

On the Feasibility of Providing Affordable Broadband Services using Backhaul in TV White Spaces

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Approval Sheet

This thesis entitled **On the Feasibility of Providing Affordable Broadband Services using Backhaul in TV White Spaces** by Gaurang Naik (Roll No. 123079009) is approved for the degree of **Master of Technology in Communication and Signal Processing**.

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Declaration

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To Amma, Anna & Priyanka

Abstract

Licensed but unutilized television (TV) band spectrum is called as TV White Space in the literature. Ultra high frequency (UHF) TV band spectrum has very good wireless radio propagation characteristics. Even though research issues related to TV White Spaces started emerging only after the FCC regulations in 2009, several issues have been identified and studied extensively in literature. These research problems range right from estimating the available White Space in TV band and proposing ideas for interference avoidance to predicting the use cases of TV White Space operations and proposing solutions for the same. Most of the research pertaining to TV White Spaces started from United States, Japan and European countries. In this report, some key questions regarding TV White Space operations in India have been raised and some solutions have been offered.

We first look at the global TV White Space usage scenario. Regulations and quantitative analysis of TV White Space in different countries have been studied. TV band utilization in India is, however, much different and interesting as compared to that in other countries. Owing to the presence of a single TV broadcaster in India, much of the TV band remains underutilized. This calls for applications different from those being studied in other countries. We look at one such application in detail — affordable provision of broadband services using backhaul in TV White Space, especially in the rural

areas. To demonstrate this idea, a pilot test-bed has been proposed and implemented in seven villages of the Palghar district in Maharashtra state. The implementation and planning details of the pilot test-bed have been detailed in this report.

The hardware and the software architecture of the test-bed has been discussed in detail. First, we discuss the UHF TV band hardware prototype developed for the test-bed deployment. We use standard IEEE 802.11g WiFi radio cards with frequency downconverters for sub-GHz operations. The open source *ath5k* WiFi drivers have been modified as per our requirement. The prototype has been configured to operate as per the requirements and restrictions of the pilot test-bed.

Next, we describe the software architecture of the pilot test-bed, and develop a system for the operation of our prototype as per the software architecture. Throughout TV White Space literature, geo-location databases have been used for the protection of the terrestrial TV broadcast receivers. We propose the use of a geolocation database for coexistence of TV White Space devices, in addition to the protection of TV receivers. To the best of our knowledge, an active online database of TV transmitters does not exist for India. We present the development of the first TVWS database for India and release the database for public access. A standardized protocol to access the TV White Space database is implemented on our hardware prototype. The source code of our implementation has been released under the GNU general public license version 2.0.

Finally, we present some preliminary experiment results performed in the pilot test-bed. These preliminary results show the superior characteristics of the UHF TV band signal in terms of larger propagation distances and Non Line-of-Sight operations. In addition to these throughout measurements, high speed Internet access has been made available to villagers across 3 villages, where Internet connectivity was otherwise non-

existent. Villagers are able to access Internet through WiFi hotspots and information kiosks at data rates in excess of 10 Mbps.

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Chapter 1

Introduction

1.1 Present Status of Broadband in India

India has seen rapid growth in the number of wireless and wireline telephone subscribers in the last few years. The total tele-density (defined as the number of telephone connections per every 100 individuals) of India has grown from 1.3 in the year 1996 to 78.16 in January, 2015 [1, 2]. The number of wireless and wireline subscribers in India in September 2014 were 957.61 million [3]. However, in the same year, the number of broadband subscribers in India were merely 254.40 million. This indicates a significant difference in access to the telephone and broadband services.

In order to proliferate broadband services in India, the Government of India, in its National Telecom Policy (NTP) 2012 [4] has set one of the objectives as “to provide affordable and reliable broadband-on-demand by the year 2015 and 600 million broadband connections by the year 2020 at minimum 2 Mbps download speed and making available higher speeds of at least 100 Mbps on demand”.

1.1.1 Rural Broadband Challenges in India

Presently, there are large areas in India where Internet access is slow or even non-existent. This is particularly true in rural areas, where sparse populations and irregular landscapes (water bodies, mountains etc.) often make it difficult or expensive to roll out high-speed Internet connections. Settlements in the rural areas are often situated several kilometers away from the nearest location with access to high speed Internet. Even in the case of wireless technologies, the sparse distribution of homes in the rural areas makes it difficult

for wireless signals to propagate in every home [5].

