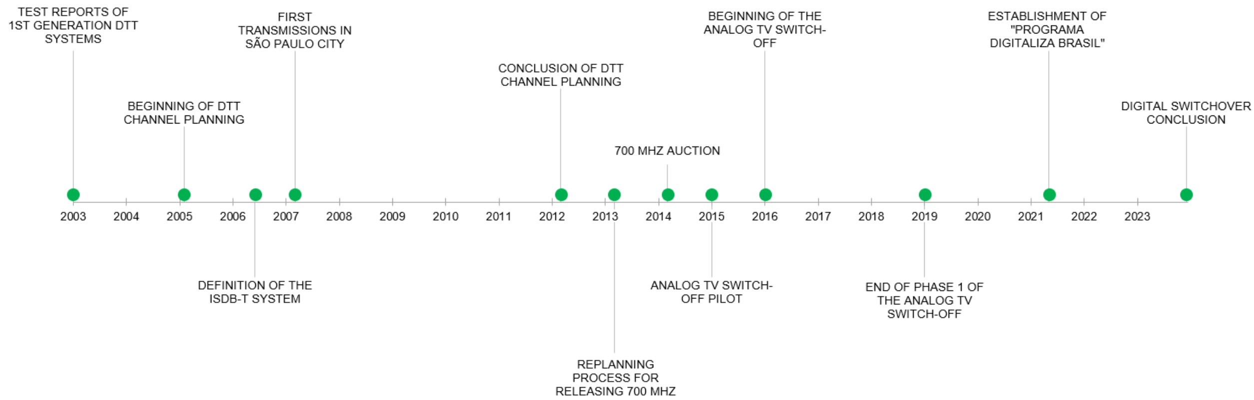

Figure 3.2: Timeline of DTT implementation in Brazil.

3.4 SPECTRUM USAGE SIMULATIONS

To evaluate spectrum usage of TV services in the Brazilian territory, simulations were made to estimate the coverage of all operating channels. The applied methodology is described in the following subsections. Figure 3.3 contains a summary of the applied methodology. First, it was established a connection to the Anatel database to acquire the technical characteristics of all TV stations. Then, some assumptions were made to estimate the operating stations and also to compute ideal antenna patterns, based on the class of operation of each station. These assumptions had to be made because there is a lack of information on Anatel database about the operating TV stations. The web-based spectrum management software, Mosaico (based in Spectrum-E), has been provided through the courtesy of Anatel for the coverage predictions, and Python libraries with data science tools were used for developing scripts for post-processing the results. Finally, a Bussines Intelligence (BI) software was used to visualize and analyze the results.

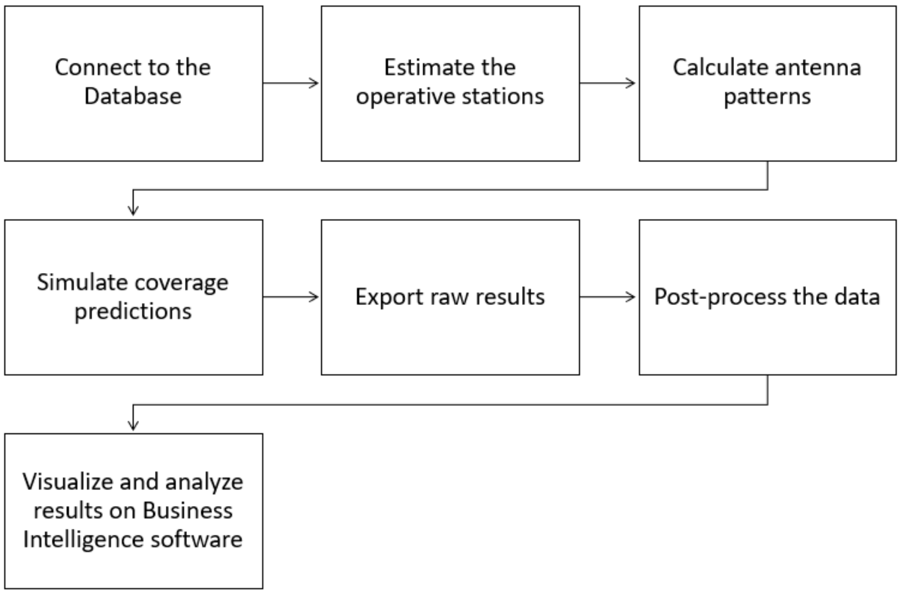

Figure 3.3: Adopted methodology to evaluate the spectrum usage of the UHF and VHF Bands.

3.4.1 Database Analysis

Since the introduction of DTT services in Brazil, 19,721 digital channels were planned and included in the Brazilian Master Register for Digital Television Channels, a database for broadcasting channels managed by the National Agency of Telecommunications (Anatel) [50]. Figure 3.4 shows the current distribution of DTT channels in Brazil over the VHF and UHF allocated bands [15] [16].

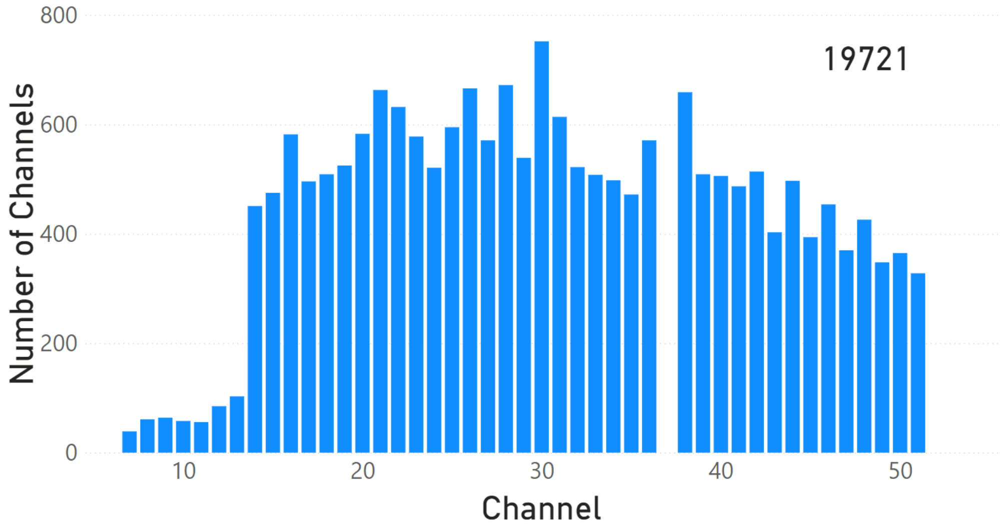

Figure 3.4: Distribution of Digital TV Channels in Brazil.

Determining the number of operating stations in Brazil is challenging. National policies were established in the past to allow broadcasters to start transmissions even before getting a formal license by Anatel [51]. It has promoted a fast process for installing new DTT channels because broadcasters were able to provide services by only paying radio frequency usage fees and just starting the required application for obtaining the license. However, many broadcasters had started licensing process and did not install transmission sites, or, on the opposite - they had installed transmission sites and did not finalize the licensing process. The result is that only 43% of authorized digital stations are currently licensed. However, this number does not reflect the real number of operating stations in Brazil.

To achieve better accuracy of coverage simulations, it is primordial that the database of DTT stations reflects as precisely as possible the currently operating ones. Considering that a database of operational DTT stations is unavailable, as mentioned before, some assumptions had to be made to retrieve data from Anatel's database source. First, it was considered that all registers containing at least a valid DTT authorization act issued by the Ministry of Communications, and an assigned radio frequency act published by Anatel, configure an operational station. These documents were considered for selecting stations due that without both of them Brazilian broadcasters are not able to start transmissions. The obtained result is that 12,711 DTT channels (about 64,45% of the total number of planned channels) are estimated to be operational in Brazil. Figure 3.5 and Figure 3.6 show the distribution of the estimated operative DTT Channels in Brazil and comparative percentage, respectively:

[15] All the evaluation of the current DTT distribution of this Chapter is based on the data acquired in May 2022 from the Brazilian Master Register for Digital Television Channels [50].

[16] The UHF Channel 37 is intentionally unused for television broadcasting, as its frequency range is allocated for radio astronomy applications (see Table 3.1).

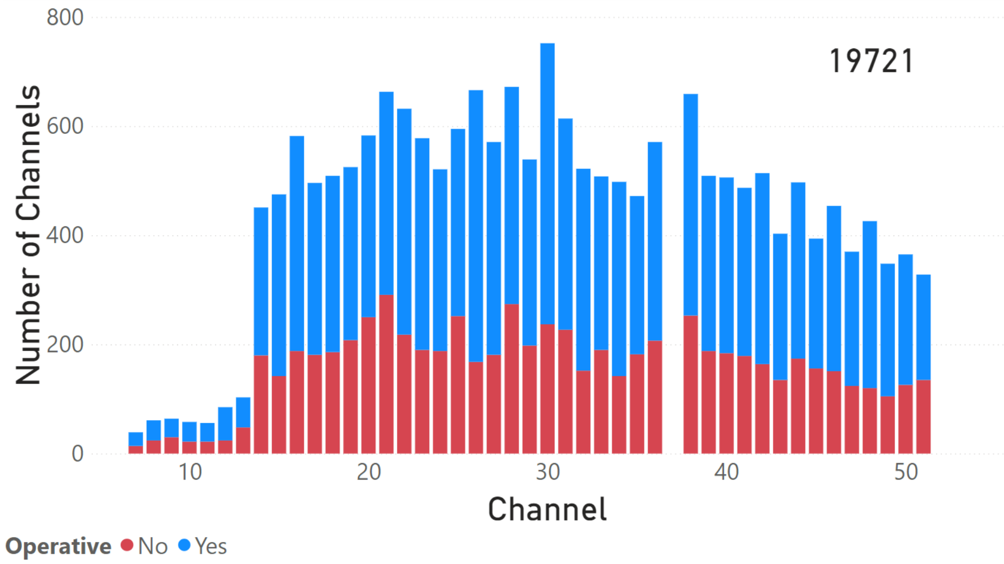

Figure 3.5: Distribution of Operative Digital TV Channels in Brazil.

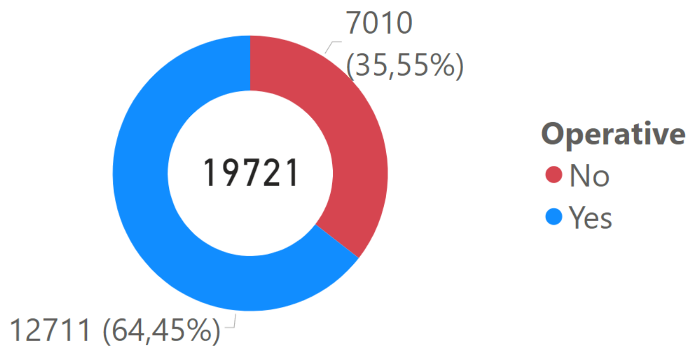

Figure 3.6: Percentage of Operative Digital TV Channels in Brazil.

Secondly, as few of the total DTT Channels are currently licensed, the availability of technical data containing the necessary inputs for simulating the estimated coverage is scarce. It occurs because only by completing the registration of the station's parameters (antenna height, radiated diagram, effective radiated power - ERP, etc) the complete technical data can be retrieved from Anatel's database. So, once again, some approximations were considered. For simulating all predicted coverage, an algorithm from Mosaico software that simulates an ideal station was applied. This algorithm calculates the best antenna diagram and ERP for a station in a determined location. It takes the maximum protected contour, determined by Anatel Technical Regulation for each station class [52], and the terrain data to perform calculations. The result is that for each channel it is created an ideal station that could reach the maximum protected contour in each direction, from 0 to 360 degrees with a 1-degree step. Figure 3.7 and Figure 3.8 show the calculated antenna pattern in different types of terrain profiles. The protected contours are plotted in those figures using Recommendation ITU-R P.1546-5 [53], which is the reference prediction method for determining the maximum protected area of a DTT station, as defined by Anatel [52].

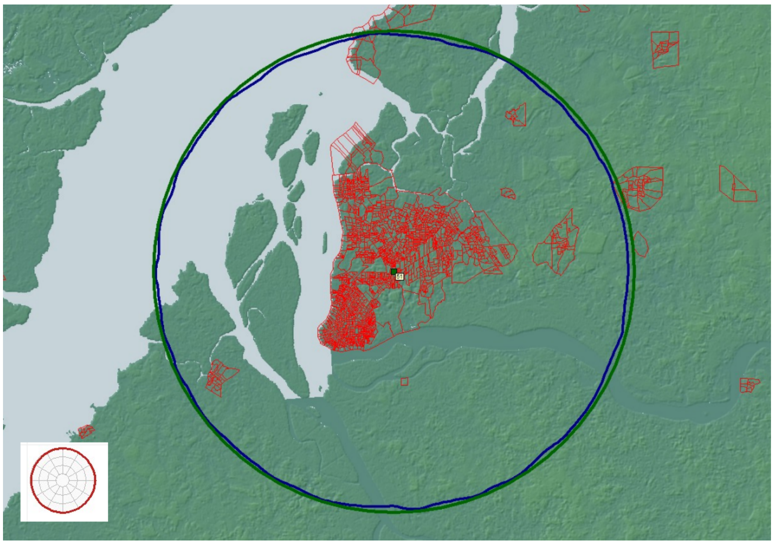

Figure 3.7: Example of a computed antenna pattern in flat terrain.

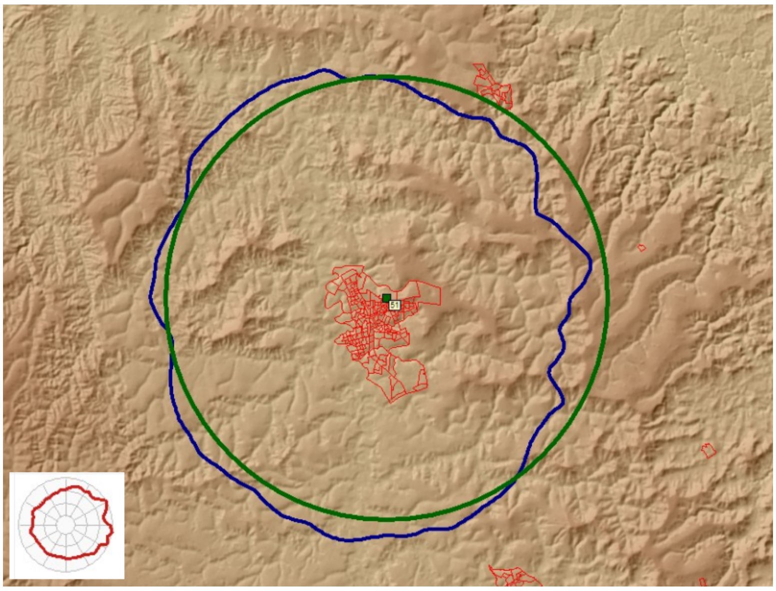

Figure 3.8: Example of a computed antenna pattern in rough terrain.

3.4.2 Coverage Predictions

The estimation of the coverage of DTT stations involves frequency management aspects and databases with equipment-related information; accurate knowledge of terrain data where the system is to be deployed; and detailed information on the distribution of the population inside the service area [54]. In addition, the nature of the propagation model in use will be of paramount importance for realistic predictions and efficient and precise network dimensioning [54].

As mentioned before, the web-based spectrum management software, Mosaico, was used to estimate the coverage of all 12,711 operating DTT channels in Brazil. The software makes available various propagation models for DTT coverage estimation. For the purpose of the present simulations, the Recommendation ITU-R P.1812-5 was chosen. This ITU-R Recommendation provides a deeper consideration of potential propagation phenomena and it will provide more accurate path loss results in some specific links. In consequence, ITU-R states that P.1812 should be used for the detailed evaluation of point-to-area signal levels [54], [55].

Furthermore, ITU-R P.1812 is a modern recommendation (last updated in August 2019) and the ease of reproducibility of results and implementation transparency of the ITU-R P.1812 model can allow for a better degree of standardization of a propagation prediction method for point-to-area terrestrial services in the VHF and UHF frequency bands [56]. Parameters of Table 3.3 were used to achieve a balance between speed and accuracy of the simulations.

Table 3.3: ITU-R P.1812 simulation parameters.

Parameter	**Value**
Receiving Height	10 m
Calculated Distance	100 km
Percentage of time	50 %
Percentage of locations	50 %
Subpath	Delta Bullington
Clutter Resolution	Default
Terminal Clutter Losses	Not considered
Profile Sampling	1,000 points

Finally, to determine the service area it was considered the minimum field strength defined by Anatel on its technical rule: 51 $dB\mu V/m$ for channels in the UHF band and 43 $dB\mu V/m$ for channels in the VHF Band (see Table 1 in [52]). After establishing all the required parameters, simulations were made to predict the service area of all considered DTT stations. Figure 3.9 illustrates the predicted coverage of channel 20 in a part of Brazil.

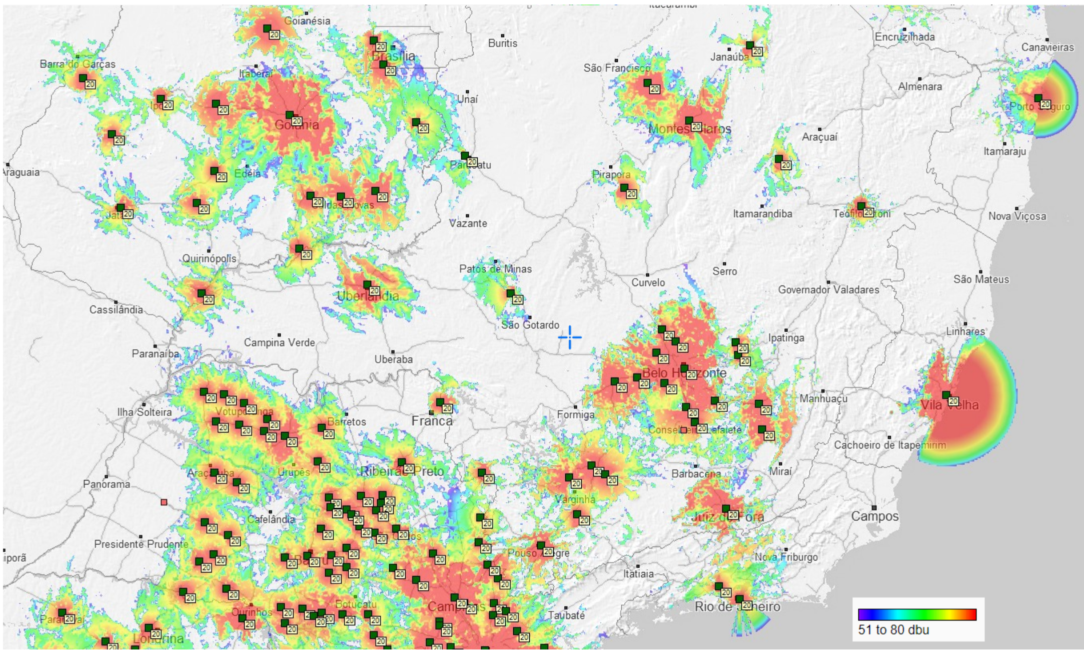

Figure 3.9: Example of predicted coverage for DTT Channel 20.

