A brief Overview TV White Space Technology around the World

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Abstract

The last two decades has seen tremendous development in the field of Wireless Communications. There is a growing need for data on the go and to cater to these needs the current resources are falling short. However, the resource for wireless communication, i.e. frequency spectrum is limited and significant research has been done in the past years to utilize this resource efficiently. TV White Spaces is a new concept that has emerged while studying the utilization of the TV band in various regions of the world. The study of TVWS has generated a ot of interest in regulators, researchers and industrialists all across the globe. Several advancements have occured in this sector and several milestones have been reached. In this document, we briefly review some of the latest developments in the field of TV White Spaces, some key challenges in deployment of networks based on TVWS and the current scenario of TVWS in India.

Contents

1 Introduction **1**

2 TV White Space around the world **4**
2.1 TV White Space in United States 4
2.1.1 Regulations 4
2.1.2 Spectrum-sensing 6
2.1.3 Geolocation databases 7
2.1.4 Beacon 8
2.1.5 Quantitative Analysis in United States 8
2.2 TV White Space in United Kingdom 9
2.2.1 Regulations 9
2.2.2 Quantitative Analysis in United Kingdom 12
2.3 TV White Space in Japan 13
2.3.1 Regulations 13
2.3.2 Quantitative Analysis in Japan 14
2.4 TV White Space in Europe 15
2.4.1 Regulations 15
2.4.2 WISE Project 17

3 Key challenges in TV White Space operation **18**
3.1 Challenges related to geo-location databases 18
3.2 Coexistence challenges 20
3.2.1 TVWS Standards 20
3.2.2 Co-channel coexistence 24
3.2.3 Adjacent channel coexistence 25
3.3 Other Challenges 25

4 TV White Space in India **27**
4.1 Current Scenario 27
4.2 Quantitative Analysis of TV White Space in India 28
4.2.1 Methodology 28
4.2.2 Experimental Results 29

5 Use cases of TV White Spaces in India **34**
5.1 Design of backhaul networks operating in TV bands 34
5.1.1 Regulatory Aspects 35
5.1.2 Technical Aspects 35

6 Conclusion **39**

List of Tables

2.1 Key parameters for sensing 10
2.2 Key parameters for geolocation 11
2.3 Expected ASO Dates for some European countries 16

3.1 Comparison of various TV White Space standards 23

4.1 Comparison of power obtained by experiment and analysis at 180 MHz 31
4.2 Comparison of power obtained by experiment and analysis at 220 MHz 32

List of Figures

1.1 Under-utilized specrum in the Broadcast TV band and ISM band. Adopted from [1] 1
1.2 The concept of TV White Space. Adopted from [3] 2
1.3 Available capacity using TV white spaces. Adopted from [7] . 3

2.1 Categorization of secondary TV band devices by FCC. Adopted from [9] 5
2.2 Protected radius and the seperation distance. Adopted from [19] 6
2.3 Functioning of the Comsearch TV White Space database. Adopted from [12] 7
2.4 Telcordia TV White Space database. [13] 8
2.5 UHF Band channels in the UK after Digital Switchover. Adopted from [14] 9
2.6 List of channels available in London as provided by Spectrum Bridge Inc.'s database[16] 12
2.7 Available number of TV channels at 18 locations in UK. Adopted from [17] 13
2.8 NICT White Space database for Japan [18] 14
2.9 Expected available channels in Japanese metropolitan areas. Adopted from [19] 15
2.10 Fairspectrum White Space database for Finland 17

3.1 Interference among two secondary networks. Adopted from [29] 24

4.1 Sensing results at 1 km from the TV Transmitter 29
4.2 Sensing results at 13 km from the TV Transmitter 30
4.3 Received power v/s Distance at 180 MHz 33
4.4 Received power v/s distance at 224 MHz 33

Chapter 1

Introduction

With the rapid development of technology the need for increased data rates, and hence bandwidth has increased tremendously over the past couple of decades. While the number of users and services keep growing, the available resource, i.e. spectrum remains limited. In the past, researchers have tried to increase the utilization of the available spectrum via several coding schemes, and this remains a research area even today. However, recently several studies have shown that by and large in most frequency bands in almost all areas the spectrum is under-utilized. Figure 1.1 [1] shows the spectrum allotment across all frequency bands in the United States.

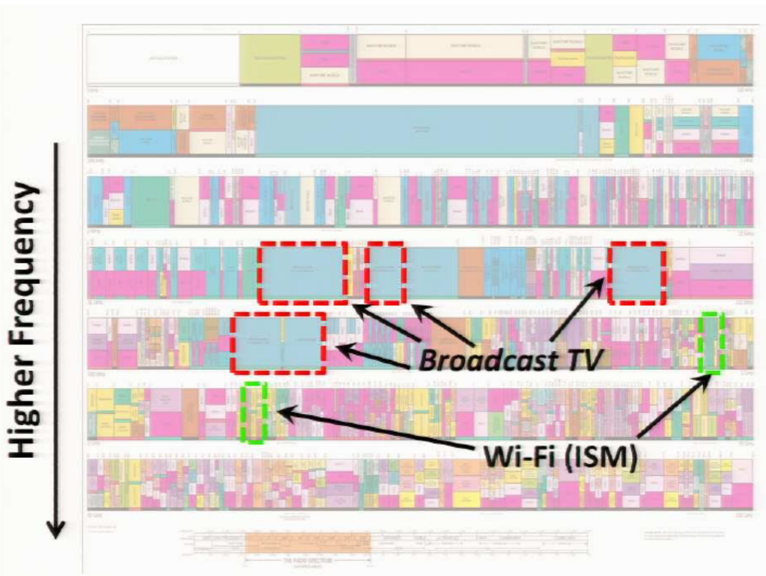


Figure 1.1: Under-utilized specrum in the Broadcast TV band and ISM band. Adopted from [1]

Among all the under-utilized chunks of spectrum, of particular interest are the Low VHF (Channels 2, 5 and 6), High VHF (Channels 7 to 13), Low UHF (Channels 14 to 51) and High UHF (Channels 52 to 69). Figure 1.1 shows this portion of the spectrum and compares it with the 2.4GHz and 5GHz ISM band. It is clear that the amount of spectrum under-utilized in the TV bands is much larger than that available for the current unlicensed applications. This sub-GHz band provides much more superior propagation characteristics as compared to the higher frequency bands, and this makes the TV spectrum expremely lucrative for wireless service providers. The Federal Communication Commission (FCC) realized the potential of such spectrum and issued a R&O on its unlicensed use in November 2008[2]. Several other countries such as The United Kingdom and Singapore have followed suit and worked towards unlicensed usage of such under-utilized spectrum.

FCC termed the unused TV spectrum as TV white space. In general, any part of the spectrum that is unused is termed as a white space. In this context, the users which have been alloted the spectrum via auction (or other mechanism) by the regulator of the particular country are termed as primary users, or simply primary. The users that make use of this spectrum when it is not being utilized by the primary, are called as secondary users or simply secondary. Figure 1.2 presents a brief idea of the existence of white spaces in between the primary user coverage areas[3].

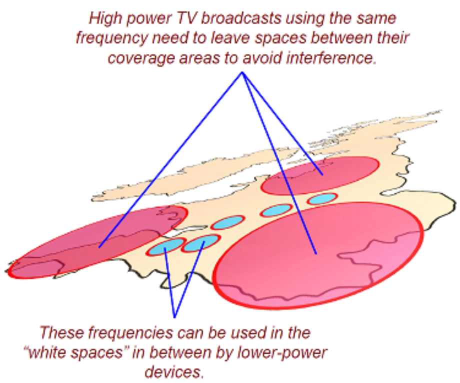


Figure 1.2: The concept of TV White Space. Adopted from [3]

Even though a significant chunk of the TV spectrum remains under-utilized, the actual unutilized spectrum available varies significantly spatially as well as temporally. A lot of research has been done on how much bandwidth can be freed up and how much capacity can be achieved by using TV white spaces[5][6][7]. These calculations take into consideration the random behavior of the primary transmitters and also their geo-spatial locations. Some studies also take into consideration the population and its distribution close to the primary transmitter.This gives a more realistic picture since the number of TV transmitters in densely populated areas is generally high leading to lesser white space. Figure 1.3 [7] shows the available capacity using TV white spaces as estimated in (sahai reference). It clearly indicates presence of significantly large amount of White Space all across continental United States, except possibly in the major cities like New York, Philadelphia, Washington D.C. etc.