1.1.2 National Optical Fiber Network Plan

There are about 6,40,000 villages in India and these are administered by about 2,50,000 gram panchayats. Presently, access to high-speed Internet through optical fiber is available only at the district headquarter and block panchayat levels. (Several gram panchayats are administered by a block panchayat. There are about 6400 block panchayats in India [1]). The Government of India launched the National Optical Fiber Network (NOFN) [6] plan in order to extend the connectivity from the block panchayat level to the 2,50,000 gram panchayats in the country. The current test-beds for NOFN provide access to high-speed broadband at 100 Mbps at each gram panchayat. The complete NOFN projects requires 5,00,000 kilometers of incremental fiber to be laid with an estimated cost of about INR 20,000 crores (approximate USD 4 billion).

1.1.3 Middle Mile/ Last Mile Problem

The objective of NOFN is to provide connectivity upto the gram panchayat level. Thus, after the completion of the NOFN project, optical-fiber connectivity would not reach every village in the country. However, a large portion of the Indian population lives in small habitat clusters away from the gram panchayats. There are more than 7 Lakh habitation clusters having a population of less than 500. The minimum distance separating any two clusters is more than 2 kilometers [4].

Laying fibers from gram panchayats to all the surrounding habitat clusters is infeasible considering the high cost and difficult terrain conditions.

Considering these issues, an economic solution to connect the gram panchayats to the surrounding habitat clusters is to establish wireless links between these distant locations. This can be addressed using a mesh based last-mile or middle-mile network. The middle-mile backhaul network can be a multi-hop wireless mesh network that is capable of providing coverage within a radius of one to five kilometers to enable seamless connectivity from the access network such as WiFi Zones/Access points to a backhaul point such as an NOFN node at the gram panchayat.

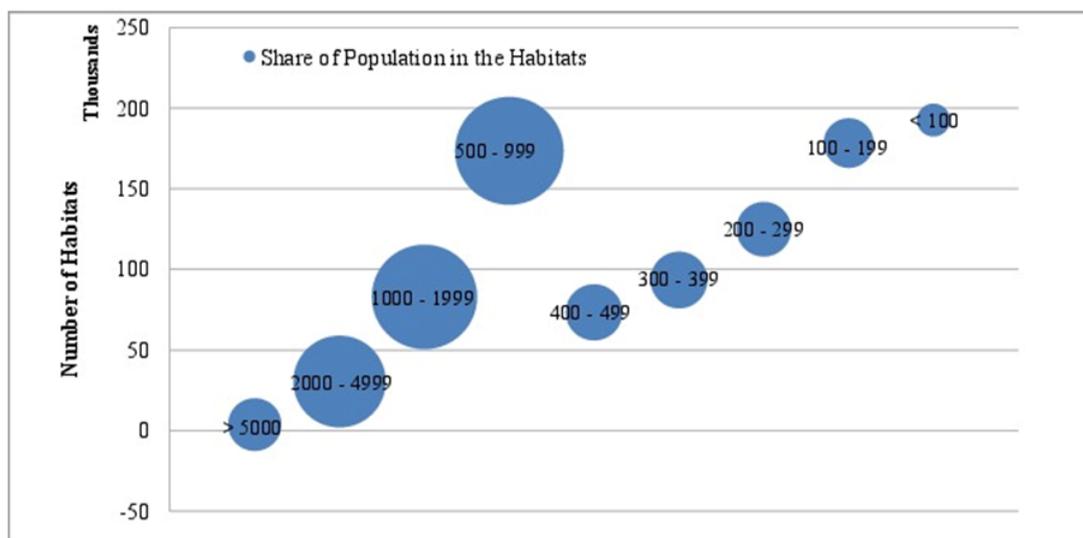


Figure 1.1: Number of Habitat clusters in India and share of population

1.2 TV White Space - A Potential Solution to the Rural Broadband Problem

Recent studies on the utilization of different frequency bands have shown that in most frequency bands, large portions of the wireless spectrum is heavily under-utilized [7, 8, 9]. Among the under-utilized portions of the spectrum, of particular interest are the Low and High Very High Frequency (VHF) bands (54 – 88 MHz and 174 – 216 MHz) and Low Ultra High Frequency (UHF) band (470 – 698 MHz), specifically owing to their superior propagation characteristics.