Brazil has a heterogeneous population distribution. So, to evaluate coverage analysis in terms of population, the service area was calculated considering the percentage of coverage on each sector of the census geographic boundary shapefiles provided by the Brazilian Institute of Geography and Statistics [17]. A municipality was considered covered by a DTT station when at least 90% of its urban population is inside the predicted coverage area. A high coverage percentage was chosen because the predictions are overestimated by the assumptions made to compute ideal antenna patterns and also because the used software automatically reduces terrain resolution on networks with a large number of entries.

Simulations were made considering the current DTT channel distribution. However, until December 2023, analog television will remain operative, as mentioned before. Applying the same estimation methodology done for DTT channels, it is estimated that 9,230 analog TV stations are still operative. Most of these stations are allocated in the VHF band as shown in Figure 3.10.

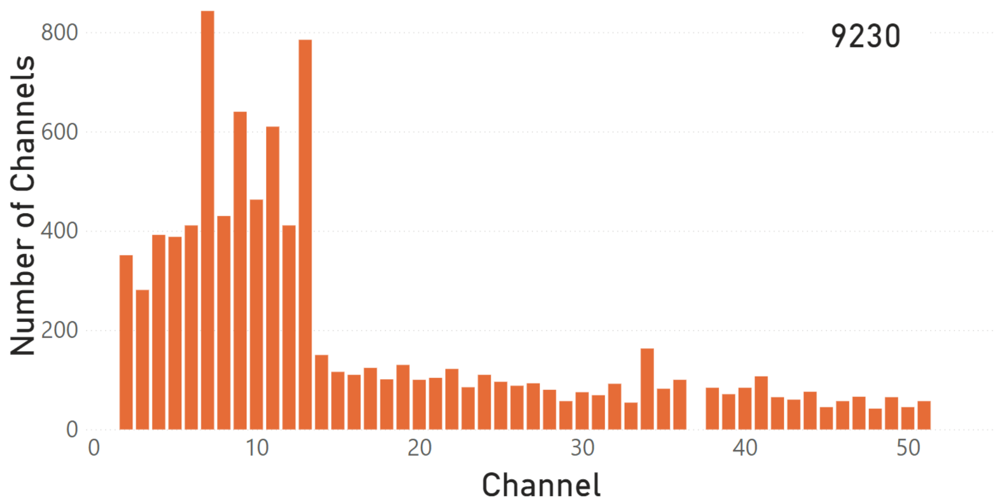

Figure 3.10: Distribution of Analog TV Channels in Brazil.

The same methodology for predicting DTT coverage was also applied to simulate the coverage of those estimated operating analog TV stations. The considered minimum field strength, however, differs from digital to analog TV, as stated in Anatel's technical rules. It was used 58 $dB\mu V/m$ for channels 2 to 6, 64 $dB\mu V/m$ for channels 7 to 13, and 70 $dB\mu V/m$ for channels in the UHF Band (see Table 1 in (52)).

3.4.3 Results

A geodatabase of all coverage simulations was created which could allow the development of concrete data analysis to investigate how DTT services are currently using spectrum resources. Simulations were organized in layers by channel and by technology (analog and digital TV) resulting in 49 layers for analog TV coverage simulations (channels 2 to 51) and 44 layers for DTT coverage simulations (channels 7 to 51). Using Python post-processing data tools it was possible to estimate the number of receiving channels in each Brazilian municipality.

An initial assessment is to evaluate how many municipalities receive at least one analog or digital TV

[17] Based on 2010 census, available at <https://www.ibge.gov.br/geociencias/organizacao-do-territorio/malhas-territoriais/26565-malhas-de-setores-censitarios-divisoes-intramunicipais.html?=&t=downloads>

channel. Figure 3.11 shows the number of municipalities covered by analog and digital TV Channels.

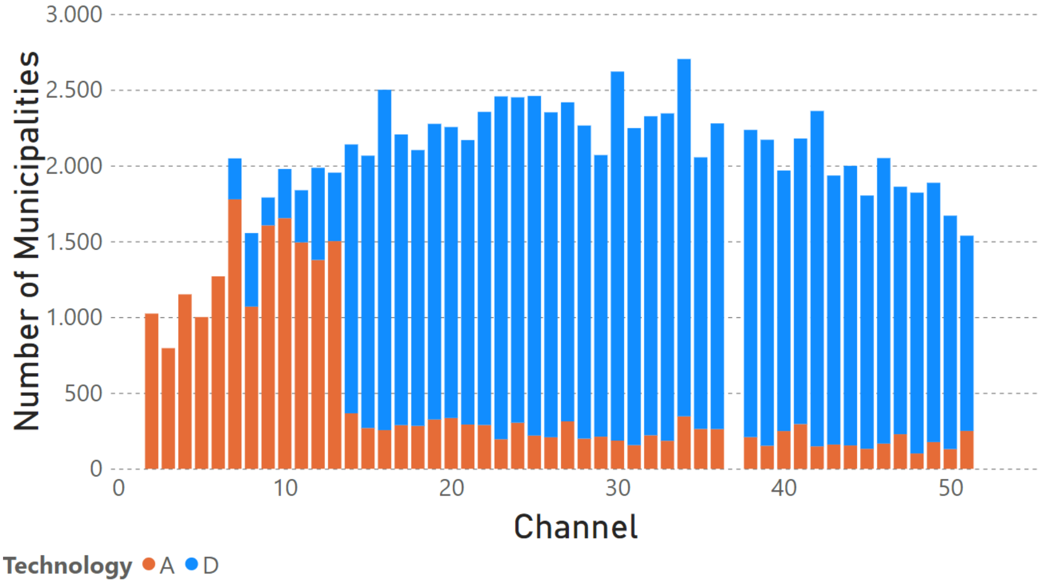

Figure 3.11: Number of municipalities covered by Analog TV (A) and Digital TV (D) per channel in Brazil.

The numerical results of the coverage simulations of digital and analog operating stations are summarized in Tables 3.4 and 3.5. One table is the opposite of the other: Table 3.4 contains the number of municipalities covered by at least one TV channel (digital, analog, or any of them), and Table 3.5 has the number of municipalities with no TV coverage (digital, analog, or none of them). Results were also classified by frequency band:

- VHF A: Channels 2 - 6 (55 - 72 MHz ; 76 - 88 MHz);
- VHF B: Channels 7 - 13 (174 - 216 MHz);
- UHF A: Channels 14 - 36 (470 - 608 MHz);
- UHF B: Channels 38 - 51 (614 - 698 MHz).

A straightforward finding that can be extracted from data analysis is that digital television has huge penetration in Brazil. As shown in Table 3.4 nearly 96% of the Brazilian municipalities can receive at least one DTT channel. Until the end of the analog switch-off, penetration may reach almost 100%, as many DTT channels are not yet operating as shown in Figure 3.5. On the other hand, analog TV is still covering about 75% of the municipalities, which shows the importance of well-defined policies for switching-off analog television.

Besides DTT penetration is undoubtedly remarkable in Brazil, but the diversity of channels is not so high. Approximately half of the Brazilian municipalities (2,767) have less than 11 DTT channels, and about 13% have no more than 2, as shown in Figure 3.12.

Geographically, the Brazilian States from the North, Midwest, and Northwest regions are the ones with a fewer average of received DTT channels. Figure 3.13 shows the average of received DTT channels per Brazilian State and Figure 3.14 contains a map view of the results.

Table 3.4: Number of municipalities covered per frequency band.

Frequency Band	**Municipalities with at least one digital channel**	**Municipalities with at least one analog channel**	**Municipalities with at least one channel**
All Bands	5,362 (96.27%)	4,209 (75.57%)	5,418 (97.32%)
VHF A Channels 2 - 6	0 (0.00%)	2,691 (48.31%)	2,691 (48.31%)
VHF B Channels 7 - 13	1,134 (20.36%)	3,787 (67.99%)	4,051 (72.73%)
UHF A Channels 14 - 36	5,262 (94.47%)	2,476 (44.45%)	5,292 (95.01%)
UHF B Channels 38 - 51	4,550 (81.69%)	1,482 (26.61%)	4,662 (83.70%)

Table 3.5: Number of municipalities with no reception per frequency band.

Frequency Band	**Municipalities with no digital channels**	**Municipalities with no analog channels**	**Municipalities with no channels**
All Bands	208 (3.73%)	1,361 (24.43%)	149 (2.68%)
VHF A Channels 2 - 6	5,570 (100%)	2,879 (51.69%)	2,879 (51.69%)
VHF B Channels 7 - 13	4,436 (79.64%)	1,783 (32.01%)	1,519 (27.27%)
UHF A Channels 14 - 36	308 (5.53%)	3,094 (55.55%)	278 (4.99%)
UHF B Channels 38 - 51	1,020 (18.31%)	4,088 (72.93%)	908 (16.03%)

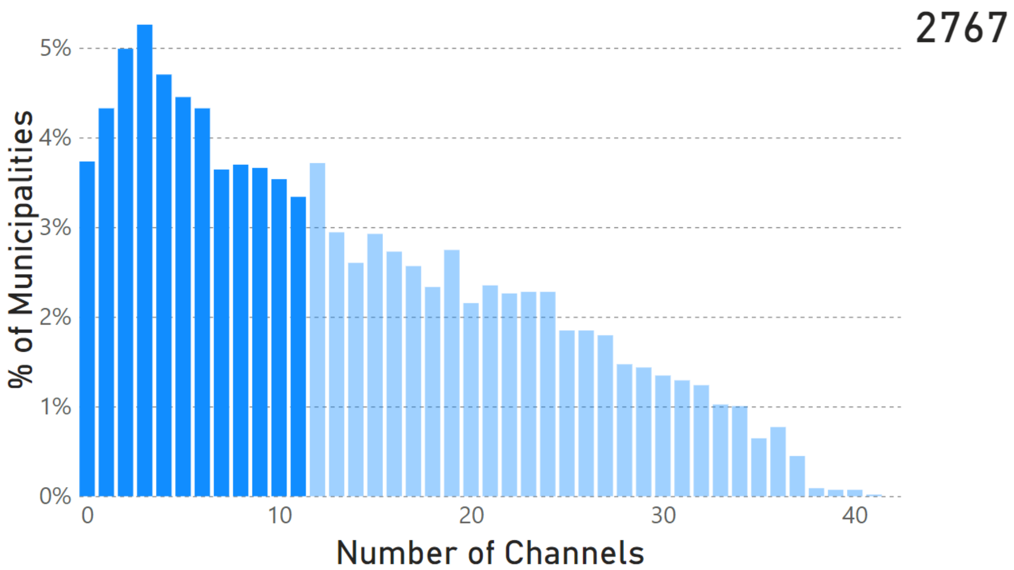

Figure 3.12: Percentage of municipalities covered per number of channels in each municipality in Brazil.

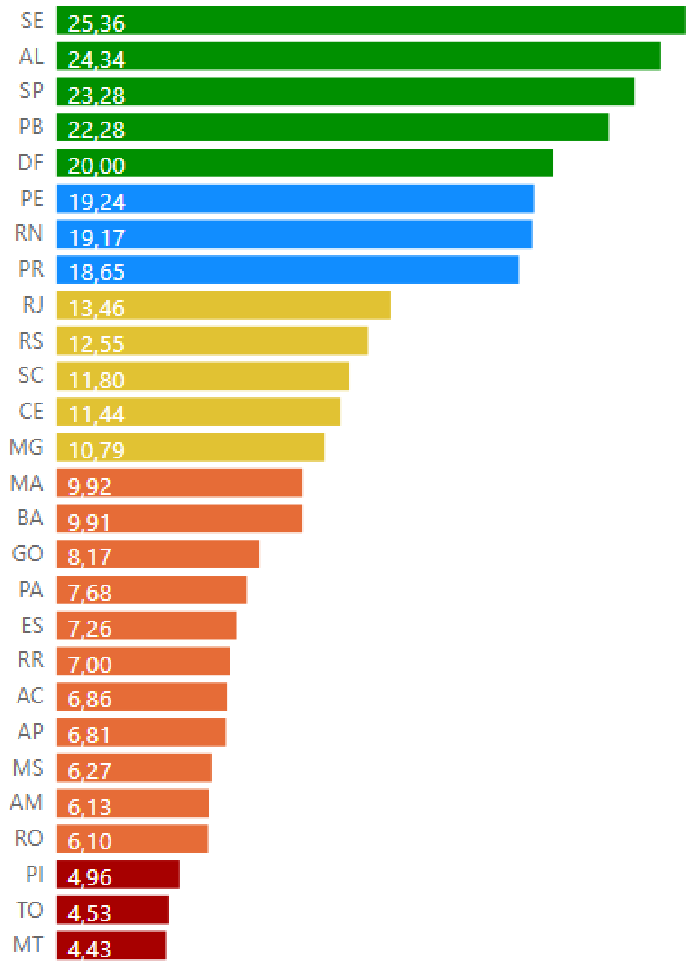

Figure 3.13: Average of received DTT channels per Brazilian State: red (less than 5), orange (from 5 to 10), yellow (from 10 to 15), blue (from 15 to 20), and green (more than 20 channels).

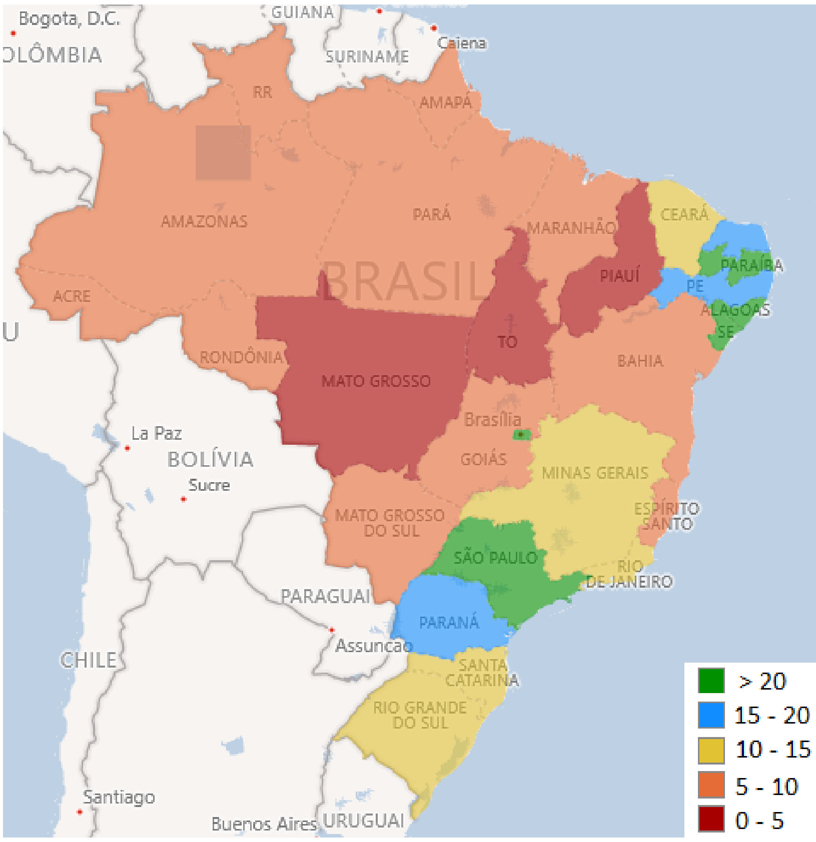

Figure 3.14: Map view - Average of received DTT channels per Brazilian States: red (less than 5), orange (from 5 to 10), yellow (from 10 to 15), blue (from 15 to 20), and green (more than 20 channels).

Table 3.4 and Figure 3.11 also show that analog and digital TV occupy spectrum sub-bands distinctively. Analog TV is concentrated on the VHF Band and DTT on the UHF Band. Historically, analog television was first implemented in Brazil in the VHF Band, which partially explains why UHF Band was preferable for DTT deployment. Furthermore, the susceptibility of some configurations of DTT systems to impulsive noise, more relevant in the lower frequencies, was found by the tests carried out in Brazil in 2001 for defining the Brazilian first-generation DTT system [45].

DTT coverage in Brazil is concentrated in the UHF band. In particular, the UHF A Band (Channels 14 - 36, 470 - 608 MHz) has a high density of received channels. Figure 3.15 contains the distribution of the number of received channels in the UHF A Band. It shows that considering the number of received channels per municipality in the UHF A Band, about 50% have no more than 7 DTT channels. In other words, in half of the municipalities in Brazil, at least about 70% of the total amount of spectrum availability of the UHF A band (16 from 23 channels) is currently not being used.

Almost the same behavior occurs in the UHF B band (Channels 38 - 51, 614 - 698 MHz). Despite in about 82% of the municipalities this band being used by at least one DTT channel, about 48% of the municipalities have no more than 3 channels. So, at least 78% of the total amount of spectrum availability of the UHF B band (11 from 14 channels) is not being used in more than half of the municipalities in Brazil. Figure 3.16 shows the distribution of the number of received channels in the UHF B Band.