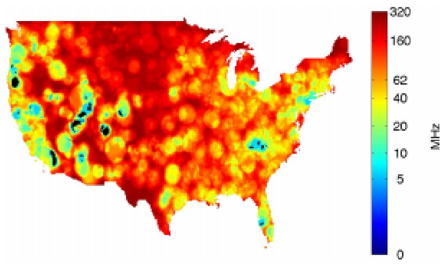


Figure 1.3: Available capacity using TV white spaces. Adopted from [7]

Chapter 2

TV White Space around the world

2.1 TV White Space in United States

2.1.1 Regulations

The Federal Communications Commission (FCC) was the reglatory body that first realized and took a step forward at utilizing the white spaces in the TV band. The FCC set several rules regarding the operation of secondary devices in the TVWS**??**. Such devices operating according to the rules set forth by the FCC were formally termed TV Band Devices (TVBDs). The primary objective of the FCC while formulatiing the rules for TVBD operations were to protect the interests of the licensed services. With this in view, the FCC categorized the TVBDs into two classes, viz. fixed and personal/portable(Figure 2.1). The personal/portable devices are further classified into Mode I and Mode II devices. The fixed devices, under no circumstances, are allowed to transmit beyond 36dBm (30dBm Power plus 6dBi antenna gain). The portable devices, on the other hand, are not allowed any antenna gain, and are not to exceed the transmission power by 20dBm.

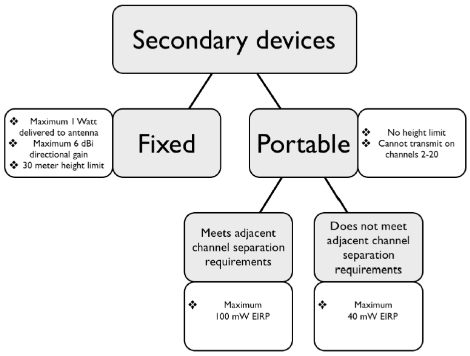


Figure 2.1: Categorization of secondary TV band devices by FCC. Adopted from [9]

The fixed devices have a specified limit on height above average terrain (HAAT). This HAAT varies from place to place and all fixed devices are expected to adhere to this limit and at no given place, should the HAAT exceed 30 metres.

In addition to all these constraints, the secondary devices have to ensure that they do not get 'too close' to the primary receivers. As studied in [9], the FCC regulations provide a certain 'protected radius (r_p)'. The protected radius is a parameter of each TV tower and as the name suggests, it indicates the minimum distance around the transmitter upto which the signal transmitted by the transmitter is successfully decoded by the TV receiver. In addition to r_p, the secondary transmitters need to maintain an additional (r_n - r_p) distance from the protected radius. This additional distance is to ensure that no TV receiver at the boundary of the protected radius experiences any interference from the secondary transmitters. These precautions need to be taken on co-channel as well as the adjacent channel. Typical values of (r_n - r_p) range from 6.0 km to 14.4 km for co-channel operation and 0.1 km to 0.74 km for adjacent channel operation. Figure 2.2 shows the protected radius r_p and the 'seperation distance' (r_n - r_p) as measured from the TV tower.

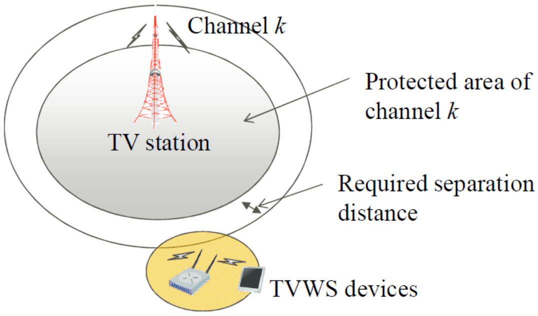


Figure 2.2: Protected radius and the seperation distance. Adopted from [19]

One of the most important tasks to be performed by the cognitive-capable secondary device is to detect the presence of primary services in its vicinity. Several mechanisms have proposed to this effect till date, and at present the two most important mechanisms are Geolocation databases and Spectrum-sensing.

2.1.2 Spectrum-sensing

When the FCC listed the rules to be followed by the secondary devices, the technology of choice for determining the presence of primary devices was spectrum sensing. Every secondary transmitter has to sense the spectrum to ascertain the absence of primary devices in the channel. The secondary device can use the channel only if the channel was found to be vacant (no primary transmission). The natural question that arose was - when to declare a channel as unoccupied? To answer this, the FCC provided with a threshold of -114dBm. Thus, any signal with power level greater than -114dBm would indicate the presence of a primary device in that band. However, as time progressed several studies indicated that the -114dBm threshold was too conservative[10]. Moreover, it could very well be possible that during the sensing instant the channel was in deep fade and the primary signal simply went unnoticed. This, along with several other factors made it necessary to develop a more reliable technique for detecting the presence of primary services in the band. At the same time, the spectrum sensing solution has not been totally discarded and is generally proposed as a supplementary solution along with geo-location databases.

Some common techniques for spectum sensing include the following.

- Energy detection
- Matched filtering
- Covariance based detection

- Cyclostationary detection

A detailed analysis of the spectrum sensing techniques, and their usefulness in the TV band can be found in [11]

2.1.3 Geolocation databases

In order to protect the primary services, the TVBD need to determine their location using GPS or any other suitable mechanism and then consult a 'geo-location' database[10] to determine which frequencies they can use at their location. In respone, the database provides a list of channels which can be used by the secondary device to transmit. TVBDs are not allowed to transmit until they have successfully determined from the database which channels, if any, are available at that location.In addition to the list of available channels, the database (optionally) provides the transmitting power and the HAAT.
In United States, the FCC decided to privatize the development of TV White Space databases and allowed 13 database providers, including Microsoft Inc., Google Inc. etc., to develop their respective databases. Among the 13 database providers, only 2 providers - Spectrum Bridge Inc. and Telcordia, have successfully tested their systems and have been approved by the FCC. Figure 2.3. shows the functioning of a typical TV White Space database provider (Comsearch).

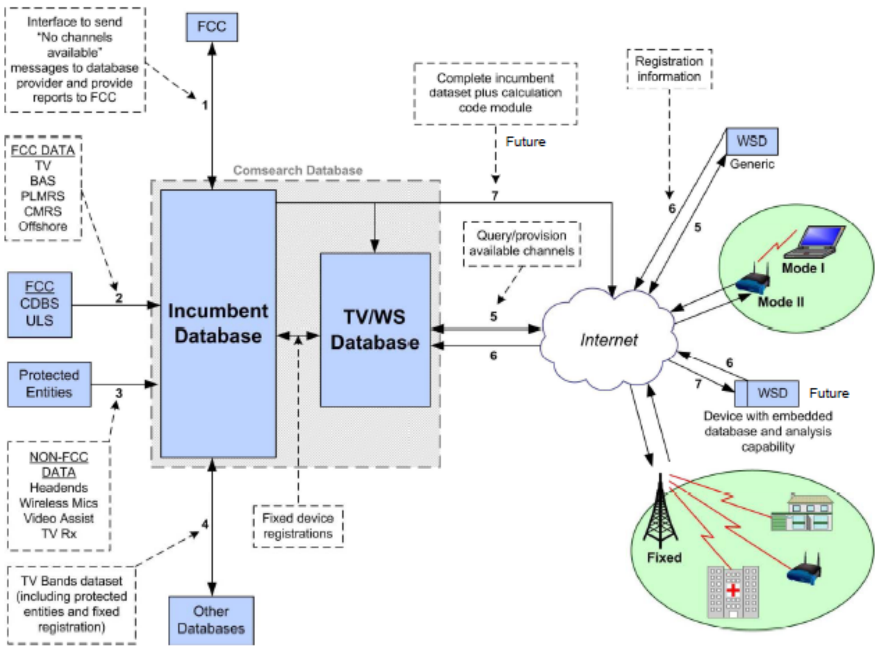


Figure 2.3: Functioning of the Comsearch TV White Space database. Adopted from [12]

Figure 2.4 shows a snapshot of the list of available channels at Scott, PA as taken from the Telcordia TVWS database.

Figure 2.4: Telcordia TV White Space database. [13]

2.1.4 Beacon

Besides Spectrum sensing and geolocation databases, there have been a few solutions proposed for detecting the presence of a primary device in the vicinity of the secondary transmitter. One such technique is the use of beacons. Beacons are signals which can be used to indicate that particular channels are either in use by protected services or vacant. The use of beacons can ease the performance requirements on devices that use spectrum sensing, by increasing the likelihood of detection at higher threshold values. The beacon used could be an enabling beacon or a disabling beacon. The enabling beacon, if received by the secondary device, would indicate that the particular channel can be used by the secondary device. In contrast, the disabling beacon would indicate that a primary device is using the particular channel and the secondary device would be forbidden to use the channel for its operation. The use of beacon signals have not received significant attention as compared to spectrum sensing or geolocation database approach, but can be used as a potential solution to the primary detection problem.

2.1.5 Quantitative Analysis in United States

To quantify the exact amount of white space availale and the capacity that can be achieved using these white spaces several studies have been carried out in the US[5][6][7][8]. We look at the approach followed in [8]. The study assumes that all the TV transmitters in the FCC high power database and master low power database are transmitting. The analysis considers only fixed devices and assumes them to be operating in channels 2, 536 and 38-

51. It takes into consideration the population data available from the US census and assumes the population to be distributed uniformly across each zip-code polygon. Some of the main results of this study is presented in [6][7][8].