The unused portions of TV band spectrum are termed as TV white space. More formally, as per the ITU Report “Digital Dividend: Insights for Spectrum Decisions” [10], TV White Spaces are “portions of spectrum left unused by broadcasting, also referred to as interleaved spectrum”. Widely, TV White Space are also referred to as those currently unoccupied portions of spectrum in the terrestrial television frequency bands in the VHF and UHF TV spectrum.

The Federal Communication Commission (FCC) realized the potential of the under-utilized TV spectrum and issued a Research & Order (R&O) document on the unlicensed use of TV White Spaces in November 2008 [11]. Several other countries such as United Kingdom and Singapore have followed suit and worked towards unlicensed usage of the under-utilized spectrum.

1.2.1 Primary and Secondary Users

In the context of TV White Space usage, the users or services that have been allocated the spectrum via auction (or other mechanism) by the regulator are termed as *primary users*. The users who can transmit in these frequency bands when the band is not used by the primary are called *secondary users*. Figure 1.2 presents a brief idea of the existence of white spaces in between the primary user coverage areas [12].

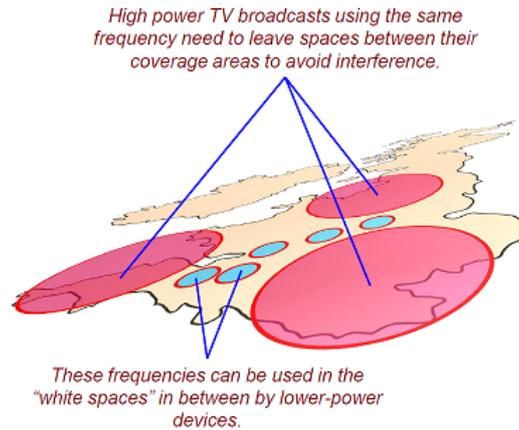


Figure 1.2: The concept of TV White Space. Adopted from [12]

Although large portions of the TV spectrum remains under-utilized, the actual unutilized spectrum available varies significantly spatially as well as temporally. There are several studies in the literature that focus on how much bandwidth can be freed up and how much capacity can be achieved using the TV white spaces [13], [14]. 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.

1.2.2 TV White Spaces and Rural Broadband

The UHF TV band (470 – 806 MHz) has good propagation and building penetration characteristics. This potentially makes the TV White Spaces ideal for use in rural broadband applications, where transmission links may be several kilometers in length and may involve challenging terrain such as hills, foliage, and water.

*Organization*¹: In this thesis, we first briefly study the TV White Space regulations in different parts of the world (Chapter 2). Our objective is to understand the TV White Space scenario in the Indian context. We study the current TV band utilization in India, specifically in the UHF TV band, and examine the feasibility of a potential use case - provisioning affordable rural broadband services through backhauling in TV band, from the Indian perspective. In Chapter 3, we propose an architecture for TV White Space based network operations in India. We describe in detail a possible hardware and software architecture for such TV White Space operations. This involves identification and suitable configuration of a UHF TV band radio prototype developed as a part of this thesis. We also describe the creation a geo-location database for India, and the implementation of a standardized protocol - Protocol to Access White Space (PAWS) on the hardware prototype. In order to demonstrate our proposed solution and architecture for a TV White Space backhaul based network, we propose a pilot test-bed in a rural area in India. The steps taken in the planning and deployment of the pilot test-bed are detailed in Chapter 4. We also discuss some preliminary experiment results in this chapter. Finally, we discuss some possible future extensions of this work and give concluding remarks in Chapter 5.

¹Chapters 2 and 3 are a part of joint work with my colleague Sudesh Singhal.

Chapter 2

TV White Space Around the World

2.1 TV White Space in United States

2.1.1 Regulations

The first regulations for the use of TV White Space were laid down by the Federal Communications Commission (FCC) in the United States of America (USA). As per the rules set by the FCC for the operation of secondary devices in the TV White Space [15], devices operating in the underutilized portions of TV spectrum were termed TV Band Devices (TVBDs). The primary objective of the FCC while formulating the rules for TVBD operations is to protect the interests of the licensed services. With this in view, the FCC categorizes the TVBDs into two classes, fixed and personal/portable (see Figure 2.1). The personal/portable devices have been further classified into Mode I and Mode II devices. The fixed devices, under no circumstances, are allowed to transmit beyond 36 dBm (30 dBm Power plus 6 dBi antenna gain). The portable devices, on the other hand, are not allowed any antenna gain, and are not to exceed the transmission power of 20 dBm. 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 the HAAT be below 30 metres at any given place.