In the current chapter, we showed how spectrum is currently being used by television services in Brazil,

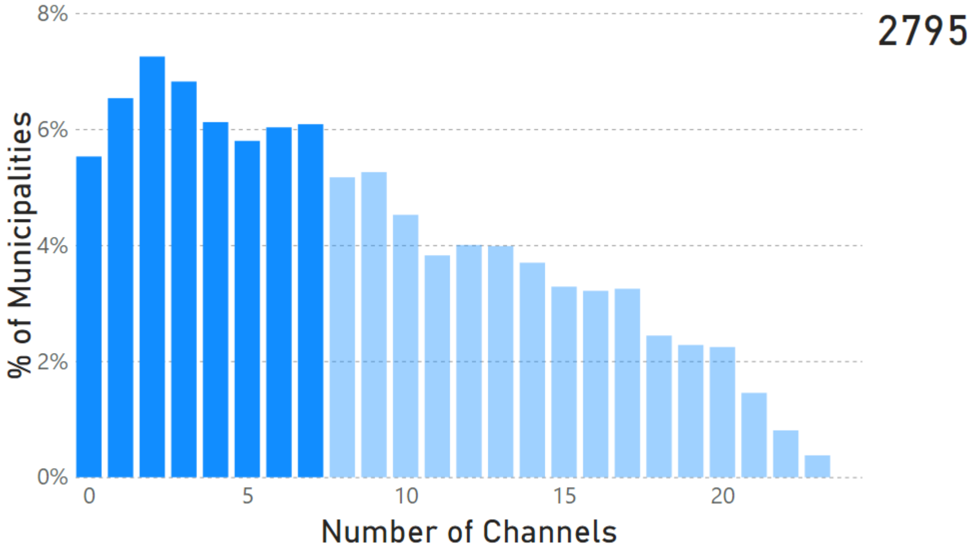

Figure 3.15: Percentage of municipalities covered per number of channels in the UHF A Band.

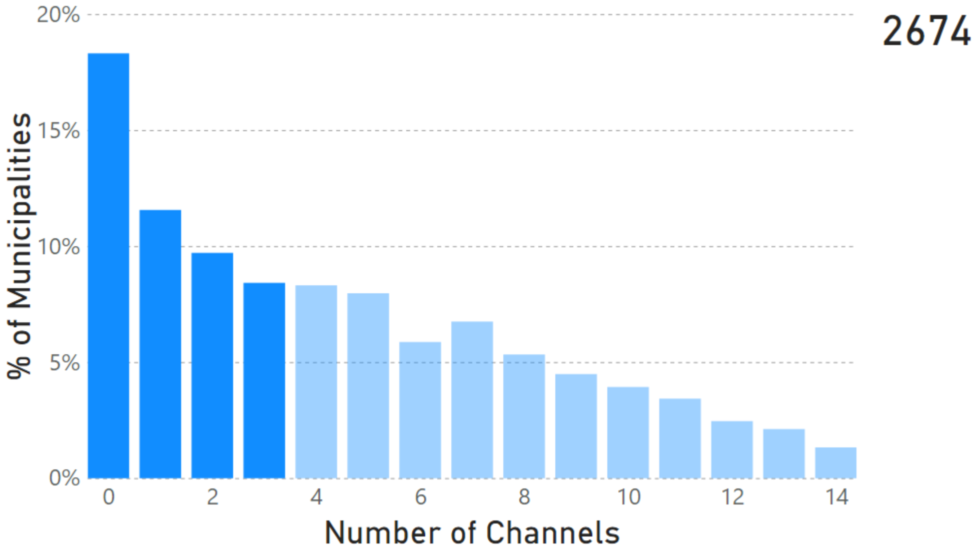

Figure 3.16: Percentage of municipalities covered per number of channels in the UHF B Band.

based on coverage simulations of all TV stations that are estimated to be in operation. However, spectrum usage is dynamic and changes practically every day. In Brazil, clearly defined spectrum policies directly impact television services for the following years. Furthermore, new technologies will certainly drive new possibilities for spectrum usage. The next chapter describes envisaged spectrum policies that will affect the use of VHF and UHF in the short and mid-term and, in consequence, can affect the provision of DTT in Brazil.

4 FUTURE SPECTRUM AVAILABILITY IN THE VHF AND UHF BANDS

The implementation of second-generation DTT systems in Brazil is planned to begin in 2025. Until this milestone, thousands of analog TV stations are expected to be switched off, which directly impacts the spectrum usage of DTT services. On the other hand, there are established public policies for the expansion of existing DTT networks that will impact the distribution of digital TV channels. This chapter analyses the spectrum availability after the analog TV switch-off and discusses possible uses of the VHF and UHF bands. It also includes some technical and regulatory proposals for the deployment of second-generation DTT systems in Brazil.

4.1 CHANNEL DISTRIBUTION AFTER THE ANALOG TV SWITCH-OFF

As detailed in Chapter 3, the television analog switch-off is expected to be completed in Brazil by the end of 2023. So, it is estimated that all 9,230 analog stations (see Figure 3.10) will soon no longer be operative after that period, impacting 4,210 municipalities (75.58%) that receive at least one analog channel, as shown in Table 3.4. A direct impact of the analog switch-off is that spectrum usage of the VHF Band will suddenly decrease, considering that about 65% of analog TV channels are operating in this band, as shown in Figure 4.1. The impact o UHF Band usage will also be relevant - 3,225 analog channels in this band will also cease operations.

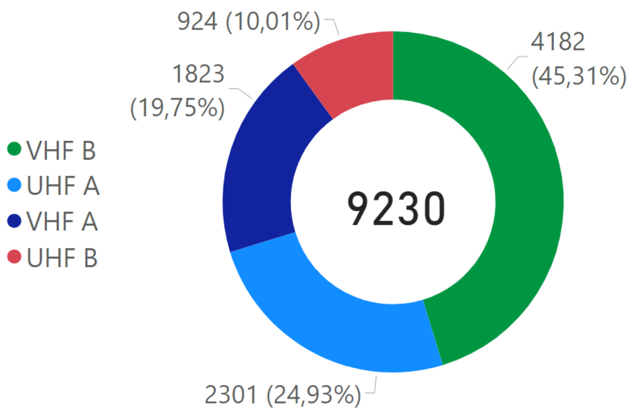

Figure 4.1: Number (Percentage) of operative analog TV channels per frequency band.

On the other hand, as shown in Figures 3.5 and 3.6, there is a huge number of planned DTT channels (7,010) that are not operative. From this total amount, analysis of the data obtained from the Ministry of Communications by means of the Brazilian “Right to Information Law" [57] indicates that 3,229 channels (46%) will not begin operation in the short or mid-term. These channels were reserved for long-term public policies that were not initiated or concluded (for educational and public broadcasting), or were planned for transitioning analog TV channels for digital operation, but were not used. The other 3,781 channels (54%) are mainly located in regions where simulcasting is still ongoing and clear public policies have already been defined.

Specifically for regions where simulcast is still ongoing, the Brazilian Ministry of Communications established in 2021 a government program to facilitate the transition for DTT [58]. The main objective of the program is to install complete shared DTT transmission sites in 1,638 small municipalities where only analog TV stations are operative. Besides transitioning current analog TV channels, the program also provides rules for expanding the variety of TV content for the population by adding two new DTT channels (up to 8 different TV programs) on each transmission site for public broadcasters. Funding for the program is provided by resources from the 700 MHz band auctioning process for 4$^{\text{th}}$ generation IMT Advanced Systems, which account for approximately R$ 850 million (US$ 160 million) specifically reserved as counterparts for the digital dividend [59].

A standardized Multichannel Transmission System (MTS) has been developed by the companies responsible for installing the channels to meet the objectives of the program by deploying low-power DTT transmissions (up to $50W$) on a shared infrastructure between different channels. The schematics of the MTS station is shown in Figure 4.2. It contains the broadcasting satellite link, that receives the DTT signals to be relayed, the transmitters, an Ethernet switch with a telemetry modem, the combiner, a transmission line, a tower, and an antenna. The aim of the developed transmission framework was to provide reduced deployment, energy, and maintenance cost [60].

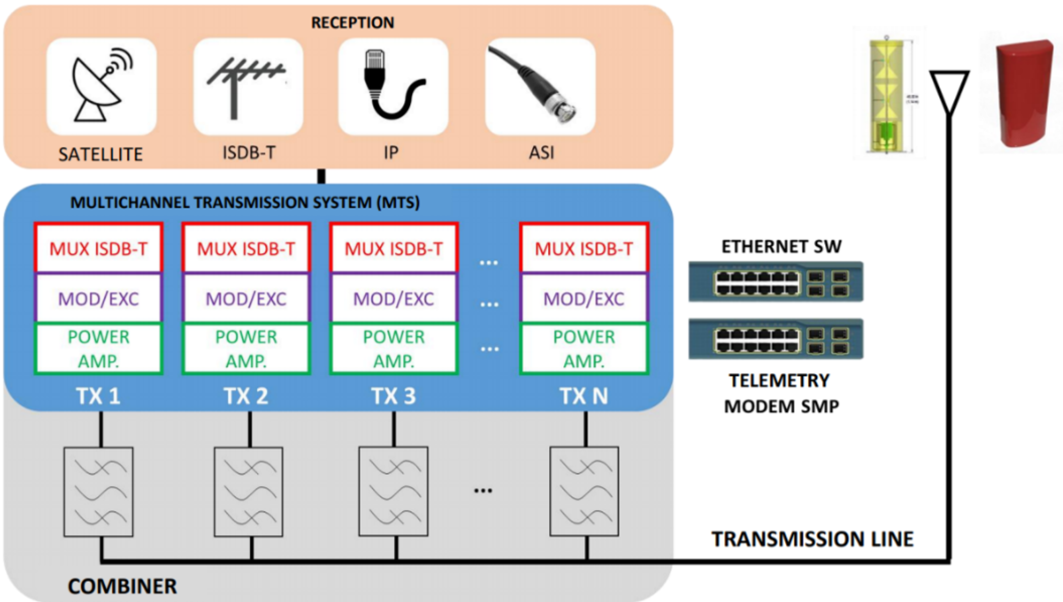

Figure 4.2: Multichannel Transmission System (MTS) schematic. Source: reproduced from [60].

To accomplish the task of implementing new DTT stations, a huge spectrum planning process for including new DTT channels has been carried out by Anatel. The analysis of Anatel's database from April 2021 to May 2022 has indicated that it was planned 4,661 channels in the 1,638 municipalities of the public program. The effective operation of the channels, however, depends on qualifying analog TV broadcasters and the municipalities, considering the requirements established in Chapter II of [58].

So, channels located in those 1,638 municipalities have a higher probability of starting operating, as public policies for funding transmission sites have already been established. Data analysis also indicates that some channels were included by request of broadcasters that wish to expand their existing DTT coverage. These channels were also considered to have a high probability to be licensed sooner and starting operating. Figure 4.3 summarizes the obtained results:

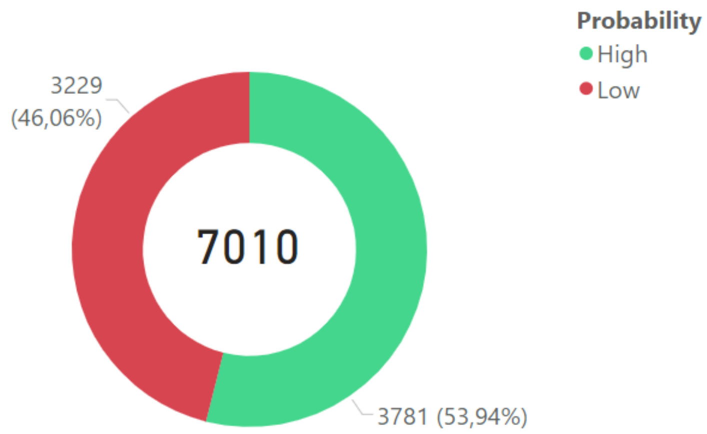

Figure 4.3: Number of DTT Channels that are not operative classified by probability to start operation in the short-term.

Lastly, the conclusion is that besides 9,230 analog channels will soon cease operations with the analog switch-off in Brazil, about 4 thousand new DTT channels are expected to start transmission in the short-term. Hence, DTT channel distribution in Brazil after the analog switch-off is expected to contain about 16,492 operative channels as illustrated in Figure 4.4.

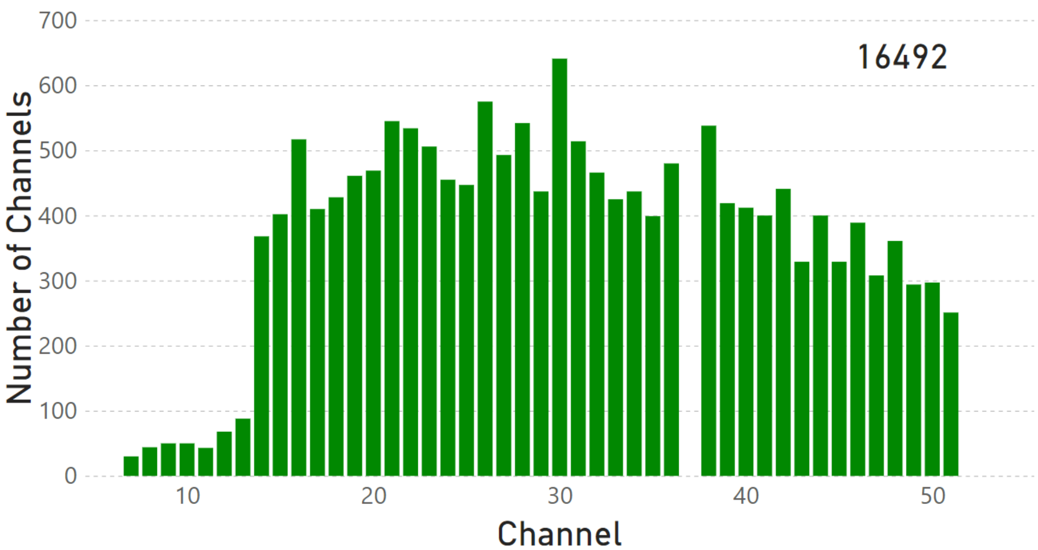

Figure 4.4: Expected distribution of Digital TV Channels in Brazil after the analog switch-off.

4.2 SIMULATIONS AND RESULTS

The analog switch-off will release huge portions of spectrum, especially in the VHF band, as mentioned in the last subsection. In Brazil, VHF A band is not used for DTT as defined in the technical regulation normative [52]. So, VHF channels 2 to 6 (54 - 72 MHz; 76 - 88 MHz) will be completely released from television services after 2023. In addition, currently, there are no defined public policies for broadcasting services in the band of channels 2 to 4 (54 - 72 MHz). This band is being only considered for the usage of TV White Spaces (TVWS) [61].

Public policies for the usage of channels 5 and 6 (79 - 88 MHz), however, have already been established in Brazil for FM broadcasting services by means of a presidential decree in 2013 [62]. The band has been firstly considered for implementing public policies to migrate AM Broadcasters to the FM Band where spectrum availability in the traditional FM band (88 to 108 MHz) is not sufficient to include new channels. Since then, Anatel is gradually planning the introduction of FM services in the band, considering the technical parameters established to guarantee the coexistence with analog TV stations that will remain in operation until the end of 2023, which were defined in [37] and [63]. Currently, Anatel has planned 192 channels [18] in the FM Extend Band (as the band is being mentioned in Brazil) and the first transmissions started in 2021 [19].

International regulation of the FM Extended Band has also been approved. Brazil has led proposals to harmonize the usage of the band in the Americas in the CITEL [64] and to define technical conditions on frequency coordination among MERCOSUR administrations [65]. Some countries in the Americas are also considering using the band for FM transmissions, including the U.S that have published in June 2022 a Notice of Proposed Rulemaking (NPR) regarding a proposal to allow certain channel 6 low-power television stations to continue to provide FM radio service as an ancillary or supplementary service under specified conditions [66].

SBTVD Forum studies are also not considering VHF A Band for the deployment of second-generation DTT Systems in Brazil. TV 3.0 over-the-air physical layer is to consider that it should, in principle, be deployed in the bands currently allocated for DTT in Brazil (High-Band VHF and UHF), using the 6 MHz channel raster and it should co-exist with adjacent ISDB-Tb channels for a long time without mutual interference [26]. Hence, only the VHF B and the UHF Band will remain available for DTT services. In the second phase of the project, where physical layer field and lab tests were performed with the proponent technologies, the documentation analysis showed that most of them fulfilled the requirements of using the frequency band of 174-216 MHz and 470-698 MHz [67], [68].

So, considering the expected DTT channel distribution in VHF B and UHF Bands, as shown in Figure 4.4, coverage simulations were computed to estimate the spectrum usage after the analog switch-off in Brazil. The same methodology and assumptions summarized in Figure 3.3 and described in Chapter 3 were adopted. Figure 4.5 (a) shows the number of municipalities covered by at least one DTT Channel after the analog switch-off compared to 4.5 (b) that contains the current coverage results that were analyzed in Chapter 3.