2.2 TV White Space in United Kingdom

2.2.1 Regulations

All the regulatory tasks related to communication industry is carried out by Ofcom in the United Kingdom. Following the FCC's take on TV White Spaces, the Ofcom in 2007 released the Digital Dividend Review Statement [14]. The UK Government decided to cease the operation of analog TV transmitters by 2012. This would allow the Digital TV Transmitters (DTT) to cover as much of the country as the Ananlog TV transmitters initially covered. This changeover would have two major consequences. Firstly, the number and range of services provided via terrestrial TV in the UK would increase significantly, and secondly, a large amount of spectrum would become available. This was termed as Digital Dividend and could be usable for other services on licensed or unlicenses basis. This review proposed to allow license exempt use of interleaved spectrum for cognitive devices. In the review, Ofcom also stated 'We see significant scope for cognitive equipments using interleaved spectrum to emerge and to benefit from international economics of scale'. Figure 2.5 shows the channels retained by the Ofcom for Digital broadcasting and those released by Digital Dividend.

Figure 2.5: UHF Band channels in the UK after Digital Switchover. Adopted from [14]

In 2009, the Ofcom released a new consultation on license-exempting cognitive devices using interleaved spectrum[15]. In this review, the Ofcom suggested the use of geo-location databases,sensing and the beacon signals for detecting the presence of and avoiding interference to the primary device. The secondary devices were to either solely rely on spectrum sensing, or make use of geolocation databases or a combination of these. The bandwidth of each TV channel in the United Kingdom is 8 MHz. The Ofcom set certain rules that needed to be followed by the secondary devices while using the white spaces. Table 2.1 lists the parameters in the scenario where the secondary device uses only spectrum sensing, while table 2.2 lists the parameters when the cognitive device uses only geolocation database. These parameters have been obtained by a mix of theory and measurement by the Ofcom.

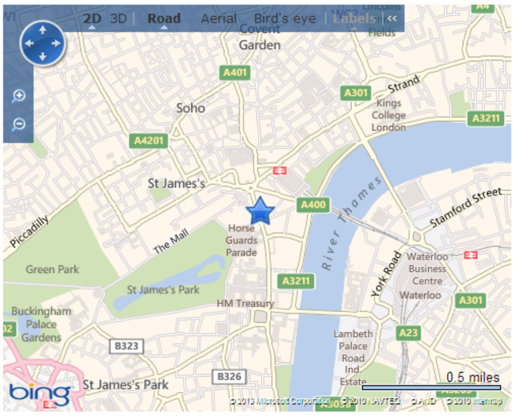
Table 2.1: Key parameters for sensing

Sensitivity assuming a 0 dBi antenna	-114 dBm in 8 MHz channel (DTT), -126 dBm in 200 kHz channel (wireless microphones)
Transmit power	13 dBm (adjacent channels) to 20dBm
Transmit-power control	Required
Bandwidth	Unlimited
Out of band performance	less than -44dBm
Time between sensing	less than 1 second
Maximum continuous transmission	400 milliseconds
Minimum pause after transmission	100 milliseconds

Table 2.2: Key parameters for geolocation

Location accuracy	100 metres
Frequency of database access	to be determined
Transmit power	As specified by the database
Transmit-power control	Required
Bandwidth	Unlimited
Out of band performance	less than -44dBm
Maximum continuous transmission	400 milliseconds
Minimum pause after transmission	100 milliseconds

As far as developing the geolocation database was concerned, there is to be a 'master' database that would contain the list of channels available for cognitive devices at every location in the UK. The licensed spectrum users are required to provide information regarding the time and the location of their spectrum usage, while the cognitive devices are required to access this database and determine the list of available channels at its location. There could be multiple copies of this master database, but with the condition that each copy database would have accurate and up-to-date version of the master database.
At present, two database providers, Spectrum Bridge Inc. and Fairspectrum provide geolocation database service in the United Kingdom. Figure 2.6 shows the list of available channels in London as provided by the Spectrum Bridge Inc.'s database.



The table shows all the TV channels between channels 21 and 60 that are potentially available for secondary use by White Space radios (i.e. TV Band Devices or TVBDs).

Available Channels

View Full Map

21	✗ < 0 dBm	35	✗ < 0 dBm	48	✗ < 0 dBm
22	✗ < 0 dBm	36	✗ < 0 dBm	49	✗ < 0 dBm
23	✗ < 0 dBm	37	✗ < 0 dBm	50	✗ < 0 dBm
24	✗ < 0 dBm	38	✗ < 0 dBm	51	✗ < 0 dBm
25	✗ < 0 dBm	39	✗ < 0 dBm	52	✗ < 0 dBm
26	✗ < 0 dBm	40	✓ 9 dBm	53	✗ < 0 dBm
27	✗ < 0 dBm	41	✗ < 0 dBm	54	✗ < 0 dBm
28	✗ < 0 dBm	42	✗ < 0 dBm	55	✗ < 0 dBm
29	✗ < 0 dBm	43	✗ < 0 dBm	56	✗ < 0 dBm
30	✗ < 0 dBm	44	✗ < 0 dBm	57	✗ < 0 dBm
31	✗ < 0 dBm	45	✗ < 0 dBm	58	✗ < 0 dBm
32	✗ < 0 dBm	46	✗ < 0 dBm	59	✗ < 0 dBm
33	✗ < 0 dBm	47	✗ < 0 dBm	60	✗ < 0 dBm
34	✗ < 0 dBm				

Figure 2.6: List of channels available in London as provided by Spectrum Bridge Inc.'s database[16]

2.2.2 Quantitative Analysis in United Kingdom

Each TV Channel in the UK has a bandwidth of 8 MHz, and there are 32 such channels i.e. 256 MHz of spectrum. Out of these, Ofcom has decided to auction off 2 channels for licensed usage. Hence, 240 MHz of spectrum is left for use of TV transmitters. However, the exact distribution of TV White Spaces varies temporally and spatially depending on the distribution of the TV transmitters across UK. The quantitative analysis of the available white space has been carried out in [17]. Figure 2.7 shows the available number of TV White Space channels at 18 locations in UK. The red bars show the number of channels before the exclusion of those vacant channels whose adjacent channels were found to be occupied by DTV transmission, and the green bars show the number of channels after the exclusion of the same.

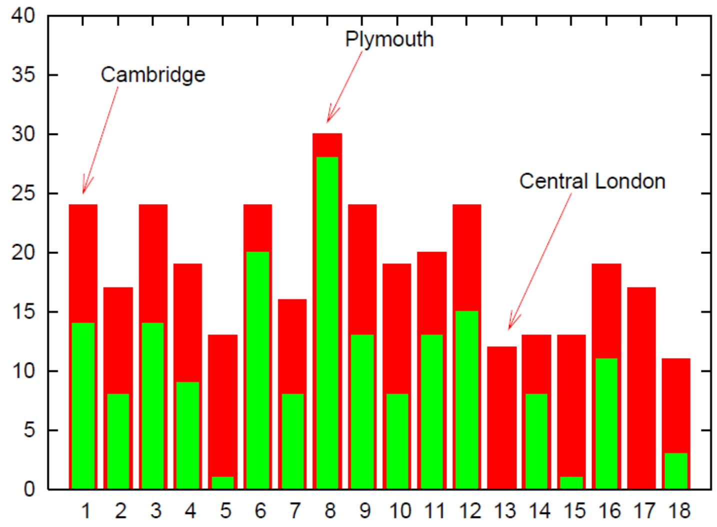


Figure 2.7: Available number of TV channels at 18 locations in UK. Adopted from [17]

2.3 TV White Space in Japan

2.3.1 Regulations

The analog TV transmissions in Japan ceased to operate in most places by July 2011 and in the remaining places the analog transmissions are expected to be replaced by digitial TV transmitters by 2013. The quantitative analysis of TV White Spaces in Japan has been carried out in [19]. However, since rules for TV White Spaces operation in Japan are still under discussion in Japan, most of the analysis carried out is based on FCC rules. The National Institute of Information and Communications Technology (NICT) has developed a white space database based on similar empirical models and primary transmitters information. Figure 2.8 shows the coverage areas of several TV transmitters in Japan. Similar white space database has been created by ISB Corporation for Japan. The Ministry of Internal Affairs and Communications (MIC) has established a working group to discuss some potential use cases of TVWS in Japan.