[18] Based on Anatel Database from November 2022

[19] <https://www.abert.org.br/web/notmenu/cerimonia-oficializa-uso-da-faixa-estendida-de-fm.html>

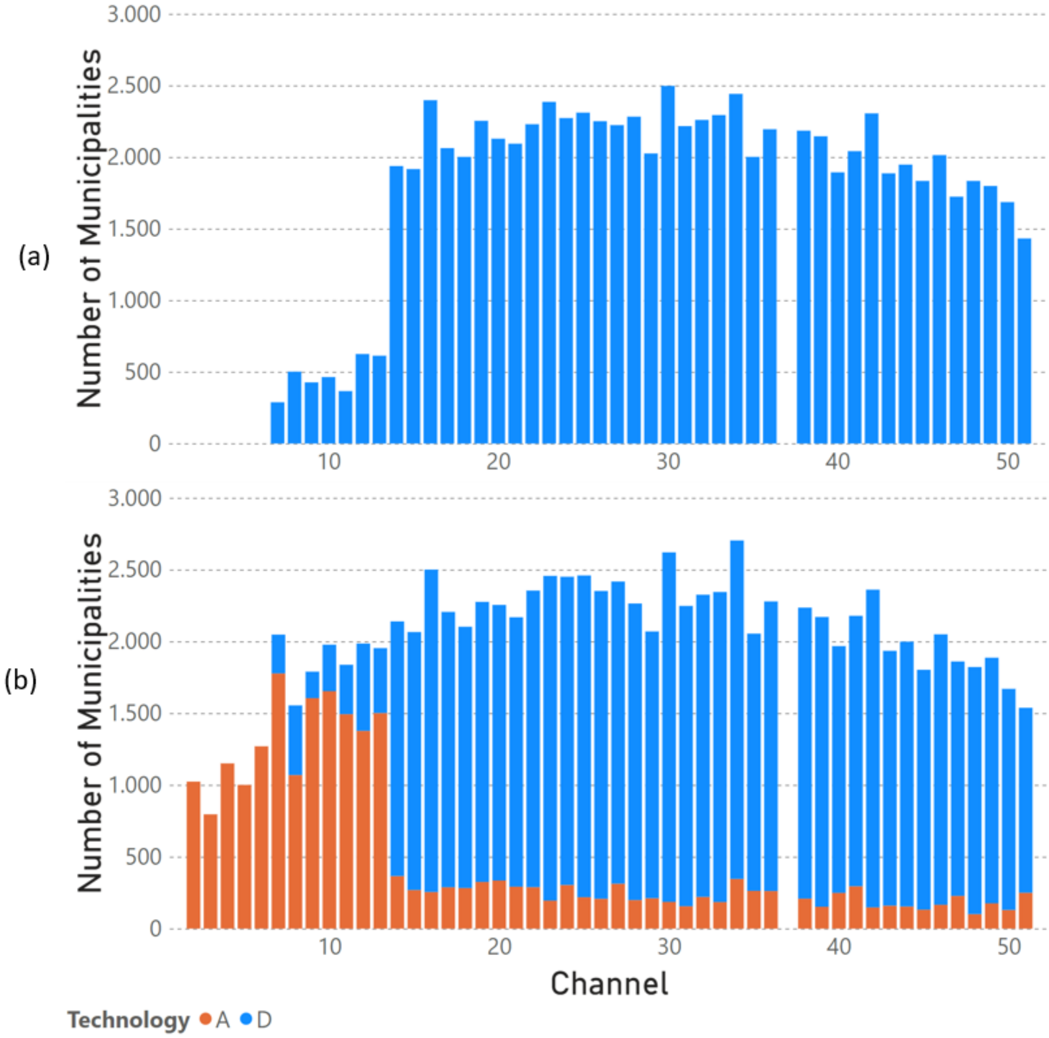

Figure 4.5: Number of municipalities covered by at least one DTT Channel after the analog switch-off (a) and before the analog switch-off (b).

A visual observation that can be directly extracted from Figure 4.5 is that coverage in VHF Band will decrease after the analog switch-off. As said before, channels 2 to 4 (54 - 72 MHz) will be completely released and channels 5 and 6 (79 - 88 MHz) is being planned for the extension of the FM service. VHF B will remain to be used, but with much less coverage, as analog TV channels will no more be operative after 2023. Numerically, the results are presented in Table 4.1.

As shown in Table 4.1, the coverage prediction results, considering the estimated future DTT channeling, show that the number of municipalities covered by at least one digital channel will increase. However, the overall percentage of covered municipalities will be increased by only 0.64%. It can be explained by the fact that most of the estimated new channels are planned to be implemented in regions where there are already operative digital channels. The analysis by frequency band shows that the VHF B Band will have a higher impact. New 368 municipalities will start receiving also in this band, an increase of 6.61%. The expansion of DTT coverage in UHF Band, however, will not be so high in the short and mid-term.

On the other hand, the overall diversity of received DTT channels will have a considerable impact as shown in 4.6. New channels will improve the availability of DTT channels in 2,542 municipalities. In most

Table 4.1: Number of municipalities with at least one digital channel per frequency band before and after the analog switch-off.

Frequency Band	Municipalities with at least one digital channel (percentage)	
	Before analog switch-off	After analog switch-off
All Bands	5,362 (96.27%)	5,398 (96.91%)
VHF B (Channels 7 - 13)	1,134 (20.36%)	1,502 (26.97%)
UHF A (Channels 14 - 36)	5,262 (94.47%)	5,334 (95.76%)
UHF B (Channels 38 - 51)	4,550 (81.69%)	4,724 (84.81%)

of these locations, the increase in diversity will achieve up to 4 new DTT channels. Reasonably, results show that the regions included in established public policies to boost DTT coverage, as detailed before, had a greater impact in improving diversity.

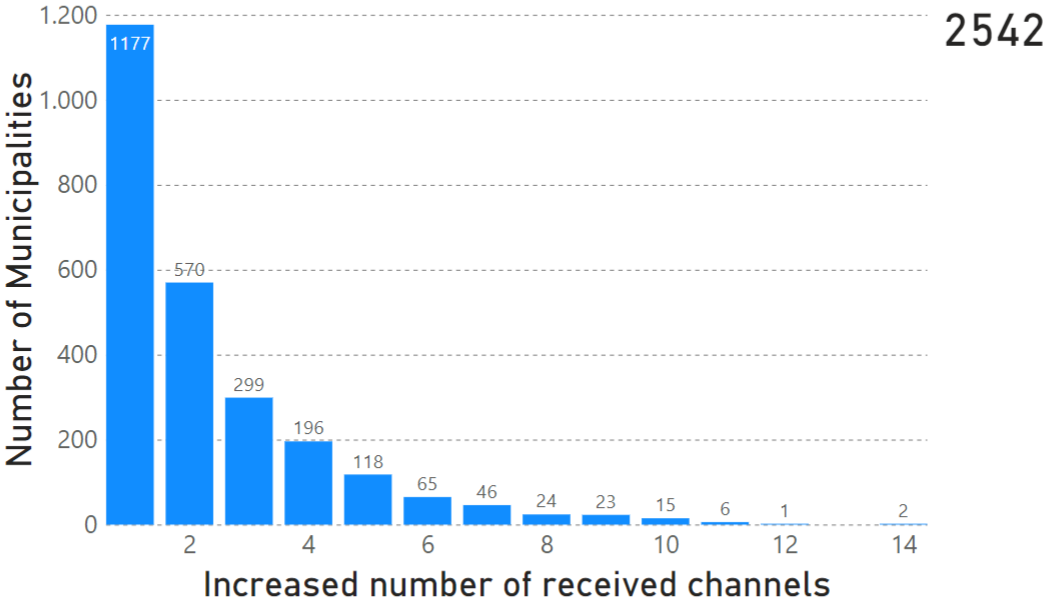

Figure 4.6: Number of increased received DTT channels by the number of municipalities after the analog switch-off.

4.3 SPECTRUM AVAILABILITY INDEX

To better evaluate the expected spectrum availability in a determined region, a spectrum index (I) was computed by normalizing the total number of received channels in the ith municipality (R_i) with the total number of allocated channels for DTT services (A), as showed in Equation 4.1.

$$I = \sum_{i=1}^{N} \frac{R_i}{A} \tag{4.1}$$

in which:

A = total number of allocated channels for DTT services
R_i = number of received channels in the ith municipality
N = number of municipalities

This approach is similar to the method provided by Chapter 3 of the Recommendation ITU-R SM.1046-3 - "Definition of spectrum use and efficiency of a radio system" [69]. However, despite dividing the geographical area into elements measuring 3 to 5 km square, as recommended in Item 3.4 of ITU-R SM.1046-3, the number of received channels R_i in the ith municipality was calculated in each sector of the census geographic boundary shapefiles provided by the Brazilian Institute of Geography and Statistics, as mentioned in Chapter 3.

So, applying the methodology of Equation 4.6 it is possible to obtain the spectrum index I in all Brazilian municipalities. It was considered all the available channels between Channels 7 to 51 for DTT deployment, so $A = 44$. Results are geographically illustrated in Figure 4.7.

As could be found in the coverage analysis, the spectrum occupancy of DTT services is not uniformly distributed. Some regions in Brazil have a high number of received DTT channels and others lack it. Figure 4.7 was classified into three regions: $I \leq 0.3$ (green areas), $0.3 < I < 0.6$ (yellow areas) and $I \geq 0.6$ (red areas).

An important conclusion that can be drawn from the results shown in Figure 4.7 is that besides there is a huge number of municipalities where the spectrum occupancy in VHF and UHF Bands is not high (green areas), the main metropolitan regions (yellow and red areas) are densely used by DTT services. Figure 4.8 shows the proportion of the population and the number of municipalities included in each classified region in terms of I.

The regions where $I \geq 0.3$ (yellow and red areas) concentrate about 73% of the Brazilian population, despite representing less than half of the Brazilian municipalities. So, there is a huge area of low spectrum occupancy, but also with low population density. It indicates that different policies may be needed to promote efficiency in spectrum usage. The next sections contains some trends and challenges that deal with this matter.

4.4 IMPLEMENTATION OF SECOND-GENERATION DTT SYSTEMS IN BRAZIL

Ideally, a smooth transition to TV 3.0 would require an additional 6 MHz channel for the transmission of new digital carriers, as there is no general requirement for backward compatibility with first-generation systems, as mentioned in Chapter 3. So, regions where $I \leq 0.5$ in principle would allow simulcasting of first and second generation of DTT systems. However, to avoid interference in zones where spectrum occupancy is higher and facilitate channel planning, establishing a margin would be advisable. So, the

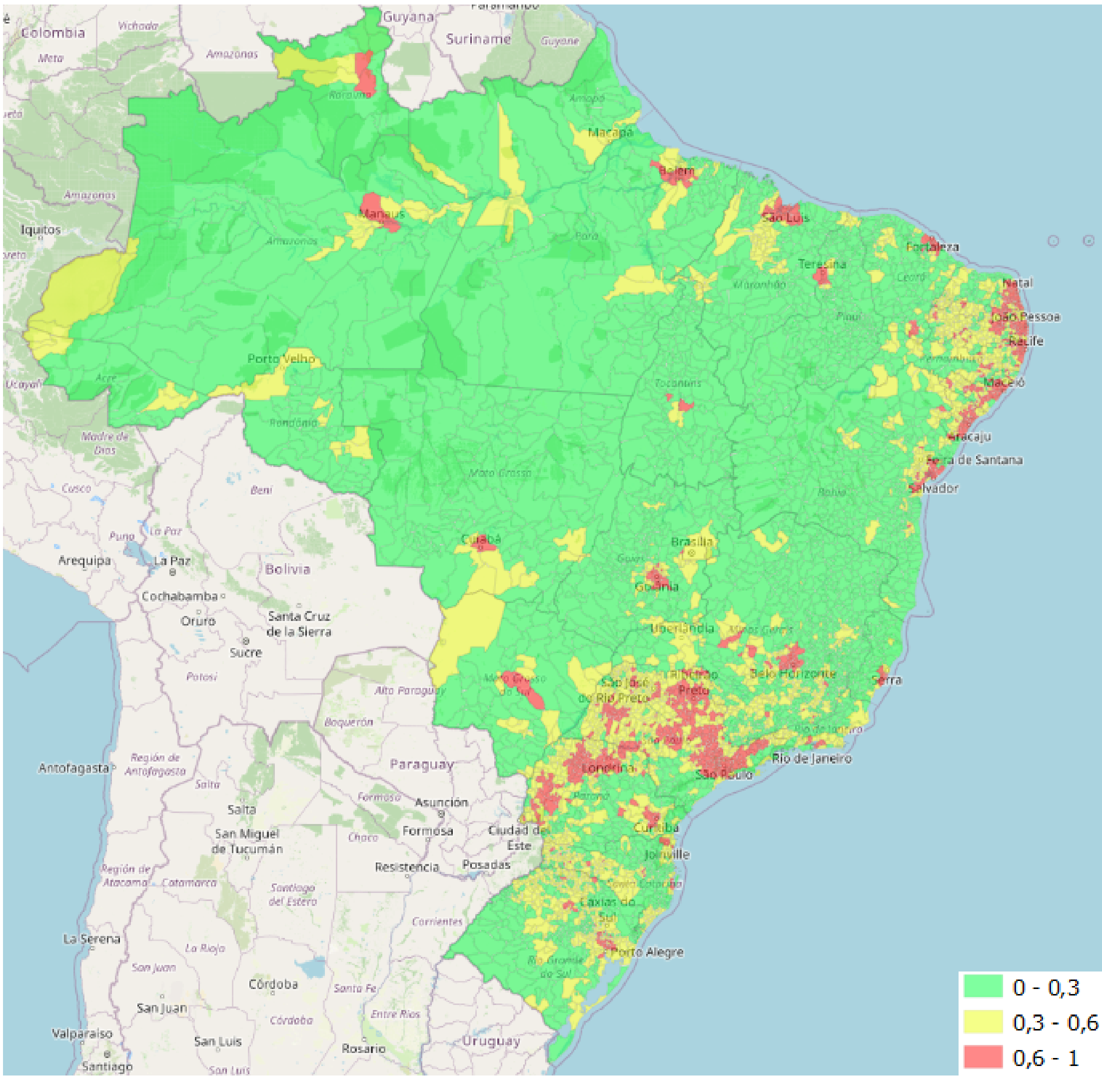

Figure 4.7: Spectrum index I per Brazilian municipality.

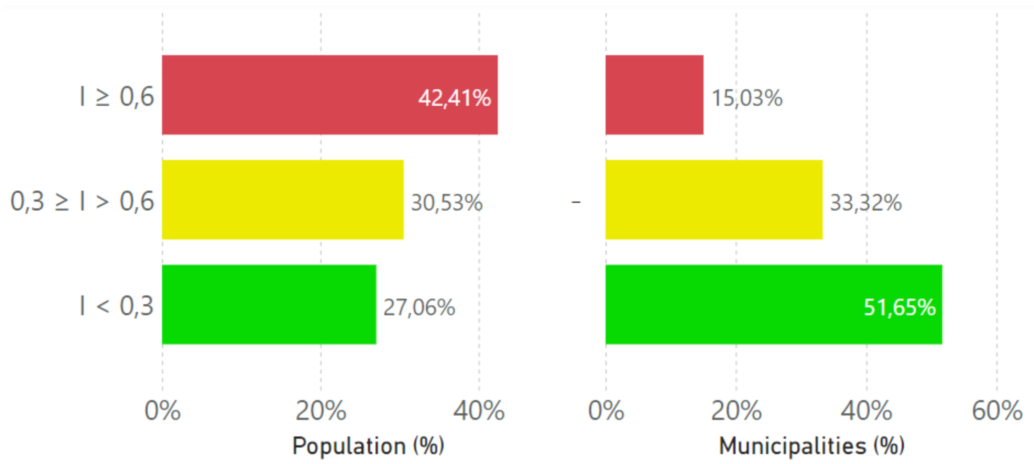

Figure 4.8: Spectrum index I in terms of percentual population and municipalities.

$I \leq 0.3$ (green areas of Figure 4.17) was considered to identify regions where there is sufficient spectrum availability and, consequently, transition policies would be effortless.

In these regions, a simulcast period between first and second-generation DTT Systems could be implemented with the allocation of a second 6 MHz channel for each authorized broadcaster. So, the same model for the implementation of the first-generation DTT system in Brazil could be promoted, when for each analog channel one digital channel was designated. Considering the future DTT channeling estimation done in Chapter 4, it would be viable to plan 7,790 new channels for second-generation DTT transmissions in regions where $I \leq 0.3$.

For $0.3 < I < 0.6$ (yellow areas of Figure 4.17) transition for TV 3.0 requires specific policies as it would not be possible to reserve additional 6 MHz channels for the transition of all operative DTT channels. This is a scenario that is currently occurring in the transition for ATSC 3.0 in the United States, as UHF spectrum availability for DTT services has declined after the conclusion of the incentive auction made by the Federal Communications Commission to re-purpose the 600 MHz Band for both licensed use and unlicensed use [20]. So, because a TV station cannot, as a technical matter, simultaneously broadcast in both ATSC 1.0 and ATSC 3.0 format from the same facility on the same physical channel, FCC has established that local simulcasting must be effectuated through voluntary partnerships that broadcasters seeking to provide NextGen TV services enter into with other broadcasters in their local markets [70].

Hence, American TV broadcasters are being encouraged to share their facilities in order to implement ATSC 3.0 and also keep ATSC 1.0 transmissions from other partners to minimize the impact on viewers that still do not have ATSC 3.0 receivers. In Brazil, a similar approach should be adopted. TV 3.0 requirements do not include backward compatibility with ISDB-Tb, so, especially in regions where $I > 0.3$, shared transmissions will be required to enable the transition of all broadcasters.

A more challenging situation is to enable the transition for TV 3.0 in regions where I is greater than 0.6. In these regions, even sharing facilities may not be sufficient to keep simultaneous transmissions between ISDB-Tb and TV 3.0. Thus, it is required to establish policies to promote direct transition to TV 3.0 in the same 6 MHz channel by switching-off ISDB-Tb transmissions of some broadcasters. To exemplify the transition complexity according to the classified municipalities shown in Figure 4.7, three cities with different spectrum indexes are included in Figure 4.9. White slots represent possible channels that can be used for the transition to TV 3.0.

São Paulo city is a clear example where few empty channels are available for the transition to TV 3.0. It is expected that only 9 slots are suitable for the transition of the expected operating DTT Channels. So, switching off ISDB-Tb transmissions of some broadcasters will be needed to promote TV 3.0 in the region. Brasilia is an example of a lower-complexity city, but sharing infrastructure will be required. Porto Seguro, on the other hand, is an example of a green region where the spectrum availability is sufficient to enable simulcasting ISDB-Tb and TV 3.0.

It is also important to highlight that new DTT channels are expected to begin operations in the mid and long-term (see Figure 4.3) and consequently increase the spectrum index in some municipalities. Two main policies are imminent: repressed demands for new relay stations and the usage of idle capacity of the facilities installed under the Ministry of Communications Program created by the act [58]. So, the total number of operative DTT channels may vary during a transition to TV 3.0.

[20] See <https://www.fcc.gov/wireless/bureau-divisions/broadband-division/600-mhz-band>

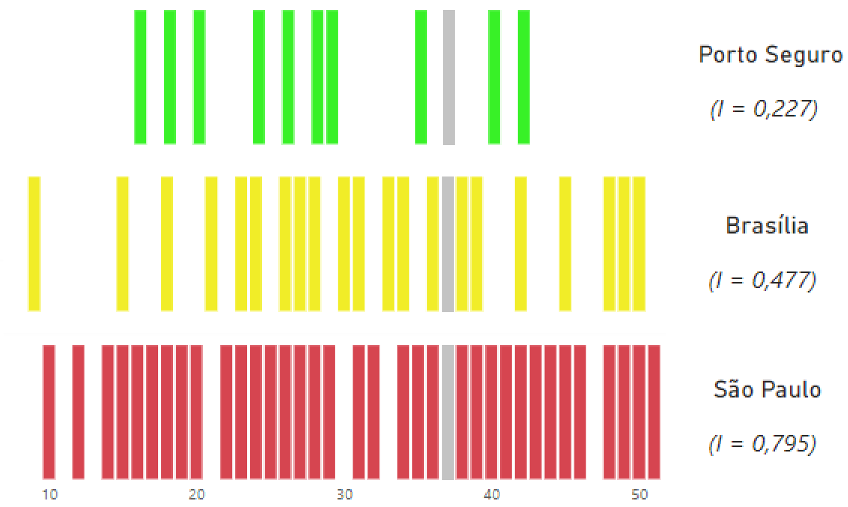

Figure 4.9: Example of cities with different spectrum indexes I. White slots represent possible channels that can be used for the transition to TV 3.0. The graphs are colored according to the subtitle of Figure 4.7.

4.5 ASSESSMENT OF THE 600 MHZ BAND

As mentioned in Chapter 2, the WRC-15 discussions resulted in new mobile allocations and identifications for IMT in portions of the frequency band 470-694 MHz for some administrations in Regions 2 and 3. Since then, 3GPP has specified Band 71 (the range 663 – 698 MHz / 617 – 652 MHz) as an operating band for Evolved UTRA (E-UTRA) based on the FCC 84 MHz band plan [71] and for the 5G New Radio (5G NR) [72]. The Arrangement A12 was further included in the Recommendation ITU-R M.1036 - " Frequency arrangements for the implementation of the terrestrial component of International Mobile Telecommunications (IMT) in the bands identified for IMT in the Radio Regulations" [73].

The usage of the Band for IMT services in Region 2 has already been initiated. The United States made the band available for mobile broadband licensees through an incentive auction that concluded in March 2017, repurposing 84 megahertz of low band spectrum for both licensed use and unlicensed use [21]. Mexico successfully cleared the band in September 2018, thereby releasing the 600 MHz band for mobile broadband use. In April 2019, Canada concluded its 600 MHz auction [74].

For a possible deployment of mobile services in the 600 MHz band, however, coexistence with DTT services in the same allocated band is quite complex, being an object of discussions at the international level, mainly within ITU, which has issued specific reports about the subject [75], [76]. That is why in most cases, having spectrum in the UHF identified for IMT indicates that the broadcasting service should be re-farmed from the band and moved to another one [77]. So, to deploy IMT services in 600 MHz band, a re-farming process to remove DTT services from the band has to be assessed.

The intent of the current section is to objectively evaluate if a possible deployment of mobile services in the 600 MHZ Band can be implemented in Brazil, considering the future DTT channel distribution. The analysis made in Chapter 4 showed that even before the analog TV switch-off the UHF band as a whole would be densely occupied in Brazil. The 600 MHz band, especially, is expected to be occupied by 5,168

[21]Complete results available at urlhttps://www.fcc.gov/600-mhz-band

DTT channels in 2,360 municipalities. The channel distribution on this band is highlighted in Figure 4.10 and the coverage predictions of all 5,168 DTT channels are illustrated in Figure 4.11.

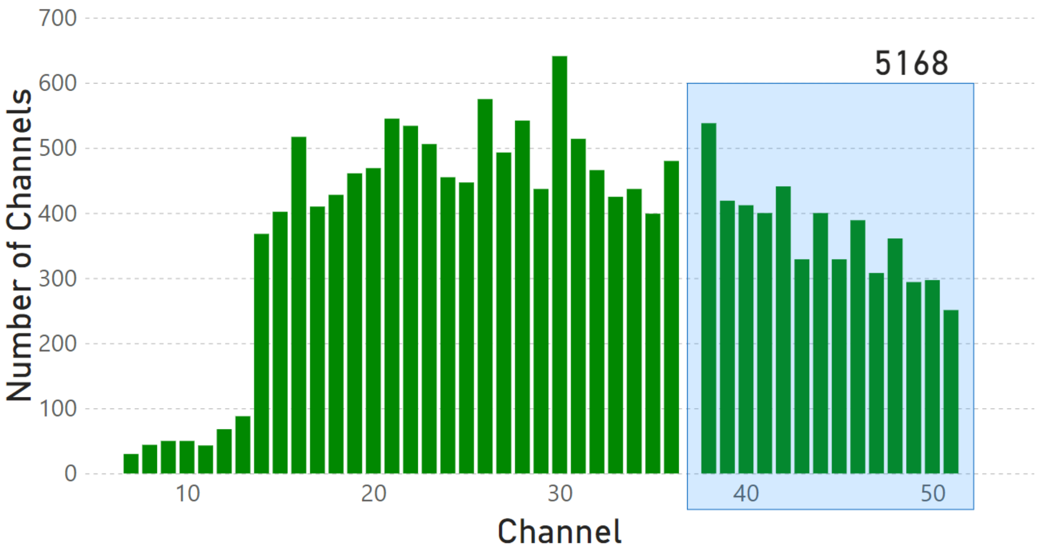

Figure 4.10: Expected distribution of Digital TV Channels in the 600 MHz in Brazil after the analog switch-off.

Based on the distribution of estimated channels that will be in operation in the 600 MHz Band after the analog switch-off (see Figure 4.10), and the spectrum index calculated in Chapter 4 for each municipality, it is possible to estimate the areas where a possible re-farming process could be developed. In the green areas of Figure 4.7, where $I \leq 0.3$, there are 2,307 DTT channels that occupy the 600 MHz Band as shown in Figure 4.12. Furthermore, Figure 4.13 shows the total amount of DTT Channels in the 600 MHz Band per municipality. It shows that in 71,95% $(42,92\% + 29,03\%)$ of the municipalities that have at least one DTT channel in the 600 MHz there are no more than 2 DTT channels in the band. So, it can be concluded that despite the fact of having a huge number of channels in the 600 MHz band, it would be possible to re-farm DTT channels, mainly in regions where the spectrum availability is high (or I is low) and the number of channels in the band is low.

A possible re-farm of the 600 MHz Band, however, should not prevent the evolution of DTT services. As mentioned in the last subsection, a smooth transition to TV 3.0 in Brazil would require an additional 6 MHz channel for the transmission of new digital carriers, as there is no general requirement for backward compatibility with first-generation systems. So, to evaluate the availability in each municipality for a possible re-farming process of the 600 MHz Band, it is indispensable to consider channels for the deployment of TV 3.0. Equation 4.6 contains the channel availability C_A calculation, considering the total amount of allocated channels for DTT services, the number of received DTT channels in the ith municipality, and the number of channels that are estimated to be in operations in the 600 MHz Band in the ith municipality.

$$C_A = A - R_i * 2 + N_{i600} \tag{4.2}$$

in which:

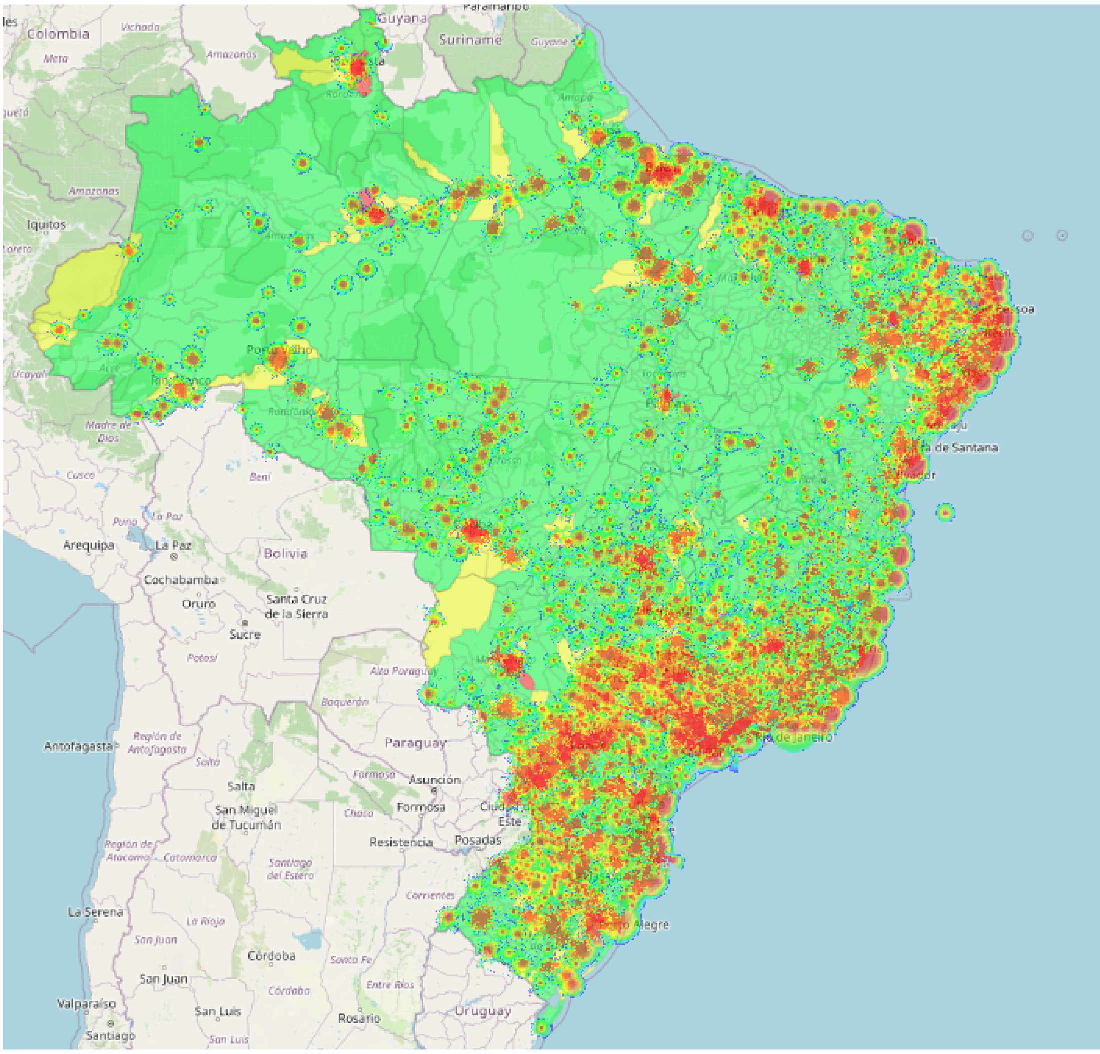

Figure 4.11: 600 MHz DTT coverage vs Spectrum Index.

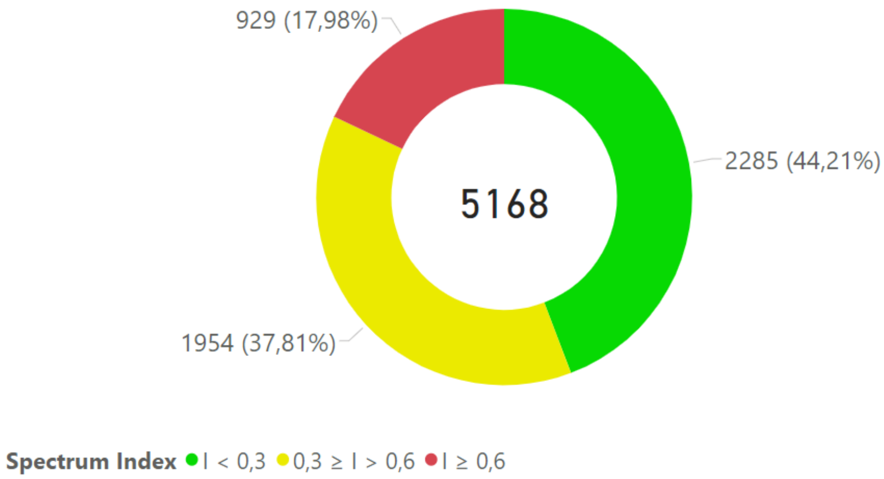

Figure 4.12: Spectrum Index per DTT channel in the 600 MHz Band.

A = total number of allocated channels for DTT services

R_i = number of received channels in the ith municipality

N_i600 = number of channels in the 600 MHz Band in the ith municipality

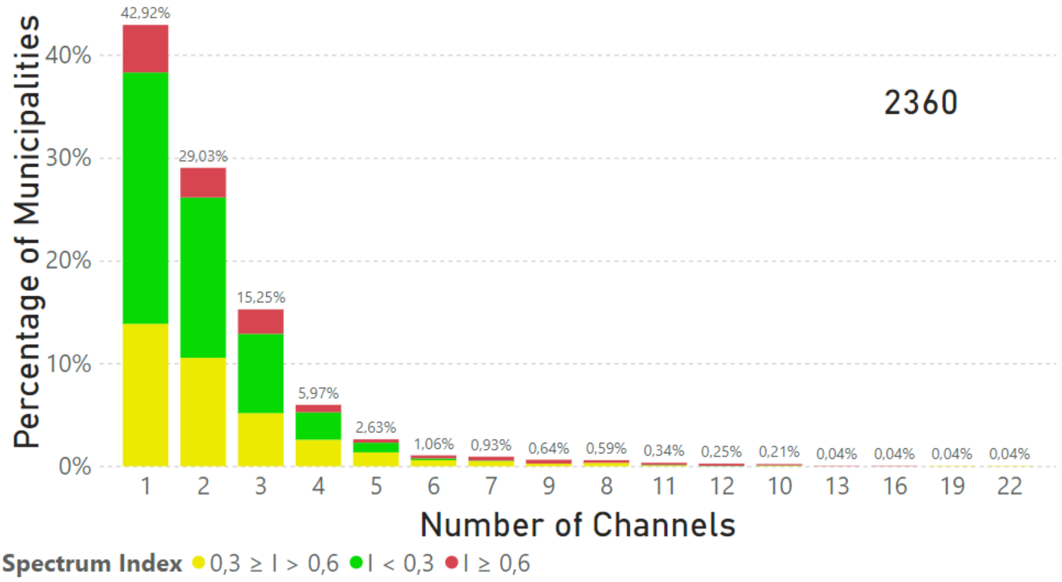

Figure 4.13: Percentage of municipalities that receives a number of DTT Channels categorized by the Spectrum Index per channel.

The channel availability C_A was computed for each municipality. All municipalities that $C_A \geq 0$ have spectrum availability to include additional channels to allow all broadcasters to implement second-generation DTT services, and also to re-plan existing channels that are currently allocated in the 600 MHz down to the VHF or UHF A Band. The obtained result is that from the total amount of 5,168 allocated channels in the 600 MHz Band, 2,328 channels (about 45%) can be re-planned. Figure 4.14 shows the channels that are feasible to be re-planned (light green). As expected, almost the totality of these channels (about 97%) is located in the green areas of Figure 4.11, where $I \leq 0.3$.

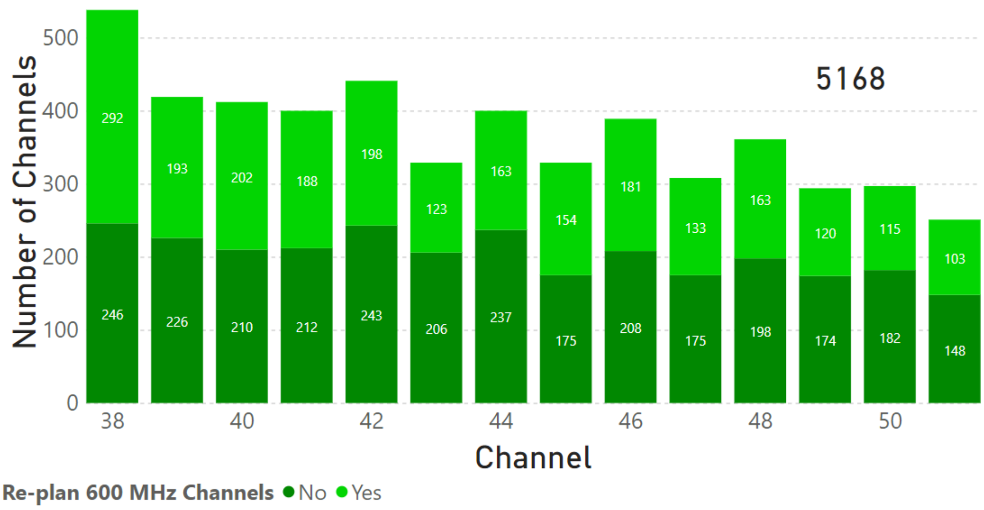

Figure 4.14: Number of channels in the 600 MHz Band classified by the possibility of be re-planned.

The other 2,840 channels in the 600 MHz Band (about 55% of the total amount) are located in regions where the spectrum availability is insufficient to promote actions toward a re-farming process that does not impact the deployment of TV 3.0. So, it is expected that in those regions, 600 MHz channels will remain to be used. Considering this scenario, it was developed a quantitative assessment of the impact of the remaining DTT channels on the 600 MHz. First, it was considered that all 2,328 DTT channels in the 600 MHz Band and located in regions where is feasible to be re-planned can be successfully removed from the Band. For the other channels (2,840), it was developed a coexistence analysis considering the impact on IMT operation.

For the current study, it was evaluated only the co-channel sharing scenario, because 600 MHz is densely occupied by DTT channels and not all the band can be re-farmed. So, this is the worst-case scenario for the implementation of mobile services in the band. Furthermore, considering the high-tower high-power transmission characteristic of DTT services, it was considered only the mobile service as a victim, by the evaluation of broadcasting transmissions into mobile base-stations. The most critical DTT channels for IMT in the 600 MHz band are channels 46 to 51, as they overlap with the uplink blocks, as shown in Figure 4.15.