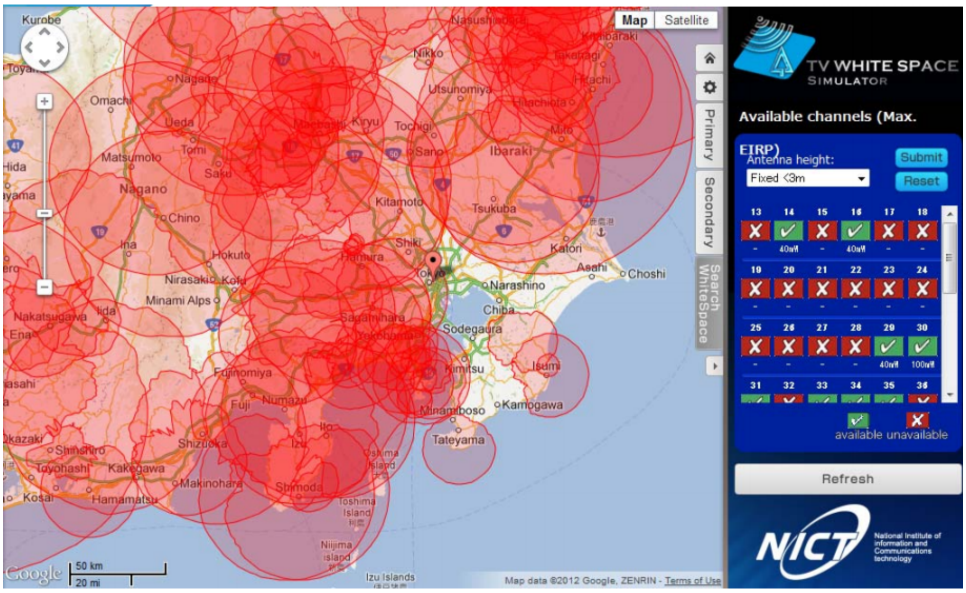


Figure 2.8: NICT White Space database for Japan [18]

2.3.2 Quantitative Analysis in Japan

The quantitative analysis of White Spaces in Japan has been carried out in [19]. By March 2013, all digital terrestrial TV broadcasting will be packed in the band from 470-710 MHz. In the 240 MHz spectrum, 40 channels of 6 MHz each can be accommodated. These channels are numbered from channel 13-52. In this analysis, most of the parameters used are as specified by the FCC. The authors make use of the ITU-R P.1546 propagation model and the F(50-90) curve. Figure 2.9 shows the number of available channels as TVWS in the major cities of Japan for different values of seperation distance (0 km, 6 km and 14 km).

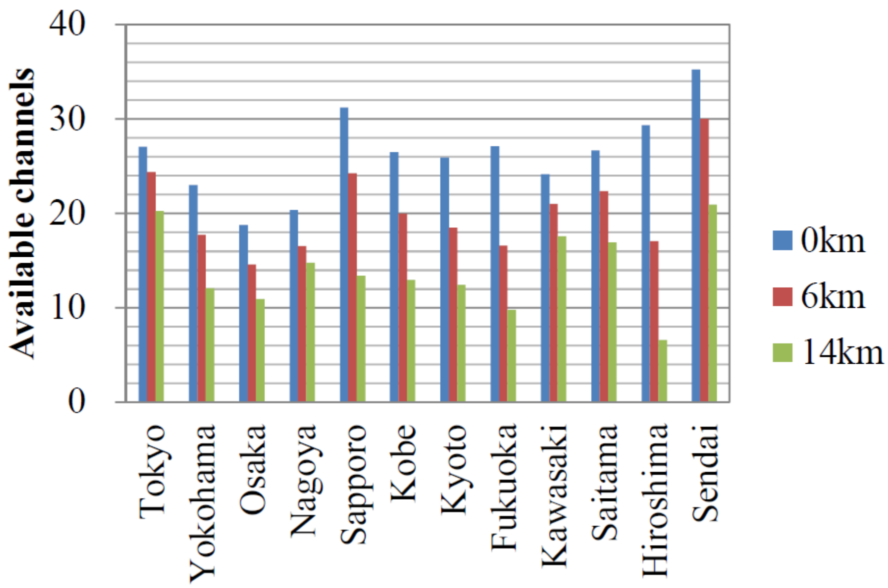


Figure 2.9: Expected available channels in Japanese metropolitan areas. Adopted from [19]

2.4 TV White Space in Europe

2.4.1 Regulations

In the 2006 meeting of International Telecommunication Union (ITU) at Geneva (GE06), it was decided that the target date for analog wstich off (ASO) should be 2015 in all ITU Region 1 countries. The following table provides the list of countries that are expected to have complete digital transmissions in the near future[20].

Table 2.3: Expected ASO Dates for some European countries

Country	DTT Launch	ASO Date
Netherlands	2004	2006
Germany	2004	2010
Finland	2002	2007
Sweden	1999	2008
Denmark	2006	2009
Norway	2007	2009
Switzerland	2005	2009
Belgium	2004	2011
Austria	2006	2010
France	2005	2011
Spain	2000	2010
Italy	2004	2012
Czech Republic	2005	2012
Hungary	2008	2011
Portugal	2009	2012

In Europe, a detailed report on on the technical and regulatory work on cognitive radio has been published out by CEPT (Confrence Europen des Administrations des Poste et des Tlcommunications). The CEPT SE43 Project teamhas developed the ECC Report 159[10] titled 'Technical and Operational Requirements for Possible Operation of Cognitive Radio Systems in the 'White Space' of the Frequency band 470-790 MHz'. This report was mainly developed to ensure the necessary level of protection to the primary services. Spectrum sensing and geolocation databases were the main techniques discussed for protection of primary services. The threshold for detection of primary services in the band was obtained to be in the range of -91dBm to -155dBm depending on various DTT receiver configurations. This report also to a large sense concluded that spectrum-sensing alone is not reliable to guarantee protection to the nearby DTT receivers operating on the same channel.

Europe is administrationally very diverse, and a result adoption of the TV White Spaces technologeies in Europe is expected to take longer. Nevertheless, several projects for testing white space standards and applications exist in Europe. One such project is the WISE project.

2.4.2 WISE Project

The WISE project [21] focusses on constructing a testbed for testing applications that could be used in TV bands. The project has three Work Packages as follows.

- WP1: Algorithms for geolocation database
  The focus of WP1 is to develop and implement algorithms for geolocation database based cognitive radio systems. The primary task is to gather information and model the geographical, spatial and temporal distributions of the signal radiated by primary services.

- WP2: Measurements and simulations
  The primary task of WP2 is to construct a testbed that can be used to study scenarios that cannot be reaized on hardware devices. One such example scenario is to study the effect of different propagation characteristics on cognitive radio systems using geolocation databases.

- WP3: Value chains and ecosystems
  The primary task of WP3 is to study the use cases and business cases of TVWS operations. Another important task of WP3 is to quantify the available spectrum in Europe, the monetary value of white spaces in Europe and the impact of various regulatory decisions on the same.

As a part of the WISE project, the database provider Fairspectrum has developed a White Space database for Finland. Figure 2.10 shows a snapshot of the list of channels available at a particular location in Finland.

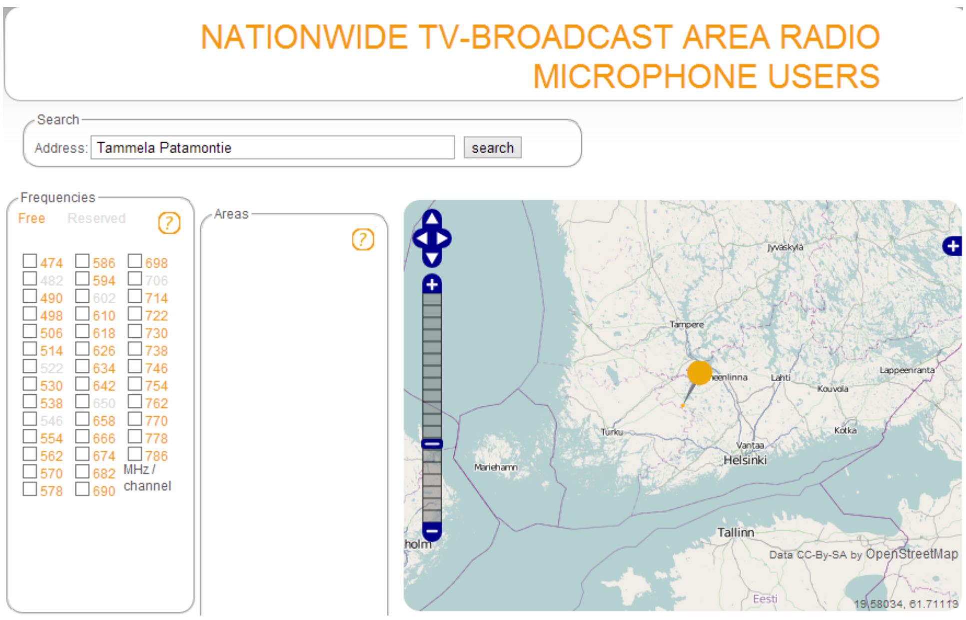


Figure 2.10: Fairspectrum White Space database for Finland

Chapter 3

Key challenges in TV White Space operation

Spectrum scarcity is not an unknown phenomena in any part of the world. And as the regulators decide to allow secondary or unlicensed use of white space, several challenges come forth. These challenges range right from regulatory related issues to design related issues. This chapter discusses some of these issues and reviews some of the solutions proposed by different bodies.

3.1 Challenges related to geo-location databases

The FCC issued notices to privatize the development and maintenance of geo-location databases and allowed 13 database providers to develop their databases. Till date only 2 database providers, viz. Spectrum Bridge Inc. and Telcordia have successfully developed their database systems, and have their systems approved by FCC. In order to get their systems approved, each system has to go through a 45-day trial period[?] At the end of the trial period, all problems are brought to the notice of FCC and the operator. Once the operators give viable soultions to these problems, their systems are approved by the FCC. At present, Google Inc.'s database system is going through its trial period.

The radio devices to be operated in these bands have been developed independently by several companies. The first company to come up with a radio device with ge-location database interface capability was Koos Technical Services (KTS). KTS came up with Agility White Space Radio(AWR) [23] that could connect to geo-location database and operate on one of the channels listed in the database response. Once the Spectrum Bridge Inc.'s database was approved by the FCC, KTS declared its association with Spectrum Bridge and officially used the services provided by Spectrum Bridge

Inc.'s database system. The next radio device capable of working in the TVWS band was developed by Adaptrum Inc. and they used the database services provided by Telcordia Inc. As more database systems are approved by FCC, several radio devices are expected to come up and operate in association with each of these database systems. The manner in which these radio terminals query the database and get a response from it is proprietary as of now. However, as time progresses there needs to be a standard protocol for accessing the white space database.To address this issue, Internet Engineering Task Force (IETF) has proposed a protocal named Protocol to Access White Space database (PAWS)[24][25].

PAWS

PAWS or Protocol to Access White Space database is a standardized protocol developed for achieving interoperability among multiple devices and databases. It categorizes the white space device as either a master or a slave device. The master device is one with geo-location capability that queries the database to find available spectrum. The slave device, on the other hand, cannot contact the database directly and relies in the master device fot the list of available channels. One important assumption made while developing this protocol is that the Master device and the database, both have connectivity to the Internet without the use of white space.
The brief outline of the protocol (as listed in the latest draft of PAWS dated 13th February 2013) is as follows.

1. The Master Device locates or discovers the regulatory domain for its location and the URI for the Database to send subsequent PAWS messages.

2. The Master Device establishes an HTTPS session with the Database.

3. The Master Device optionally sends an initialization message to the Database to exchange capabilities.

4. If the Database receives an initialization message, it responds with a message in the body of the HTTP response.

5. If required by regulatory domain, the Database registers the Master Device.

6. The Master Device sends an available-spectrum request message to the Database.

7. If the Master Device is obtaining the schedule on behalf of a Slave Device, and if required by the regulatory domain, the Database validates the Slave Device.

8. The Database responds with an available-spectrum response message in the body of the HTTP response.

9. Depending on regulatory domain requirements and database implementation, the Master Device sends a spectrum-usage notification message to the Database.

10. If the Database receives a spectrum-usage notification message, it responds by sending the Master Device a spectrum-usage acknowledgement message.

PAWS is under development stages and might go through several stages of refinement in the future. Nevertheless, PAWS or similar such protocol is needed for standardizing the process of communication between the database and the white space device.

3.2 Coexistence challenges

While the opening up of large chunks of spectrum in the sub-GHz TV band seems to be extremely promising, large number of operators, regulators and service providers are competing to come up with economically efficient technologies and standards. Ever since the FCC made its intentions public to make use of white spaces for secondary services, several standards have been developed for wide range of use cases. Since all these technologies would come up on secondary basis, they are not entitled to any sort of protection by the regulations. Moreover, since all these technologies intend to operate on the same bands, several coexistence related issues arise. Similar situations existed in the 2.4GHz band due to large number of technologies coming up in the unlicensed band. Coexistence studies in such scenarios have been studied in great depth in literature. One such study is as described in [26]

3.2.1 TVWS Standards

Before discussing the coexistence related issues, it is necessary to review the standards developed to operate in the TVWS band[27]. Each of these standards have been developed with different use cases in sight.

IEEE 802.22

The IEEE 802.22 WRAN is a long range and high power network. It has been developed with the objective of enabling rural broadband access using congnitve radio technology in TV White spaces. The first draft of the standard was published on July 1st, 2011. It was designed for a maximum throughput of 22.69Mbps and provide a coverage area of about 17-33 kms.

The IEEE 802.22 can access the white space database for a list of available chennels as well as sense the spectrum to determine if the particular channel is occupied by a primary service. However, the IEEE 802.22 system does not support mobility and handover support, neither does it support inter-system coexistence.

IEEE 802.11af

The IEEE 802.11af is a Wi-Fi extension to TV White Spaces. Its objective is to define modifications to the 802.11 PHY and MAC layers to meet the legal requirements for channel access and coexistence in TVWS. It makes use of OFDM PHY with 5 MHz, 10 MHz and 20 MHz channel widths, thus making use of more than two contiguous TV channels if available. This ensures higher throughput at the end user. The draft development for IEEE 802.11af began in January 2010 and currently Draft 2.2 has been realeased. In October 2012, Japan based NICT developed the first IEEE 802.11af (Draft 2.0) compliant prototype capable of operating in 470-710 MHz range. This is standard is often called Super Wi-Fi or the White-Fi.

IEEE P1900.7

The IEEE P1900.7 standard defines the radio interface for White Space dynamic spectrum access radio system suppoerting fixed and mobile operation. This standard is in nascent stages of development and the work started in early 2012. Currently, only the Table of Contents (ToC) and the use cases have been developed and first draft is expected to be finalized by around the end of 2013. The significant difference between P1900.7 and the other standard is that in addition to accessing White Space database and the other cognitive capabilities, it also supports cellular architecture and mobility and handover support. It is also exepected to support inter-system coexistence.

ECMA 392

The ECMA 392 [28]defines the PHY and MAC Layer for personal/portable cognitive wireless networks operating in TV White Space. It also defines a MUX sublayer for higher level protocols. This standard categorized the devices into three types - master, peer or slave. As defined in ECMA 392, a master is device acting as a centralized coordinator of medium access on behalf of at least one slave device, a peer is a device coordinating medium access with other devices without a centralised coordinator and a slave is a device associated with and coordinated by a master device for medium access. These devices are capable of operating in the 6 MHz, 7 MHz or 8 MHz band. However, it does not support cellular architecture and handover support.

IEEE 802.16h

The PAR-Title of IEEE 802.16h-2010 was 'Improved coexistence mechanism for License-Exempt operation.' The objective of this standard was to specify improved mechanisms to enable coexistence among license-exempt systems based on the IEEE 802.16 standard and to facilitate coexistence of such systems with primary users(reference in downloads). The IEEE 802.16h standard provides variable channel bandwidth from 1.5 MHz to 20 MHz and provides a peak data rate of 80 Mbps. It supports mobility and full handover support as well as support for cellular topology. Similar to IEEE 802.22, it supports long range applications. Besides the TV White Spaces, IEEE 802.16h can also function in the 3.65 GHz and 5.8 GHz bands.

Table 3.1 lists and compares and contrasts some of the features of these standards[**?**].

Table 3.1: Comparison of various TV White Space standards

Feature	ECMA 392	IEEE 802.22	IEEE 802.11af	IEEE 802.16h	IEEE P1900.7
Support of multiple frequency channels	No	No	Yes (only adjacent channels)	Yes only adjacent channels)	TBD
Mobility support	Yes	No	Yes	Yes	Yes
Maximum throughput	31.56 Mbps	22.69 Mbps	10-1000 Mbps	80 Mbps	several tens of Mbps
Typical range	-	17.33 km	Short and mid range	17-33 km	several tens of km
Channelization	6,7,8 MHz	6,7,8 MHz	5,10,20,40 MHz	1.5 to 20 MHz, TBD	
Modulation	OFDM	OFDM	OFDM	OFDM	TBD
Cellular Topology support	No	Yes	No	Yes	Yes
Handover support	No	No	Yes	Yes	Yes
Mesh topology support	Yes	No	Yes	No	Yes
Power efficiency	Yes	No	Yes	Yes	Yes
Self-coexistence	Yes	Yes	Yes	Yes	Yes
Multiple access technique	CSMA/CS, TDMA	OFDMA	CSMA/CS, TDMA	TDMA, OFDMA	TBD
Iterface with spectrum sensors	Yes	Yes	No	Yes	Yes
Iterface with geolocation device	No	Yes	Yes	No	Yes
Quiet period for spectrum sensing	Yes	Yes	No	Yes	Yes
Inter-system coexistence	No	No	No	Yes	Yes

3.2.2 Co-channel coexistence

It is clear from the preceeding list of standards that a large number of technologies are likely to operate in the same frequency band in areas close to each other. Furthermore, the extremely good propagation characteristics in the sub-GHz band aggravate this coexistence problem further. Several secondary networks can be set up in close proximity to each other. Figure 3.1 shows one such scenario when coexistence of a WRAN and WLAN network becomes a problem. (coexchal reference)