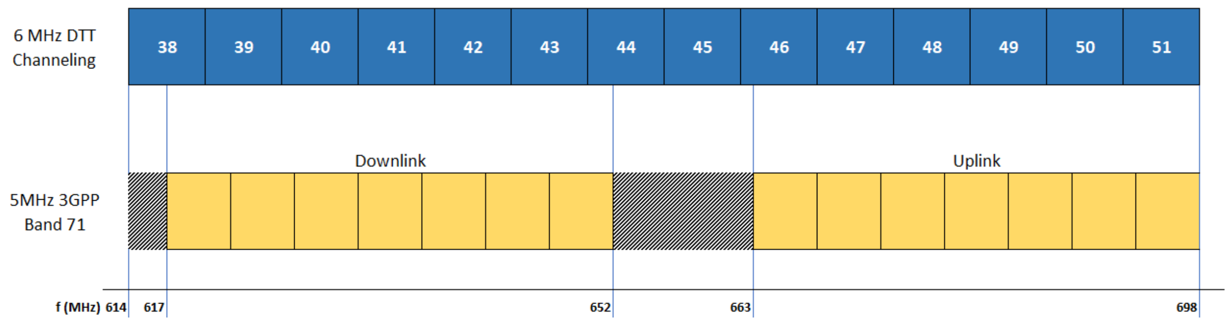

Figure 4.15: Position of DTT channels to Arrangement A12 of Rec. ITU-R M.1036 (3GPP Band 71)

The future DTT channel distribution of the 600 MHz contains 1,085 channels from 46 to 51 (dark green in columns between 46 and 51 of Figure 4.14). So, interference simulations of these channels were computed to estimate the impact on the IMT 600 MHz uplink blocks. The same methodology and assumptions summarized in Figure 3.3 and described in Chapter 3 were adopted. Furthermore, simulations using ITU-R P.1812 have been carried out for a percentage of time 10%, instead of 50%, because it is generally used for interference analysis of broadcasting signals. The other simulation parameters are the same as the ones described in Table 3.3.

For the simulation of the mobile network and obtaining the interference threshold, it was considered the parameters used by the Report ITU-R BT.2337-1 - "Field measurement and analysis of compatibility between DTTB and IMT" (See Chapter 2.2.1.2) [75]. A similar methodology is included also in a study of the Broadcast Network Europe (BNE) submitted to the meetings of Task Group 6/1, responsible for the development of draft Conference Preparatory Meeting (CPM) text under WRC-23 Agenda item 1.5 [78]. The limit of interference is based on I/N of -6 dB as protection criteria, which corresponds to a 1 dB desensitization of the up-link receiver at the base station. The calculation of the interference threshold for the mobile base-station is detailed in Table 4.2, including the respective equations.

The field strength interference threshold obtained is 15.9 $dB\mu V/m$ as can be seen in the calculations of Table 4.2 using the referenced equations. Using this value, it is possible to evaluate the impact of the 1,085 DTT channels in the 600 MHz up-link blocks. Results show that in 89.3 % of the Brazilian municipalities, IMT base-stations will not have guaranteed protection from DTT services. For the quantitative evaluation, it was considered that a municipality would be interfered if at least 20% of its urban population is inside

Table 4.2: Calculation of interference threshold for base-station (Based in [75]).

Parameter	**Value for Base Station**	**Unit**	**Comment**
Frequency	665	MHz	F
Rx Noise figure	5	dB	NF
Bandwidth	5	MHz	BW
Temperature	290	K	T
Thermal Noise (5 MHz)	-102	dBm	Equation 4.3
I/N protection criterion	-6	dB	I/N
Interference power threshold	-108	dBm	Equation 4.4
Downtilt	3	°	
Rx antenna discrimination	1,19	dB	Dant (Rec ITU-R F 1336)
Polarization discrimination	3	dB	Dpol
Rx antenna gain	15	dB	Grx
Feeder loss	1	dB	Dfl
Field strength interference threshold at Rx antenna height	**15,9**	**dBμV/m**	**Equation 4.5**
Antenna height	30	m	Hant

$$PN = 10log(kTB) + NF \tag{4.3}$$

$$PI = PN + I/N \tag{4.4}$$

$$Eunwanted = 77.21 + PI + 20log(F) - Grx + Dant + Dpol + Dfl \tag{4.5}$$

the predicted interference threshold area. This value was chosen due to the current coverage commitments established by Anatel for mobile services providers that have to reach at least 80% of the urban area of the main districts [22]. Results are illustrated in Figure 4.16.

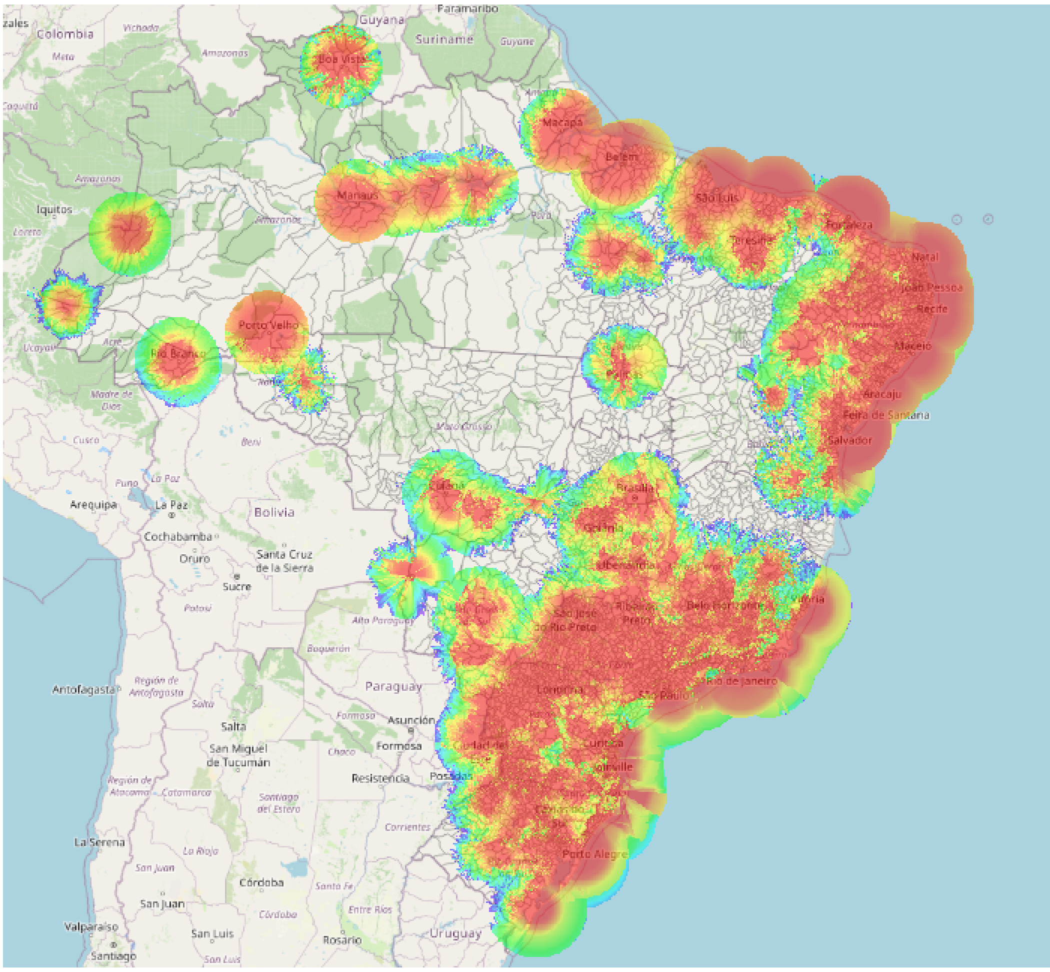

Figure 4.16: Interference threshold generated by DTT channels in the uplink frequency band of 3GPP Band 71 Arrangement.

The conclusion that can be drawn from the results is that despite a re-farming process of the 600 MHz being technically viable to be implemented, in only 596 (10.7 %) Brazilian municipalities IMT services could be deployed without receiving interference from DTT services in urban areas. This area contains about 5.3% of the Brazilian population. The occurrence of few available areas is a direct impact of the scarcity of spectrum resources that do not allow all DTT channels allocated in the 600 MHz Band to be re-planned for another band.

Another scenario that can be computed is to consider a relaxed I/N of 0 dB. So, in Equation 4.4, $PI = PN$, resulting in a field strength interference threshold of 21.9 $dB\mu V/m$ (6 dB more than the previous evaluation). In this scenario, 698 (12.53 %) of the Brazilian municipalities IMT services could be deployed without receiving interference from DTT services in urban areas, whose area corresponds to about 6.3% of the Brazilian population.

[22] See mobile services coverage requirements on Anatel's website at <https://www.gov.br/anatel/pt-br/regulado/universalizacao/telefonia-movel>.

From a practical point of view, implementing such a process would also require enormous effort. To release 698 municipalities it would be necessary to promote actions to reimburse broadcasters that operate all 2,328 channels that re-planing is feasible. Hence, cost-benefit analysis should also be considered in re-purposing policies for UHF Band utilization.

4.6 TV WHITE SPACES AVAILABILITY

The obtained results of the future spectrum usage of the VHF and UHF Bands show that there will be considerable areas with a lack of diversity of DTT services after the analog TV switch-off. So, idle spectrum portions on these bands are likely to be over the next years.

Discussions about the usage of idle spectrum in VHF and UHF Bands have already been initiated in Brazil. In October 2021, Anatel issued a resolution to define criteria for the usage of TVWS [61]. This resolution defines frequency band blocks for the deployment of White Spaces Devices (WSD) and also the methodology to guarantee the protection of television services. The maximum peak power of the White Space Devices, measured at the transmitter output, cannot exceed 1 $Watt$. However, the further technical detailing is still under discussion. As the transmission power of WSD will be low compared to the high-power high-tower broadcasting transmission schema, it is not expected interference issues in DTT services. However, the feasibility of introducing TVWS Devices will require spectrum management tools to identify the spectrum availability by using geo-referenced databases or sensing methods, as already required by national regulations.

To evaluate the expected spectrum availability average S, the methodology of Equation 4.6 was considered. It is a similar approach to Eq 4.6 but in terms of frequency band availability (in MHz). Furthermore, this approach does not consider any reservation of channels for new DTT channels nor for re-planning channels in the 600 MHz band.

$$S = \frac{\sum_{i=1}^{N}(A - R_i).B}{N} \tag{4.6}$$

where:

A = total number of allocated channels for DTT services
R_i = number of received channels in the ith municipality
B = DTT channel bandwidth (MHz)
N = number of municipalities

The spectrum availability average of all Brazilian municipalities after the analog TV switch-off was computed using $N = 5,570$, $B = 6$, and $A = 44$. The value of A reflects the total number of 6 MHz channels available in the 174-216 MHz VHF band and 470-698 MHz UHF band together. The result shows that on average 177 MHz will be idle in Brazil after the analog switch-off. In most of the cities (73%) the 174-216 MHz VHF band (42 MHz) will be totally released. Results are geographically illustrated in Figure 4.17 - greener areas have more spectrum availability.

It is worth mentioning that Figure 4.17 considers the minimum field strengths for DTT reception and the

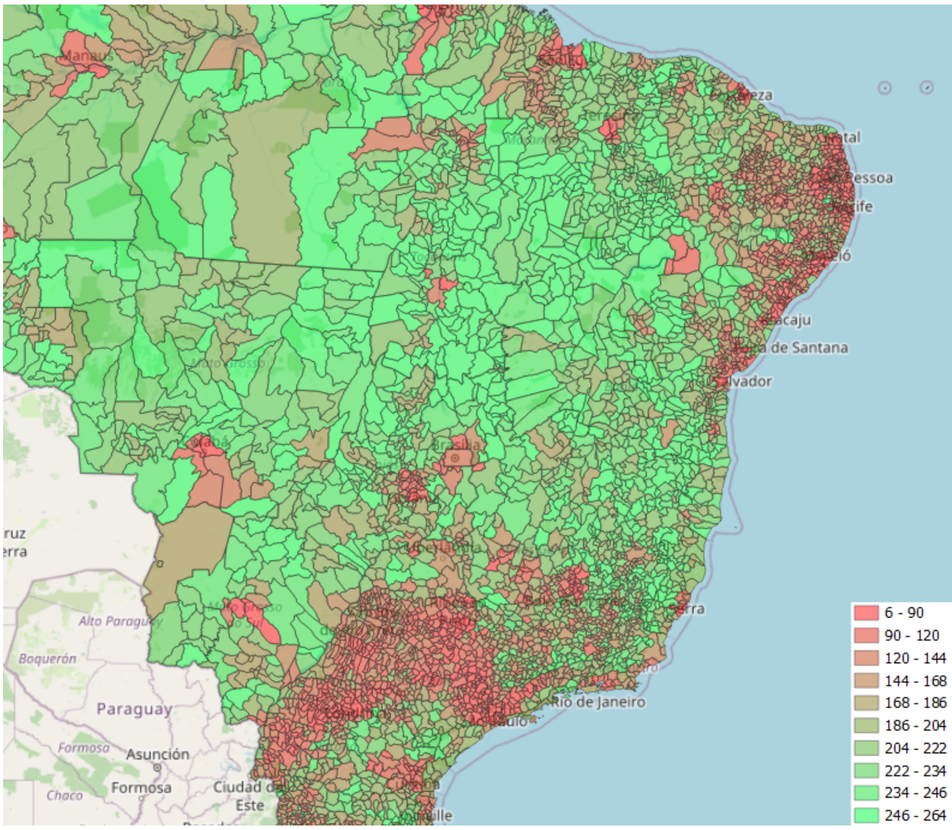

Figure 4.17: Estimated spectrum availability per municipality (in MHz).

results did not include adjacent channel interference, just a co-channel analysis. So, further investigation using the Adjacent Channel Leakage Ratio (ACLR) is necessary to guarantee DTT protection from WSD. Furthermore, some studies show the necessity of defining a separation distance between the WSD zone and the DTT protected area of about 2,2 km for co-channel protection considering a threshold of 51 $dB\mu V/m$ for DTT reception [79]. However, the impact of including such distance would not significantly change the overall obtained results but should be considered in detailed studies in practical situations.

4.7 INTERNATIONAL FREQUENCY COORDINATION ISSUES

The assessment done in this chapter considered the available data about TV broadcasting stations in Brazil. However, it is important to highlight that in border areas the usage of the VHF and UHF Bands is undersized due to the lack of information about operative stations in other South American countries. No information about DTT stations can be retrieved from ITU Master International Frequency Register (MIFR) [23], for example. Furthermore, regional agreements for coordinating DTT channels among Southern Common Market countries (MERCOSUL for its Portuguese initials), are still under discussion in the Sub-working Group n.º 1 "Communications" (SGT1) [80], and an official list of coordinated channels is currently unavailable.

[23]The MIFR can be downloaded in the ITU-R BR IFIC (Terrestrial Services) available at <https://www.itu.int/en/ITU-R/terrestrial/brific/Pages/default.aspx>

So, the calculated spectrum index I, which is illustrated in Figure 4.7, is presumably higher in international borders, mainly in the tri-border area along the junction of Argentina, Brazil, and Paraguay. In these regions, the density of coordinated analog stations and the discussions that are being held in SGT1 indicate that the demand for DTT channels for the digital switch-over will require spectrum availability and coordination actions to guarantee equitable usage of spectrum resources.

In addition, the transition to digital television services in Brazil is much more advanced than in other countries of the region. Most countries have not completed, or even initiated, the analog TV switch-off. So, in those countries, the demand for spectrum to allow simulcast transmissions between analog and digital TV has to be considered in future spectrum availability analysis, regardless of the decision to implement new broadcasting services or other services in the VHF and UHF Bands.

International matters are very important in regional coordination among different services. For instance, Figure 4.16 shows that an eventual usage of the 600 MHz band for services rather than broadcasting would be difficult to be adopted in border zones of countries near Brazil. Paraguay would be the most affected country, as the interference threshold of DTT on IMT uplink covers relevant areas. Other countries in South America could also have urban areas affected by DTT.

4.8 TECHNICAL AND REGULATORY PROPOSALS

The quantitative assessment of the VHF and UHF Bands after the analog TV switch-off, detailed in this Chapter, indicates that spectrum occupancy of VHF and UHF Bands over the Brazilian territory is very heterogeneous. It implies the need to develop hybrid approaches to promote spectrum efficiency according to the spectrum availability in each region. The next subsections contain some regulatory and technical proposals to meet the objective of promoting spectrum efficient policies.

4.8.1 Reserve High-VHF Band (Channels 7 to 13) for the transition to TV 3.0

After the analog TV switch-off, the High-VHF Band will be released in most municipalities. The future channel distribution indicates that it is estimated that 373 DTT channels will be operative in this band the VHF Band. Most of the channels are located in regions where the Spectrum Index I is lower than 0.6 and re-planning such channels to the UHF Band would be possible. Furthermore, the CfP for TV 3.0 in Brazil includes the requirement that the over-the-air Physical Layer should consider the deployment in this band.

Hence, updating the regulation to reserve the band would bring the benefit of having a specific spectrum portion to deploy TV 3.0 networks. Another important technical requirement of TV 3.0 that would facilitate the use of the band is the Physical Layer reuse-1. If any candidate technology fulfills this requirement, all channels from 7 to 13 could be used simultaneously and independently in all Brazilian locations. Hence, up to 7 national channels could be implemented in the High-VHF Band, with the possibility of inserting regional content without interference between different stations. Even considering the scenario of not having any technology that fulfills the reuse-1 requirement, reserving the band would also bring benefits to the channel planning process to deploy second-generation DTT systems.

The High-VHF Band is the only band that would be possible to deploy TV 3.0 national networks. As could be seen in the last sections of this chapter, the UHF Band will be densely occupied even after the analog TV switch-off. On the other hand, handheld reception of TV 3.0 operating in the High-VHF Band would be limited, as physical constraints do not allow the design of built-in VHF reception antennas on smartphones or tablets, for instance.

4.8.2 Promote installation of shared infrastructure

DTT was implemented in Brazil in a selfish way. Broadcasters have taken advantage of their current analog TV infrastructure to install DTT transmission sites on their own, doing the transition channel by channel. So, there are a few unbidden initiatives in Brazil where DTT transmission sites were shared by more than one broadcaster. Recent public policies have been established to install complete shared DTT transmission sites in small municipalities to facilitate the transition from analog to digital television, but more incisive policies are required for the deployment of shared second-generation DTT transmission sites.

One possibility is to develop policies to obligate, as technical as possible, that the first broadcasters that want to transmit second-generation DTT systems install transmission infrastructure that allows smooth expansion for new interested broadcasters. Despite it implies higher investments in the short-term, future infrastructure maintenance costs could be reduced.

4.8.3 Re-plan current DTT channels in some areas to free continuous spectrum portions

The DTT channel planning in Brazil was developed in a simulcast scenario where analog TV channels had to be protected to guarantee a smooth transition. So, the planning process was not optimized because DTT channels were allocated according to the available channels in each planning region. It generated a complex channel distribution, despite the technical planning effort to consider networks according to the content of each broadcaster.

Hence, it is highly probable that re-planing current DTT channels in some areas will be viable. Channeling optimization would free continuous spectrum portions and promote spectrum efficiency by releasing parts of the UHF and VHF spectrum, facilitating the deployment of second-generation DTT networks. It would also allow the assessment of idle spectrum portions and, consequently, the introduction of TVWS services. However, investments will be necessary to promote such changes and should be considered in the overall amount that will be needed to evolve DTT services.

4.8.4 Update regulation to allow multi-programming

The current Brazilian regulation just allows public broadcasters to transmit more than one program in a single 6 MHz channel. So, despite being a requirement since the adoption of DTT in Brazil, multi-programming transmissions are very limited. In 2020, a government Decree expanded the scope of multi-programming during the COVID-19 pandemic [81]. Commercial and educational broadcasters were authorized to transmit more than one content in a single 6MHz channel for education, science, technology, innovations, citizenship, and health purposes, in order to help the population to access more information during the restrictions imposed by the pandemic.

Due to the high utilization of the VHF and UHF bands by first-generation DTT transmissions, it will not be possible to allocate a second 6 MHz channel for all broadcasters for the transition to second-generation DTT Systems, mainly in Brazilian state capitals regions and highly dense metropolitan areas. So, public policies should be set up to make permanent the multi-programming capability for all TV broadcasters. Such policies may enable partnerships between small DTT broadcasters to share infrastructure and reduce maintenance costs. Consequently, it would promote more efficient use of the spectrum and facilitate the introduction of TV 3.0.

4.8.5 Promote the production of TV sets with ISDB-Tb and TV 3.0 receiving capability as soon as the system technology has been defined

The spectrum availability analysis has indicated that in many regions there will be no sufficient channels for simulcasting both generations of DTT systems. Hence, a strong policy for the production of TV sets with TV 3.0 receiving capability will be required to accelerate the replacement of the current digital television receivers and minimize the impact on viewers.

This is a similar approach used in the implementation of first-generation DTT systems, when the production of TV sets was required to include both digital and analog receivers. However, in a transition to TV 3.0 technology, such policies have higher importance due to the lack of spectrum availability for simulcast transmissions. Thus, many broadcasters will have to directly migrate to TV 3.0 without a transition period, which requires a fast replacement of TV sets and the development of TV 3.0 set-top-boxes.

4.8.6 Keep the 600 MHz Band for DTT transmissions and promote TVWS usage

The quantitative assessment of the future use of the 600 MHz showed that despite a re-farming process that can be technically viable to be implemented in some areas, in just 12.5 % of Brazilian municipalities IMT services could be deployed without receiving interference from DTT services in urban areas. The evaluation was done considering a scenario that the re-farming process of 600 MHz does not prevent the introduction of TV 3.0, this means considering channels not only for re-planning but also for TV 3.0 transmissions. From all 5,168 channels in the 600 MHz band, 2,328 could be reallocated.

The effort to develop such a process, however, would be demanding. It would involve not only a complex technical re-planning process but also a public policy to reimburse broadcasters to release the band, as done in the regulatory framework adopted in Brazil for releasing the 700 MHz Band. Another possibility would be implementing the American approach of a reverse auction in which broadcast television licensees submitted bids to voluntarily relinquish their spectrum usage rights in exchange for payments. In both scenarios, would be necessary to carry out complex domestic negotiations in Brazil and also at the international level with all stakeholders.

So, from a practical point of view, it is highly probable that the cost-benefit analysis of repurposing the 600 MHz band indicates difficulties in starting this process. However, the quantitative assessment of the usage of VHF and UHF bands clearly showed that idle spectrum will remain mainly in small cities, and actions for promoting the usage of the band are recommended. Hence, TVWS usage should be focused on instead of IMT deployment in the UHF band, considering the objective results of the spectrum availability assessment. Furthermore, WSD operates on low power and on a secondary basis, facilitating its implementation.

4.8.7 Give flexibility to DTT authorizations to promote the provision of converged media services

The second-generation DTT systems provide undoubtedly improvements in terms of spectrum efficiency, audio and video quality, and interconnectivity with other services, among others. However, broadcasting regulation is extremely outdated and dispersed in various rules. The Brazilian Code of Telecommunications, from the 60s, was the first law to regulate the broadcasting and telecommunication sectors and is still the main legal framework for broadcasting in the country, despite significant changes in this market [82].

Even before the establishment of the Brazilian DTT System in 2006, nothing had significantly changed in terms of broadcasting regulation. Multiplexing different contents in a unique 6 MHz channel was the main improvement provided by DTT services that somehow impacted the diversity in the TV broadcasting market, but as mentioned before, it was restricted only to public broadcasting transmissions. New TV authorizations still have a complex flowchart that involves actions from the Ministry of Communications, Anatel, and Congress. Studies from the Ministry of Communications indicate that due to this complicated procedure, the average time to complete an authorization for broadcasting services is 9.4 years [83].

To promote TV 3.0 in Brazil, however, a complete regulation rearrangement is needed. Firstly, giving flexibility to TV authorizations is a crucial necessity. In the U.S., for instance, new regulatory frameworks are being developed to allow more flexibility in the use of TV broadcasting spectrum resources. In 2020, the FCC announced that it would seek mechanisms to promote “Broadcast Internet” or “datacasting” using ATSC 3.0 [84]. Although that proceeding is still in its comment phase, the FCC noted in launching the proceeding that wireless networks are becoming more dynamic, relying on various spectrum bands for inbound and outbound data paths. The Commission also observed that, although ATSC 3.0 transmissions presently lack a return path, the technology is well positioned to support a host of next-generation applications, both on its own or as part of a hybrid wireless network [85].

Flexibility would promote innovative possibilities in the usage of broadcasting channels and, consequently, new revenue streams for broadcasters. Geo-targeted content and advertisement, for example, is a TV 3.0 use case that is technically possible to be used with reuse-1 capability, but its implementation needs a new regulatory framework, as most TV relay stations are not allowed to include regional content. Some studies to promote the flexibility of TV relay station authorizations have already been proposed (see [86]) and should be deemed to evolve DTT services. Another possibility is to allow broadcasters to provide additional subscription content in a broadcasting channel, but it is also currently prohibited by the Brazilian legal framework.

Some proposals to simplify authorizations have already been developed. Given the increased convergence of communication services over IP networks, the Organisation for Economic Cooperation and Development (OECD) has recommended introducing a single-class licensing regime for communication and broadcasting services. Simplifying licensing would considerably reduce transaction costs, facilitate market entry, and speed up the administrative processes for network deployment throughout Brazil [82].

A converged media service over a TV broadcasting channel would also need changes in the organizational framework. Proposals to centralize broadcasting regulation in a unique organization – in Anatel, for instance - have already been discussed [86]. The OECD has also recommended creating a converged independent regulator overseeing the Brazilian communication and broadcasting sectors through a merger of the regulatory functions of Anatel, Brazilian National Film Agency (Ancine), and the Ministry of Communications. A converged independent regulatory body should be entrusted with regulating the entire broadcasting and pay TV value chain under an integrated and coherent set of rules [82]. Both approaches can foster the evolution of TV broadcasting services and are essential for the implementation of a new regulation framework of broadcasting services, but complex legal arrangements will need to be developed.

5 CONCLUSIONS

This work presents contributions to the transition to second-generation DTT Systems in Brazil. It contains coverage simulation results using Recommendation ITU-R P. 1812 that quantifies the spectrum availability in the 174-216 MHz VHF band and 470-698 MHz UHF band. Simulations were made considering also the expected deployment of new DTT channels after the analog TV switch-off in Brazil, based on the assessment of Anatel's database and public policies that have been established by the Ministry of Communications.

Three categories of regions were defined based on their spectrum availability, which was calculated considering the number of receiving DTT channels that were predicted by coverage simulations. Results indicate that in the main metropolitan regions, which concentrate most of the Brazilian population (about 73%), there will be no spectrum availability after the analog TV switch-off for simulcast transmissions between the current ISDB-Tb System and the future TV 3.0. So, hybrid approaches should be implemented to introduce a new digital television system in Brazil. In areas with high spectrum usage, the approach is to consider sharing transmission infrastructure and spectrum with more than one broadcaster to reduce implementation costs and also promote spectrum efficient policies.

An objective evaluation of the usage of the UHF Band for services rather than broadcasting was also done. It shows that the usage of 600 MHz as a second digital dividend would require a huge re-planning process of about 2,328 channels, but only 12.5 % of the Brazilian municipalities could implement IMT services in the band without interference from DTT transmissions and not affecting TV 3.0 implementation. So, developing policies to promote TVWS to operate in the idle spectrum would be a better regulatory choice. The obtained results can help regulators to prioritize regions according to their spectrum occupancy.

Furthermore, some policies are proposed to facilitate the transition for second-generation TV Systems in Brazil: reserve High-VHF Band (Channels 7 to 13) for TV 3.0, re-plan current DTT channels in some areas to free continuous spectrum portions, update regulation to allow multi-programming, promote the installation of shared infrastructure, promote strong policies for the production of TV sets with TV 3.0 receiving capability as soon as the system technology has been defined, keep the 600 MHz Band for DTT transmissions, promote TVWS usage, and give flexibility to DTT authorizations for the provision of converged media services.

A future work suggested is to simulate the estimated denied spectrum generated by DTT channels considering co-channel and adjacent channel interference field strength to optimize DTT frequency planning and better identify areas where spectrum can be used for facilitating the introduction of TV 3.0 and TVWS. Furthermore, it was identified that simulations contain conservative values due to software restrictions for the prediction of a high number of channels. So, it is worth considering developing an open-source implementation of ITU-R propagation models to repeat simulations in to have better coverage resolution and comparisons. Finally, it is suggested to develop methods to gather better information from Anatel's database about the technical parameters of DTT stations, as database assumptions were made to estimate the number of operative DTT channels.

REFERENCES

1 International Telecommunications Union (United Nations). *ITU-R Recommendation BT.1306-8*: Error-correction, data framing, modulation and emission methods for digital terrestrial television broadcasting. Last updated in February 2015. Available: <https://www.itu.int/rec/R-REC-BT.1306-8-202004-I/en>.

2 International Telecommunications Union (United Nations). *Status of the Transition to Digital Terrestrial Television*. Available: <https://www.itu.int/en/ITU-D/Spectrum-Broadcasting/DSO/Pages/default.aspx>.

3 International Telecommunications Union (United Nations). *ITU-R Recommendation BT.1877-3*: Error-correction, data framing, modulation and emission methods and selection guidance for second generation digital terrestrial television broadcasting systems. Last updated in April 2021. Available: <https://www.itu.int/rec/R-REC-BT.1877-3-202012-I/en>.

4 NAKAMURA, M.; SATO, A.; MIYASAKA, H.; AASAKURA, S.; SHITOMI, T.; SHIRAI, N.; TAKEUCHI, T.; OKANO, M.; TSUCHIDA, K.; NARIKIYO, Y.; MURAYAMA, K. A study on the transmission system of an Advanced ISDB-T. In: *2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. [S.l.: s.n.], 2019. p. 1–5.

5 European Telecommunications Standards Institute . *5G Broadcast System for linear TV and radio services; LTE-based 5G terrestrial broadcast system*: Etsi ts 103 720 v1.1.1 (2020-12). Available: <https://www.etsi.org/deliver/etsi_ts/103700_103799/103720/01.01.01_60/ts_103720v010101p.pdf>.

6 International Telecommunications Union (United Nations). *ITU-R Recommendation BT.2016-2*: Error-correction, data framing, modulation and emission methods for terrestrial multimedia broadcasting for mobile reception using handheld receivers in VHF/UHF bands. Last updated in September 2022. Available: <https://www.itu.int/rec/R-REC-BT.2016/en>.

7 International Telecommunications Union (United Nations). *ITU-R Report BT.2343-6*: Collection of field trials of uhdtv over dtt networks. Available: <https://www.itu.int/pub/R-REP-BT.2343-6-2020>.

8 EIZMENDI, I.; VELEZ, M.; GóMEZ-BARQUERO, D.; MORGADE, J.; BAENA-LECUYER, V.; SLIMANI, M.; ZOELLNER, J. Dvb-t2: The second generation of terrestrial digital video broadcasting system. *IEEE Transactions on Broadcasting*, v. 60, n. 2, p. 258–271, 2014.

9 European Telecommunications Standards Institute . *Digital Video Broadcasting (DVB); Frame structure channel, channel coding and modulation for a second generation digital terrestrial broadcasting system (DVB-T2)*: Etsi en 302 755 v1.4.1 (2015-07).

10 International Telecommunications Union (United Nations). *Handbook on Digital Terrestrial Television Broadcasting networks and systems implementation*. Last updated in 2016. Available: <https://www.itu.int/dms_pub/itu-r/opb/hdb/R-HDB-21-2015-PDF-E.pdf>.

11 SONG, J.; YANG, Z.; WANG, J. Second-Generation DTTB Standards. In: ____. *Digital Terrestrial Television Broadcasting: Technology and System*. [S.l.: s.n.], 2015. p. 215–254.

12 Federal Communications Commission (United States of America) . *REPORT AND ORDER AND FURTHER NOTICE OF PROPOSED RULEMAKING*: Authorizing Permissive use of the “Next Generation” Broadcast Television Standard, fcc 17-158. 2017. Available: <https://www.fcc.gov/document/fcc-authorizes-next-gen-tv-broadcast-standard-0>.

13 Advanced Television Systems Committee. *ATSC 3.0 System*: A/300:2022-04. 2022. Available: <https://www.atsc.org/atsc-documents/type/3-0-standards/>.

14 NOLAND, M.; WHITAKER, J. Progress report of the advanced television systems committee. *SMPTE Motion Imaging Journal*, v. 131, n. 8, p. 60–63, 2022.

15 AHN, S.; KWON, S.; AHN, S.; JUNG, H.; PARN, S.-I. ATSC 3.0 for future broadcasting: Features and extensibility. *SET Int. J. Broadcast Eng.*, v. 6, p. 21–36, 2020.

16 MICHAEL, L.; GÓMEZ-BARQUERO, D. Bit-interleaved coded modulation (BICM) for ATSC 3.0. *IEEE Transactions on Broadcasting*, IEEE, v. 62, n. 1, p. 181–188, 2016.

17 Advanced Television Systems Committee. *Physical Layer Protocol*: A/322:2022-0,. 2022. Available: <https://www.atsc.org/atsc-documents/type/3-0-standards/>.

18 SONG, J.; ZHANG, C. Technical Review on DTMB-Advanced (DTMB-A) Standard. In: *2016 International Conference on Engineering and Telecommunication (EnT)*. [S.l.: s.n.], 2016. p. 128–133.

19 SONG, J.; ZHANG, C.; PENG, K.; WANG, J.; PAN, C.; YANG, F.; WANG, J.; YANG, H.; XUE, Y.; ZHANG, Y.; YANG, Z. Key Technologies and Measurements for DTMB-A System. *IEEE Transactions on Broadcasting*, v. 65, n. 1, p. 53–64, 2019.

20 NAKAMURA, M.; SATO, A.; MIYASAKA, H.; AASAKURA, S.; SHITOMI, T.; SHIRAI, N.; TAKEUCHI, T.; OKANO, M.; TSUCHIDA, K.; NARIKIYO, Y. et al. A Study on the Transmission System of an Advanced ISDB-T. In: IEEE. *2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. [S.l.], 2019. p. 1–5.

21 OMI, J.; SANTIAGO, N. S.; OLIVEIRA, G. H. M. G. D.; FILHO, E. F.; SANTANA, M. A.; SANTOS, L. N. D.; SOUZA, W. H. S. D.; VALEIRA, G. D. M.; LOPES, P. B.; STOLFI, G.; SANTOS, E. T. C. D.; MELONI, L. G. P.; AKAMINE, C. Performance Analysis of TV 3.0 Over-the-Air Physical Layer Protocols. In: *2022 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. [S.l.: s.n.], 2022. p. 1–5.

22 SHITOMI, T.; ASANURA, S.; KAWASHIMA, S.; SATO, A.; MIYASANA, H.; SHIRAI, N.; NARINIYO, Y.; TANEUCHI, T.; KAMBARA, K.; NANAMURA, M. et al. Fixed reception performance of FDM-based transmission system for advanced ISDB-T. *Set Int. J. Broadcast Eng.*, v. 6, p. 11, 2020.

23 SATO, A.; SHITOMI, T.; TAKEUCHI, T.; NAKAMURA, M.; OKANO, M.; TSUCHIDA, K. Study on hierarchical transmission toward the advanced ISDB-T development : – Comparison of FDM with LDM –. In: *2019 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. [S.l.: s.n.], 2019. p. 1–5.

24 FURUYA, K.; ASAKURA, S.; KAMBARA, K.; OKANO, M.; SAITO, K. Verification of Low-Latency Channel for Advanced ISDB-T. In: *2022 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. [S.l.: s.n.], 2022. p. 1–6.

25 European Broadcasting Union. *Contribution 6A/156 submitted to ITU-R Study Group 6 (Broadcasting) Working Party 6A meeting*: Introduction of 5G broadcast in ITU SG6 documents. Available: <https://www.itu.int/md/R19-WP6A-C-0156/en>.