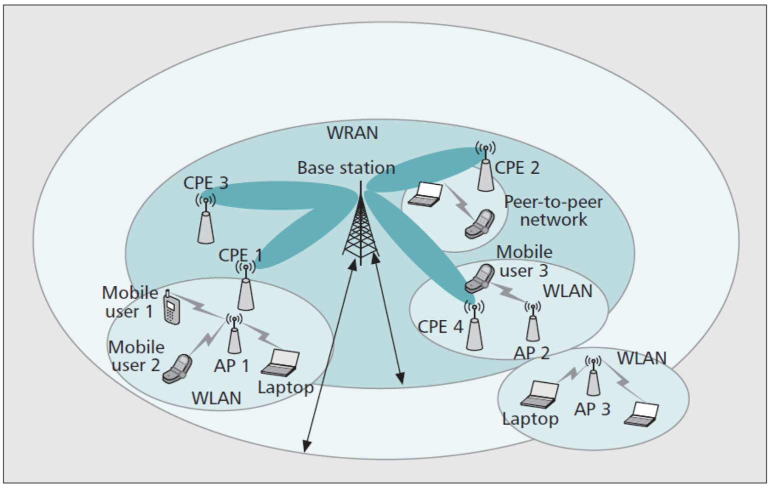


Figure 3.1: Interference among two secondary networks. Adopted from [29]

In absence of any coexistence mechanism between these networks, there is a finite probability that all these networks decide to operate on the same channel. This can give rise to several interference issues thus effecting the throughput of each network. For instance, in the scenario depicted in figure 3.1, if the AP or node of the WLAN falls in the path of main lobe of CPE's directional antenna, the noise floor of WLAN device rises (owing to the higher power used in WRAN) and some packets may get lost.
The level of interference also depends on the bandwidth of the channel used by each network. If for example, AP2 uses 20MHz channel (4 contiguous TV channels) and CPE4 uses a 5MHz channel, then the entire 20MHz band would not intereference, but only part of it would experience interference from CPE4.
Since there are many standards, several such interference scenarios exist. Hence, in order to ensure QoS requirements of each network, it is necessary to have coexistence mechanisms between secondary networks. The IEEE 802.19.1 WG focusses on coexistence between secondary white space networks.(reference Nokia)

IEEE 802.19.1

The Task Group 1 of IEEE 802.19 has been assigned the responsibility of wireless coexistnce in TV White Space. The standard specifies radio technology independent methods for coexistence among dissimilar or independently operated TV Band Device (TVBD) networks and dissimilar TV Band Devices. The purpose of the standard is to enable the family of IEEE 802 Wireless Standards to most effectively use TV White Space by providing standard coexistence methods among dissimilar or independently operated TVBD networks and dissimilar TVBDs. This standard addresses coexistence for IEEE 802 networks and devices and will also be useful for non IEEE 802 networks and TVBDs. Until now, the most significant decision of the Task Group has been to agree to use the IETF PAWS as interface between Coexistence Manager and TVWS database. The System architecture and reference model of IEEE 802.19.1 are shown in [31]

3.2.3 Adjacent channel coexistence

The secondary services operating in a channel can cause interference to primary services in adjacent bands. Similar studies have been carried out in the 2.4GHz ISM band, where out of band emission from Wi-Fi nodes can cause interference to the neighbouring LTE or WiMax devices[30]. Most of the TVWS standards are designed to operate in 470-698MHz bands. In ITU Region 3 nations, the band 698-806MHz has been reserved for IMT-A applications. Also the band around 467.5MHz has been earmarked for similar IMT applications. If any TVBD operate at a channel at the boundary (around 470MHz or 698MHz), it is likely to cause interference to these IMT applications, which is unacceptable. Also, in the Region 3 frequency allocation table, the band from 470MHz-585MHz are reserved for Fixed/Mobile wireless applications. The secondary devices operating in TVWS are expected to avoid interference to these applications as well. Limited work has been done in such areas to the best of our knowledge and thus, forms a significant part of our future work.

3.3 Other Challenges

Besides the challenges mentioned in the previous two sections, several challenges exist in the deployment of TV White Space based networks. A extensive study of several such challenges has been done in [4]. The design of RF Architecture is one such challenge. The available white space varies with location, and at each location it varies with time. A TVWS system may be tuned to a particular channel, but as soon as a primary transmitter is switched on, the TVWS device must switch to another channel so as to not cause any interference to the primary receivers. Moreover, if the TVWS

system uses Frequency Division Duplexing, then there are two such channels that are prone to switchover by the sudden swicthing on of primary device. This complicates the design of the RF Architecture and is studied in [4].
The Spectral mask requirements and the Out of band emission (OOB) constraints specified by the FCC are stringent. The FCC has stated that "In the 6 MHz channels adjacent to the operating channel, emissions from TVBD devices shall be at least 55 dB below the highest average power in the band." The design of filters that ensure such strict limits on OOB and at the same time ensuring the cost of secondary devices do not shoot beyond the reach of users is a challenging task.
To ensure reliable communications via spectrum sensing, several techniques have been proposed in the literature. One such technique is spectrum sharing. There are several approaches to spectum sharing. This divides the spectrum sharing techniques into three categories.

- Non-cooperative techniques
- Rule-based techniques
- Message-based techniques

Design of these spectrum sharing techniques also pose several challenges as discussed in [4]

Chapter 4

TV White Space in India

4.1 Current Scenario

In India, the sole terrestrial TV service provider is Doordarshan, which currently at most locations transmits at only two-three channels and these channels occupy a bandwidth of 7 (VHF bands) or 8 MHz (UHF bands). All other operators provide their services via Satellite and Direct to Home (DTH) services. Most of the Doordarshan TV transmitters operate in the VHF bands. As a result barring 10-20 MHz, almost the entire UHF bands are unutilized in India.

The National Frequency Allocation Plan 2011 (NFAP 2011) [32] has reserved the 470-585 MHz band for Fixed, Mobile and Broadcasting applications. In the 585-610 MHz band, Radionavigation is an additional application and the 610-890 MHz band is used for the same three applications. However, India being a part of ITU Region 3, the 698-806 MHz band is earmarked for IMT-A applications.

Starting from 31st October 2012, the four metros - Mumbai, New Delhi, Chennai and Kolkata stopped transmitting analog signals. In the second phase, 38 other cities with population of more than one million would undergo digitization. The digitization of TV signals in the rest of India is expected to be completed by 2015 in several phases[33][34]. Once the digitization takes place, the digital channels are expected to be restricted in the 585-646 MHz band. The band from 646-698MHz is used for defense applications. A brief review of the TV Broadcasting scenario has been done in [35].

Measurements conducted and data from Department of Telecommunications (DoT) reveals that 470-585 MHz band is almost nowhere used for TV Broadcasting. Hence, unlike the US or European countries, the situation of TV White spaces in India is entirely different. The Telecom Regulatory Authority of India (TRAI) or DoT has currently no regulations for TVWS operations in India. There is limited literature on the study of TVWS, its quantitative analysis and possible regulations in India. Hence, we dedicate this chapter for studying the TV White Space scenario in India.

4.2 Quantitative Analysis of TV White Space in India

4.2.1 Methodology

The exact list of TV transmitters in India is available with the WPC wing of the DoT and Doordarshan. Based on this data of TV transmitters, their locations, operating frequencies, transmission power, and antenna heights, we have tried to estimated the approximate amount of 'white' space available in India. We have taken the threshold to declare a band as 'unoccupied' as -114dBm, the same as specified by the FCC.

In order to carry out the analysis, a propagation model is required. Most of the ITU-R propagation models are unsuitable for Indian terrain conditions. A basic study of the available propagation models and their suitability according to the operating frequencies, transmitter heights etc. is done in [36]. Based on the frequency range covered in each model, the range for base station and terminal station heights in outdoor model, the Okumura Hata model was chosed for our analysis.

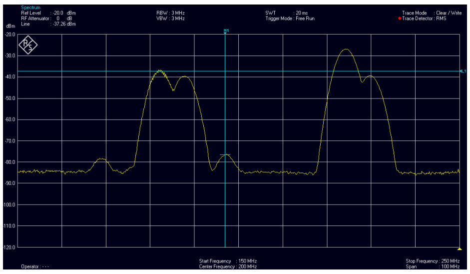
For preliminary analysis, we have used the Okumura-Hata model as the propagation model for signals transmitted by these transmitters. We categorized the locations of the TV transmitters into Urban, suburban and rural according to the surrounding area and applied the Okumura Hata model appropriately.

The entire analysis has been carried out in MATLAB. The transmitter locations and the coverage areas of each transmitter have been plotted on the map of India using the mapping toolbox of MATLAB. Seperate plots are generated for every operational channel and a single plot is generated that shows the coverage areas of all the TV transmitters in India irrespective of the band of operation. (Currently, there are certain discrepencies in the data of TV transmitters obtained from WPC and Doordarshan and also the frequency of operation of these towers. Hence, at this stage we cannot provide the exact white space availability.)

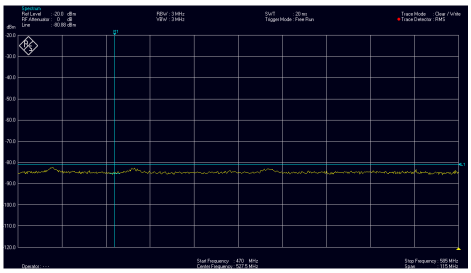
4.2.2 Experimental Results

To begin with the study of TV White Spcae in India, we carried out experiments in the Mumbai area and determined the power level of signal obtained at several places in Mumbai. We then compared it with the power level obtained by the above analysis at the same locations. For the experiments, we used a wideband antenna covering 470-698MHz manufactured by Kenbotong Communications, China. We used the Rohde & Schwarz FSH8 Spectrum Analyzer for measuring the power levels at various locations in the 150-250 MHz band, 470-585 MHz band, 585-698 MHz band and 698-806 MHz band. The scanning was done in the 150-250 MHz band since the TV transmitter in Mumbai used two channels in this range, one close to 180 MHz and another close 224 MHz.

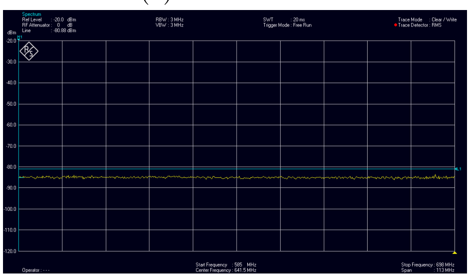
The following figures show the results obtained at 1 km and 13 km from the TV transmitter, respectively.



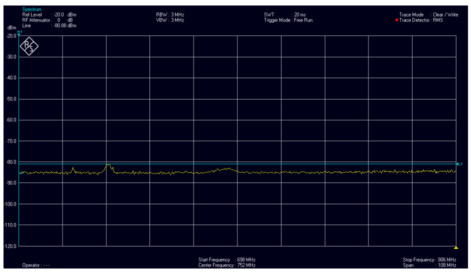
(a) 150-250 MHz



(b) 470-585 MHz

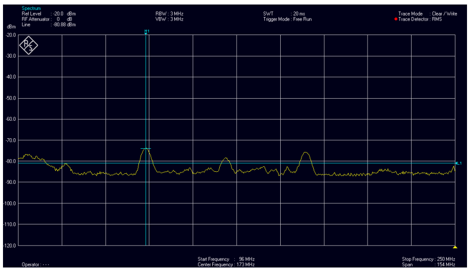


(c) 585-698 MHz

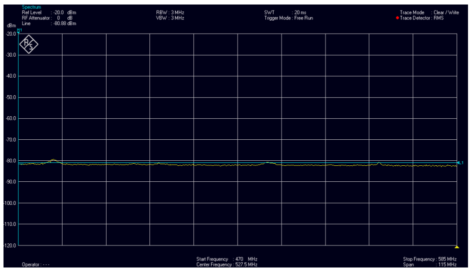


(d) 698-806 MHz

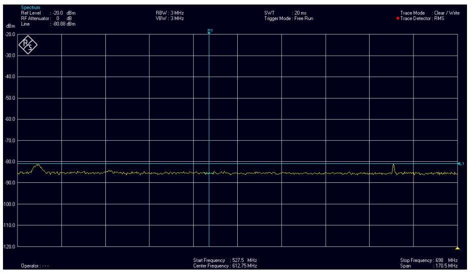
Figure 4.1: Sensing results at 1 km from the TV Transmitter



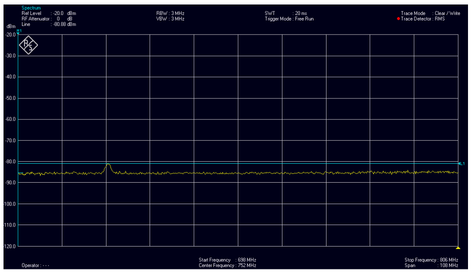
(a) 150-250 MHz



(b) 470-585 MHz



(c) 585-698 MHz



(d) 698-806 MHz

Figure 4.2: Sensing results at 13 km from the TV Transmitter

In both the figures, as well as in the other images, the entire band from 470 MHz - 806 MHz is completely unoccupied, except within the campus of one defense establishment, in which case the band within 646-698 MHz had a low power transmission. This confirms that the band from 646-698 MHz is used at some locations for defense applications. Nevertheless, in almost all other areas the entire band was vacant.

As far as the actual TV transmissions are concerned, there are only two channels of 7 MHz operating in the 150 - 250 MHz band in Mumbai. We carried the aforementioned experiments at different times on different days, and in all cases, the band from 470-806 MHz was found to be vacant within Mumbai. This is inspite of the fact that Doordarshan has plans to operate its Digital TV Transmitter at 474, 522, 546, 570, 578 and 582 MHz in Mumbai on trial basis. While just conducting these experiments in Mumbai area is insufficient to claim that the band from 470-806 MHz is vacant everywhere in India, the data from WPC wing suggests that band is indeed unoccupied.

Even though the band of interest (470-806 MHz) remains unoccupied in Mumbai, for the sake of testing our approach in the quantitative analysis we have tabulated the power levels obtained for the two available TV channels and compared them with those obtained by analysis at the same frequencies. The following tables compares the experimental values of power levels obtained at different places in Mumbai with those obtained by Okumura-Hata model at the corresponding distances. In most cases, the spectrum was scanned at same distance from the TV tower in different directions. Table

4.1 shows the results at 180 MHz and Table 4.2 shows the results at 220 MHz.

Table 4.1: Comparison of power obtained by experiment and analysis at 180 MHz

Distance from Tower (km)	Power-Level (Experimental) (dBm)	Power-Level (Okumura-Hata) (dBm)
1	-43.02	-50.38
1	-37.26	-50.38
2	-52.00	-59.62
3	-56.71	-64.06
3	-59.33	-64.06
3	-68.00	-64.06
3	-56.00	-64.06
3.5	-55.33	-65.84
4.5	-67.22	-68.80
4.5	-82.33	-68.80
4.5	-69.11	-68.80
5	-57.70	-71.12
5	-69.40	-71.12
6	-69.56	-72.32
6	-77.74	-72.32
8	-60.00	-76.12
8	-52.74	-76.12
9	-75.75	-78.66
9	-71.98	-78.66
9	-63.06	-78.66
12	-79.67	-81.55
13.5	-82.67	-82.84
13.5	-65.33	-82.84
13.5	-80.52	-82.84
15	-71.11	-84.21
15	-72.22	-84.21
17.5	-63.78	-86.30
17.5	-67.78	-86.30

Table 4.2: Comparison of power obtained by experiment and analysis at 220 MHz

Distance from Tower (km)	Power-Level (Experimental) (dBm)	Power-Level (Okumura-Hata) (dBm)
1	-43.21	-52.74
1	-26.94	-52.74
2	-43.11	-61.98
3	-43.81	-66.42
3	-53.11	-66.42
3	-68.00	-66.42
3	-52.44	-66.42
3.5	-50.89	-68.20
4.5	-63.06	-71.16
4.5	-73.17	-71.16
4.5	-67.56	-71.16
5	-56.11	-72.38
5	-70.00	-72.38
6	-76.44	-74.67
6	-72.58	-74.67
8	-64.22	-78.48
8	-50.00	-78.48
9	-79.72	-80.10
9	-70.99	-80.10
9	-62.06	-80.10
12	-82.00	-83.91
13.5	-84.00	-85.20
13.5	-59.33	-85.20
13.5	-78.73	-85.20
15	-70.00	-86.52
15	-66.67	-86.52
17.5	-67.33	-88.41
17.5	-67.82	-88.41

Figures 4.3 and 4.4 show the variation of received power as a function of distance from the TV transmitter. Each figure shows this relation for the analysis as well as for the experimental results. From the figure it is clear that the experimental results and theoretical results match at certain places and vary drastically at some other places. One major reason for this variation is that Mumbai has extremely irregular terrain for a single city.

Hence applying one single propagation model for an entire city is unlikely to produce accurate results. This makes it necessary to have a propagation model that gives accurate results in the context of Indian cities.