26 Brazilian Digital Terrestrial Television System Forum. *Call for Proposals: TV 3.0 Project*. Available: <https://forumsbtvd.org.br/tv3_0/>.

27 Brazil (Federative Republic of). *Contribution 6/210 submitted to ITU-R Study Group 6 (Broadcasting) meeting*: Brazilian Next generation Digital Terrestrial Television (Information Document). Available: <https://www.itu.int/md/R19-SG06-C-0210/en>.

28 Brazil (Federative Republic of). *Contribution 6/249 submitted to ITU-R Study Group 6 (Broadcasting) meeting*: Brazilian next generation digital terrestrial television (information document). Available: <https://www.itu.int/md/R19-SG06-C-0249/en>.

29 STARE, E.; GIMENEZ, J.; KLENNER, P. WiB – A New System Concept for Digital Terrestrial Television (DTT). *EBU Technical Review*, 03 2017.

30 GOMEZ-BARQUERO, D.; LEE, J.-Y.; AHN, S.; AKAMINE, C.; HE, D.; MONTALABAN, J.; WANG, J.; LI, W.; WU, Y. Ieee transactions on broadcasting special issue on: Convergence of broadcast and broadband in the 5g era. *IEEE Transactions on Broadcasting*, v. 66, n. 2, p. 383–389, 2020.

31 International Telecommunications Union (United Nations). 2020. (ITU Radio Regulations, v. 1). Available: <https://www.itu.int/pub/R-REG-RR>.

32 PAHL, J. *Interference Analysis: modelling radio systems for spectrum management*. [S.l.]: John Wiley & Sons, 2016.

33 International Telecommunications Union (United Nations). *Handbook National Spectrum Management*. Last updated in 2015. Available: <https://www.itu.int/dms_pub/itu-r/opb/hdb/R-HDB-21-2015-PDF-E.pdf>.

34 National Agency of Telecommunications (Brazil). *Plano de Uso do Espectro de Radiofrequências no Brasil, 2021 a 2028*. Available: <https://www.gov.br/anatel/pt-br/regulado/radiofrequencia/plano-de-uso-do-espectro-de-radiofrequencias>.

35 EL-MOGHAZI, M. A.; WHALLEY, J. et al. The international radio regulations. *Springer Books*, Springer, 2021.

36 MANNER, J. A. *Spectrum Wars: The Rise of 5G and Beyond*. [S.l.]: Artech House, 2021.

37 National Agency of Telecommunications (Brazil). *Resolução nº 721, de 11 de fevereiro de 2020. publicado no Diário Oficial da União em 12 de fevereiro de 2020*. Available: <https://informacoes.anatel.gov.br/legislacao/resolucoes/2020/1383-resolucao-721>.

38 Ministry of Communications (Brazil). *Portaria nº 14, de 6 de fevereiro de 2013*: Estabelece diretrizes para a aceleração do acesso ao sistema brasileiro de televisão digital terrestre - sbtvd-t e para a ampliação da disponibilidade de espectro de radiofrequência para atendimento dos objetivos do programa nacional de banda larga - pnb. Publicada no Diário Oficial da União em 7 de fevereiro de 2013. Available: <https://www2.camara.leg.br/comunicacao/rede-legislativa-radio-tv/arquivos/legislacao-arquivos/portarias-ministerio/Portarian1406FEV2013Desocupaodafaixa700MHz.pdf>.

39 National Agency of Telecommunications (Brazil). *Resolução nº 625, de 11 de novembro de 2013. publicado no Diário Oficial da União em 14 de novembro de 2013*. Available: <https://informacoes.anatel.gov.br/legislacao/resolucoes/2013/644-resolucao-625>.

40 International Telecommunications Union (United Nations). *RESOLUTION 811 (WRC-19)*: Agenda item 1.5 for the 2023 World Radiocommunication Conference. Available: <https://www.itu.int/dms_pub/itu-r/oth/0c/0a/R0C0A00000D0041PDFE.pdf>.

41 International Telecommunications Union (United Nations). *FINAL ACTS of the World Radiocommunication Conference (WRC-2007)*. Available: <https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.8-2007-PDF-E.pdf>.

42 International Telecommunications Union (United Nations). *FINAL ACTS of the World Radiocommunication Conference (WRC-2015)*. Available: <https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.12-2015-PDF-E.pdf>.

43 International Telecommunications Union (United Nations). *FINAL ACTS of the World Radiocommunication Conference (WRC-2012)*. Available: <https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.9-2012-PDF-E.pdf>.

44 International Telecommunications Union (United Nations). *FINAL ACTS of the World Radiocommunication Conference (WRC-2019)*. Available: <https://www.itu.int/dms_pub/itu-r/opb/act/R-ACT-WRC.14-2019-PDF-E.pdf>.

45 Research and Development Center in Telecommunications - CPqD. *Planejamento de Canais de Televisão Digital,PD.33.10.53A.0007A/RT-01-AB*. 2003.

46 Brazil (Federative Republic of). *Decreto nº 5820, de 29 de junho de 2006*: Dispõe sobre a implantação do sbtvd-t, estabelece diretrizes para a transição do sistema de transmissão analógica para o sistema de transmissão digital do serviço de radiodifusão de sons e imagens e do serviço de retransmissão de televisão, e dá outras providências. Publicado no Diário Oficial da União em 30 de junho de 2006. Available: <http://www.planalto.gov.br/ccivil_03/_ato2004-2006/2006/decreto/d5820.htm>.

47 International Telecommunications Union (United Nations). *ITU-R Report BT.2140-13*: Transition from analogue to digital terrestrial broadcasting. Last updated in March 2021. Available: <https://www.itu.int/pub/R-REP-BT.2140-13-2021>.

48 National Agency of Telecommunications (Brazil). *Edita de Licitação nº 2/2014-SOR/SPR/CD-ANATEL, de 21 de agosto de 2014. publicado no Portal de Anatel em 21 de agosto de 2014*. Available: <https://sei.anatel.gov.br/sei/modulos/pesquisa/md_pesq_documento_consulta_externa.php?eEP-wqk1skrd8hSlk5Z3rN4EVg9uLJqrLYJw_9INcO5i_L0bEBLbZbCPVcrUx73hkr1VVOJ1e7TlbuTvL6obH0Kec6fdzJmfN_hsplR28Fb_8IS2YcL4W8bhAa_3DL7->.

49 Ministry of Communications (Brazil). *Portaria nº 2.992, de 26 de maio de 2017*: Estabelece o cronograma de transição datransmissão analógica dos serviços de radiodifusãode sons e imagens e de retransmissãode televisão para o sbtvd-t. Publicada no Diário Oficial da União em 28 de maio de 2017. Available: <https://www.in.gov.br/materia/-/asset_publisher/Kujrw0TZC2Mb/content/id/20242266/do1-2017-05-29-portaria-n-2-992-de-26-de-maio-de-2017-20242069>.

50 National Agency of Telecommunications (Brazil). *Plano Básico de Distribuição de Canais de Televisão Digital*. Available: <http://sistemas.anatel.gov.br/se/public/view/b/srd.php>.

51 Ministry of Communications (Brazil). *Portaria nº 159, de 11 de junho de 2013*: Autoriza o funcionamento em caráter provisório das entidades prestadoras de serviços de radiodifusão e seus ancilares. Publicada no Diário Oficial da União em 12 de junho de 2013.

52 National Agency of Telecommunications (Brazil). *Requisitos Técnicos de Condições de Uso de Radiofrequências para os Serviços de Radiodifusão de Sons e Imagens e de Retransmissão de Televisão, aprovado pelo Ato nº 9.751, de 06 de julho de 2022. publicado no Diário Oficial da União em 18 de julho de 2022*. Available: <https://informacoes.anatel.gov.br/legislacao/atos-de-requisitos-tecnicos-de-gestao-do-espectro/2022/1688-ato-9751>.

53 International Telecommunications Union (United Nations). *ITU-R Recommendation BT.1546-6*: Method for point-to-area predictions for terrestrial services in the frequency range 30 MHz to 4 000 MHz. Last updated in August 2019. Available: <https://www.itu.int/rec/R-REC-P.1546/en>.

54 ARAGóN-ZAVALA, A.; ANGUEIRA, P.; MONTALBAN, J.; VARGAS-ROSALES, C. Radio propagation in terrestrial broadcasting television systems: A comprehensive survey. *IEEE Access*, v. 9, p. 34789–34817, 2021.

55 International Telecommunications Union (United Nations). *ITU-R Recommendation BT.1812-5*: A path-specific propagation prediction method for point-to-area terrestrial services in the frequency range 30 MHz to 6 000 MHz. Last updated in August 2019. Available: <https://www.itu.int/rec/R-REC-P.1812/en>.

56 Spectrum Center. *ITU-R P.1812-5*: Terrestrial point-to-area service propagation prediction method in the vhf and uhf bands, March 31st 2020. Available: <https://public.spectrum.center/public/wp-content/uploads/2020/04/ITU-R-P.1812-5-Report_vfinal.pdf>.

57 Ministry of Communications (Brazil). *Resposta à Manifestação Fala.BR 53125.000975/2022-10.*

58 Ministry of Communications (Brazil). *Portaria nº 2.524, de 04 de maio de 2021*: Institui o programa digitaliza brasil, que estabelece as diretrizes para a conclusão do processo de digitalização dos sinais da televisão analógica terrestre no brasil e dá outras providências. Publicada no Diário Oficial da União em 05 de maio de 2021. Available: <https://www.in.gov.br/en/web/dou/-/portaria-mcom-n-2.524-de-4-de-maio-de-2021-317928590>.

59 National Agency of Telecommunications (Brazil). *Acórdão nº 242, de 28 de junho de 2021. publicado no Boletim de Serviço Eletrônico da Anatel em 29 de junho de 2021.*

60 Brazil (Federative Republic of). *Contribution 6A/317 submitted to the Working Party 6A of ITU-R Study Group 6 (Broadcasting) meeting*: Proposal for modifications of report itu-r bt.2140. Available: <https://www.itu.int/md/R19-WP6A-C-0317/en>.

61 National Agency of Telecommunications (Brazil). *Resolução nº 747, de 05 de outubro de 2021. publicado no Diário Oficial da União em 06 de outubro de 2021.* Available: <https://informacoes.anatel.gov.br/legislacao/index.php/component/content/article?id=1593>.

62 Brazil (Federative Republic of). *Decreto nº 8139, de 07 de novembro de 2013*: Dispõe sobre as condições para extinção do serviço de radiodifusão sonora em ondas médias de caráter local, sobre a adaptação das outorgas vigentes para execução deste serviço e dá outras providências. Publicado no Diário Oficial da União em 08 de novembro de 2013. Available: <http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2013/decreto/d8139.htm>.

63 National Agency of Telecommunications (Brazil). *Requisitos Técnicos de Condições de Uso de Radiofrequências para os Serviços de Radiodifusão Sonora em Frequência Modulada, Retransmissão de Rádio na Amazônia Legal e Radiodifusão Comunitária, aprovado pelo Ato nº 8.104, de 10 de junho de 2022. publicado no Diário Oficial da União em 18 de junho de 2022.* Available: <https://informacoes.anatel.gov.br/legislacao/atos-de-requisitos-tecnicos-de-gestao-do-espectro/2022/1687-ato-8104>.

64 Inter-American Telecommunication Commission (CITEL), Permanent Consultative Committee II: Radiocommunications (CCP.II). *Resolution PCC.II/REC. 66 (XXXIX-22)*: Fm sound broadcasting services in the 76-88 mhz frequency band. 2022. Available: <https://www.oas.org/citelevents/en/Documents/DocumentsFile/2620>.

65 Mercado Comum do Sul (MERCOSUL). *Resolução 47/2021*: Marco regulatÓrio para o serviÇo de radiodifusÃo sonora em frequÊncia modulada (fm) (modificaÇÃo da resoluÇÃo gmc n° 31/01). 2021. Available: <https://normas.mercosur.int/public/normativas/4235>.

66 Federal Communications Commission (United States of America) . *Amendment of Parts 73 and 74 of the Commission's Rules to Establish Rules for Digital Low Power Television and Television Translator Stations*: The commission adopts a notice of proposed rulemaking regarding a proposal to allow certain channel 6 low power television stations to continue to provide fm radio service as an ancillary or supplementary service under specified conditions, fcc-22-40. 2022. Available: <https://www.fcc.gov/document/fcc-seeks-comment-channel-6-lptv-stations-maintaining-fm-service>.

67 Brazilian Digital Terrestrial Television System Forum). *Testing and Evaluation Report:TV 3.0 Project - Over-the-air Physical Layer Laboratory Tests*. Available: <https://forumsbtvd.org.br/wp-content/uploads/2021/12/SBTVD-TV_3_0-PL-Lab-Report.pdf>.

68 Brazilian Digital Terrestrial Television System Forum). *Testing and Evaluation Report:TV 3.0 Project - Over-the-air Physical Layer Field Tests*. Available: <https://forumsbtvd.org.br/wp-content/uploads/2021/12/SBTVD-TV_3_0-PL-Field-Report.pdf>.

69 International Telecommunications Union (United Nations). *ITU-R Recommendation SM.1046-3*: Definition of spectrum use and efficiency of a radio system. Last updated in September 2017. Available: <https://www.itu.int/rec/R-REC-SM.1046-3-201709-I/en>.

70 Federal Communications Commission (United States of America) . *SECOND FURTHER NOTICE OF PROPOSED RULEMAKING*: Authorizing Permissive use of the “Next Generation” Broadcast Television Standard, fcc 21-116. 2021. Available: <https://www.fcc.gov/document/fcc-seeks-comment-atsc-30-multicast-requirements>.

71 3GPP. *3rd Generation Partnership Project; Technical Specification Group Radio Access Network; US 600 MHz Band for LTE; (Release 15)*: TR 36.755 V15.0.0 (2017-09). 2017. Available: <https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3200>.

72 3GPP. *3rd Generation Partnership Project;Technical Specification Group Radio Access Network;NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone(Release 17)*: Ts 38.101-1 v17.7.0 (2022-09). 2022. Available: <https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3283>.

73 International Telecommunications Union (United Nations). *ITU-R Recommendation SM.1036-6*: Frequency arrangements for implementation of the terrestrial component of International Mobile Telecommunications (IMT) in the bands identified for IMT in the Radio Regulations. Last updated in October 2019. Available: <https://www.itu.int/rec/R-REC-M.1036>.

74 International Telecommunications Union (United Nations). *ITU-R Report M.2480-1*: national approaches of some countries on the implementation of terrestrial imt systems in bands identified for imt.

75 International Telecommunications Union (United Nations). *ITU-R Report BT.2337-1*: Sharing and compatibility studies between digital terrestrial television broadcasting and terrestrial mobile broadband applications, including imt, in the frequency band 470-694/698 MHz. Last updated in November 2017. Available: <https://www.itu.int/pub/R-REP-BT.2337>.

76 International Telecommunications Union (United Nations). *ITU-R Report BT.2247-3*: Field measurement and analysis of compatibility between dttb and imt. Available: <https://www.itu.int/pub/R-REP-BT.2247-3-2015>.

77 EL-MOGHAZI, M.; WHALLEY, J. IMT-2020 standardization: Lessons from 5G and future perspectives for 6G. *Available at SSRN 3901148*, 2021.

78 European Broadcasting Union - Broadcast Network Europe. *Contribution 6-1/120 submitted to ITU-R Task Group 6/1*: Co-channel sharing study between mobile and broadcasting services - potencial impact of dttb in spain into posible imt in north africa below 694 mhz. Available: <https://www.itu.int/md/R19-TG6.1-C-0120/en>.

79 OYAMA, T.; SHIMOMURA, T.; SEKI, H. Tv white space availability in japan estimated using d/u-based and i/n-based protection rules. In: *2012 IEEE Global Communications Conference (GLOBECOM)*. [S.l.: s.n.], 2012. p. 1302–1307.

80 Mercado Común del Sur - Mercosur. *MERCOSUR/CTRd/ACTA Nº 1/2022*: LVIII Reunión Ordinaria de la Comisión Temática de Radiodifusión. 2022. Available: <https://documentos.mercosur.int/public/reuniones/doc/8980>.

81 Brazil (Federative Republic of). *Decreto nº 10312, de 04 de abril de 2020*: Amplia, temporariamente, o escopo de multiprogramação com conteúdo específico destinado às atividades de educação, ciência, tecnologia, inovações, cidadania e saúde de entidades executoras de serviço de radiodifusão de sons e imagens em tecnologia digital, com fins exclusivamente educacionais ou de exploração comercial, em razão da pandemia da covid-19. Publicado no Diário Oficial da União em 04 de abril de 2020. Available: <http://www.planalto.gov.br/ccivil_03/_ato2019-2022/2020/decreto/D10312.htm>.

82 Organisation for Economic Cooperation and Development (OECD). *OECD Telecommunication and Broadcasting Review of Brazil 2020*. 2020. Available: <https://www.oecd.org/digital/broadband/oecd-telecommunication-and-broadcasting-review-of-brazil-2020-30ab8568-en.htm>.

83 Ministry of Communications (Brazil). *Resposta à Manifestação Fala.BR 53125.001726/2022-33*.

84 Federal Communications Commission (United States of America) . *Promoting Broadcast Internet Innovation through ATSC 3.0*: Report and order – mb docket no. 20-145. 2020. Available: <https://www.fcc.gov/document/promoting-broadcast-internet-innovation-through-atsc-30-0>.

85 United States of America. *Contribution 6A/79 submitted to ITU-R Study Group 6 (Broadcasting) Working Party 6A meeting*: Information document: An atsc 3.0 broadcast 5g heterogeneous network. Available: <https://www.itu.int/md/R19-WP6A-C-0079/en>.

86 CARDOSO, Paulo Eduardo dos Reis. *Avaliação da implementação da TV digital: propostas regulatórias para melhoria da qualidade do serviço prestado*: Tese (doutorado) - Universidade Estadual de Campinas, Faculdade de Engenharia Elétrica e de Computação, Campinas, SP. 2018. Available: <https://hdl.handle.net/20.500.12733/1635764>.