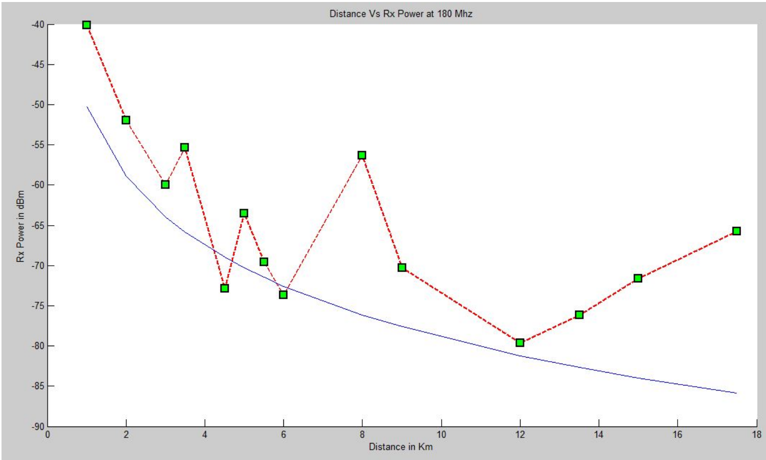


Figure 4.3: Received power v/s Distance at 180 MHz

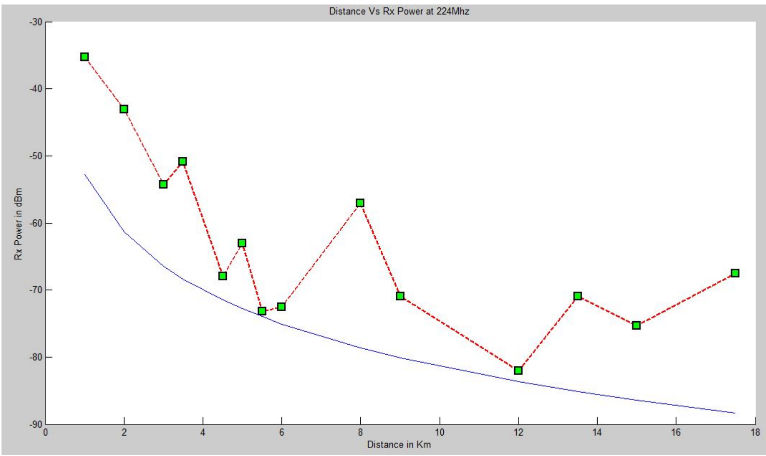


Figure 4.4: Received power v/s distance at 224 MHz

Chapter 5

Use cases of TV White Spaces in India

As mentioned in the previous chapter, the future of TV White spaces is not certain in the Indian context. Measurements and data from Department of Telecommuncations (DoT) reveal that no TV transmitters are functional in the 470-585MHz band. Hence, many of the research problems related to TVWS operations present in the other countries do not hold in the Indian scenario. However, the absence of any transmissions in the TV band opens up a possibility of using this TV band for some of the potential use cases of TV White Spaces. In this chapter, we discuss some of the potential use cases of TV White Spaces, specifically in the Indian context.

5.1 Design of backhaul networks operating in TV bands

Currently, a few operators provide broadband connectivity over entire cities using the 2.4 GHz Wi-Fi systems as the backbone, specially in the urban areas. A typical use case scenario is in which the TV band can be used to supplement these networks as backhaul networks and extend these services to provide broadband connectivity to rural areas. This is a promising application in the Indian context since providing broadband connectivity to the rural areas in India has been in the minds of the regulators since long. The Government of India has already invested several crores in laying Optical fiber systems to select rural areas in India. Optical fibers guarantee the QoS requirements for such a backhaul network, but are extremely expensive. If the TV band can be used to this effect, it would turn out to be a very economical alternative. [37] discusses the design of such a backhaul network in New Jersey, USA.

5.1.1 Regulatory Aspects

The regulatory issue in this respect is that since the band from 470-806 MHz is unoccupied, technically speaking this band is not generating any revenue for the government. The natural choice of any regulator in this scenario is to delicense this band and auction it off to other competing technologies. This would generate a extremely large amount of revenue looking at the amount of revenue generated by auctioning off any part of the spectrum in the previous decade[38]. The major hindrance in this approach is that since the spectru would be bought by any operator at a very high cost, the cost to be borne by the end user would be extremely large. Secondly, the band from 470 - 520 MHz is under the Ministry of Information & Broadcast, while the band from 520 - 585 MHz is under the Department of Telecommunications. As a result, any dealings with these portions of the spectrum would involve more than one government entities.

Another alternative is to delicense a particular chunk (contiguous or non-contiguous) of the spectrum and use this spectrum for applications similar to those in TV White Spaces on an unlicensed basis. However, a very important issue in this approach is that spectrum being a very scarce and expensive resource, delicensing any portion of it would mean potentially significant losses to the government considering its possible applications in the future. To check the feasibilty of such an approach, an economic analysis needs to be carried out comparing the amount of revenue the band can generate in the future with the benefits an end-user would enjoy if the band is used on an unlicensed basis. One such study of the economic aspects of unlicensing spectrum has been cnducted in [39]

5.1.2 Technical Aspects

Apart from the regulatory issues mentioned in the previous section, there are several technical issues in the design of a backhaul network. Some of these issues are described briefly in this section.

Study of propagation model in the 470-585Hz band in the Indian context

In order to determine the spacing between two consecutive base stations, it is necessary to have an accurate propagation model in the band of interest. As mentioned in the previous sections, the band from 585-646 MHz is to be used for digital TV broadcasting in the future. The band from 646-968 MHz is used for defense applications and the band from 698-806 MHz is reserved for IMT-A applications. Hence, the only possible band that can be considered for unlicensed use is the 470-585 MHz band, where currently only Fixed (point-to-point or point-to multipoint) and Mobile wireless services are used.

Hence, a major task is to study the propagation characteristics in the 470-585 MHz band under different terrain conditions. Unlike other countries, India experiences a wide range of terrain conditions in relatively short distances. Some of the terrain conditions under which these characteristics need to be carried out are as follows.

- Hilly areas
- Flat terrain with rocks or sand
- Areas close to water bodies
- Areas with moderate vegetation
- Areas with dense vegetation
- Small cities
- Large cities

Minimum amount of spectrum needed to be delicensed required to ascertain a fixed throughput at the end user

Any backhaul network would need to guarantee certain QoS requirements. Simulation studies need to be carried out assuming different channel bandwidths (5 MHz, 10 MHz and 20 MHz) of the unlicensed band. Under each scenario, the throughput at the end user must be calculated and accordingly an appropriate channel bandwidth is to be proposed. However, it is necessary to consider a multi-operator environment while carrying out this study. For initial study, it is reasonable to assume that the number of operators providing backhaul connectivity is less than or equal to 5. The amount of spectrum delicensed must be such that it must be compatible with the available TVWS standards.

Technology to be used for backhaul network

There are several technologies that can be used in the TV band as described in Section 3.1. We need to first determine which technology is to be used for the backhaul network based on the amount of spectrum delicensed and the throughput required at the end user.

Frequency of operation & Coexistence study with adjacent band technologies

Once the amount of spectrum required to be delicensed is determined, it is necessary to suggest the actual frequency of operation of the backhaul networks. This has to be determined by taking into consideration the technologies operating in the adjacent bands. Suppose if by simulations we arrive at the conclusion that 10 MHz of channel is required to be delicensed. One possible band of operation in this scenario is 470-480 MHz, in which case the coexistence study of the backhaul network needs to be carried out with the adjacent band technology. It is proposed that in future the 467.5 MHz band is to be used for IMT application. Hence, a coexistence study needs to be carried out between the TVWS standard and the IMT standards. Another possibility is that the band of operation is 575-585 MHz. In this case, coexistence study needs to be carried out between the TVWS standard and the TV broadcast services. In either of these scenarios, the other side of the channel would have fixed and mobile services. Hence, a coexistence study needs to be carried out between the TVWS standard and these fixed and mobile service devices.

Spectral mask and out-of-band performance

Based on the technology present in the adjacent bands, and the technology adopted in the channel used for backhaul networks, appropriate spectral mask and roll-off characteristics need to be defined. The out-of-band emissions must be extremely low so as to ensure minimum interference to the primary services in the adjoining bands.

Deployment Scenarios

There can be multiple deployment scenarios of the backhaul network. (CEWiT reference) In India, typically there is a town within 15-20 km from most villages. The optical fiber network in India currently provides service to all such towns. Thus, it is in between this 20-30 km distance that the broadband connectivity is to be provided using the TV band. There are two typical scenarios that exist in Indian villages. In some cases, the region between the villages are covered by highways or connecting roads with very little or almost no population. Similar scenario exits when the rehion between two villages is seperated by forests, desert areas or water bodies. In all these scenarios, we need to simply relay the signal from one base station to the next using relay stations. These relay stations do not provide any coverage within its vicinity.

Another major deployment scenario is when the region between two base stations need services themselves. In such a scenario, the intermediate base station has to relay the signal to the next base station as well as provide services to its surrounding area. This gives rise to a mess topology. Under this scenario, we need to design a scheduling algorithm that ensures the desired throughput levels. Both these scenarios need to be simulated for different channel bandwidths in a multi-operator environment and the throughput at the end user needs o be determined.

While the 470-585MHz band primarily remains unoccupied by broadcasters today, digitization of TV signals brings out a possibility of transmission in these bands in the future. Unlike the United States, it is possible to design the entire TV Transmission system in such a manner so as to make sure that there are no temporal and spatial white spaces in these bands. Such a design would form an interesting research problem.

Chapter 6

Conclusion

In this document, we have discussed some of the key developments in the TV White Space technology ever since its exception. Once we gained a brief idea about the ongoing reserach in TVWS in the world, the main focus of this document has been the future of TV White Space technology in India. Clearly, the research challenges in India differ from that across the globe. Several challenges in the Indian context have been highlighted and the approach to address them have been discussed.

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