In addition to these constraints, the secondary devices must ensure that they do not get ‘too close’ to the primary receivers. As studied in [16], the FCC regulations provide a certain ‘protected radius (r_p)’. The protected radius is a parameter of each TV transmitter and it indicates the minimum distance from the transmitter upto which the signal

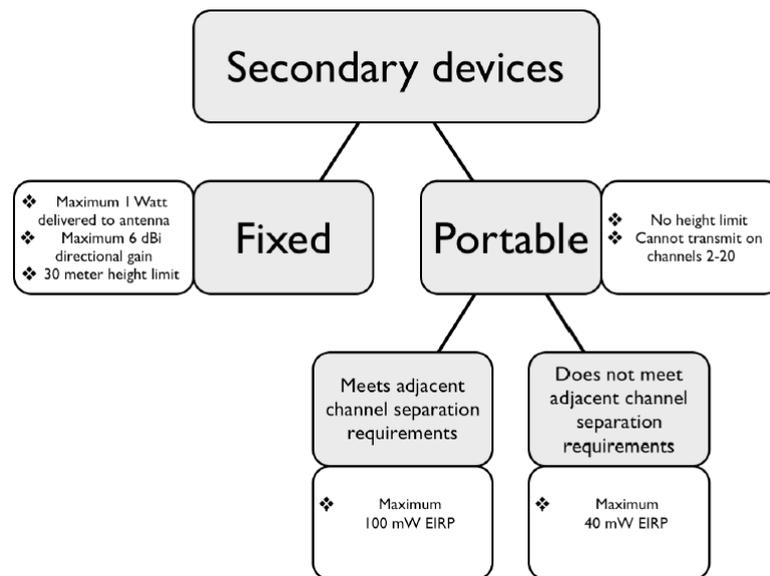


Figure 2.1: Categorization of secondary TV band devices by FCC. Adapted from [16]

transmitted by the transmitter is successfully decoded by the TV receiver. In addition to r_p , the secondary transmitters must 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 kilometers to 14.4 kilometers for co-channel operation and 0.1 kilometers to 0.74 kilometers for adjacent channel operation [17]. Figure 2.2 shows the protected radius r_p and the ‘separation distance’ $(r_n - r_p)$ as measured from the TV tower.

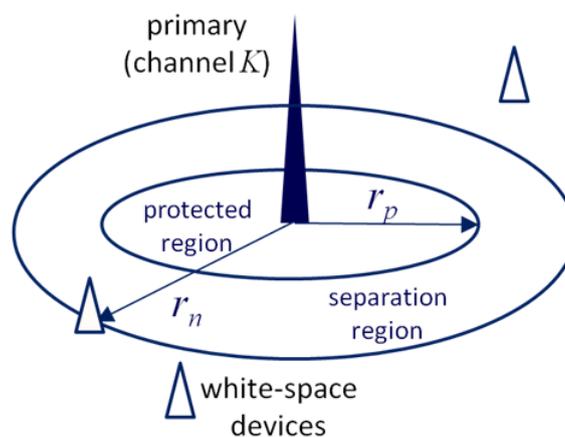


Figure 2.2: Protected radius and the separation distance.

An important task to be performed by the cognitive-capable secondary device is to detect the presence of primary transmitters in its vicinity. Several mechanisms have been proposed to this effect till date, and at present the two most important mechanisms are the use of geolocation database and spectrum-sensing.

2.1.2 Spectrum Sensing

The presence of primary devices can be detected through spectrum sensing. Under this mechanism, 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 there is no transmission from the primary transmitter on a particular channel. The FCC declared a threshold of -114 dBm to decide if a channel is occupied by a primary user. Thus, any signal with power level greater than -114 dBm would indicate the presence of a primary device in the band. This threshold of -114 dBm has, however, been considered too conservative [20]. Moreover, it is possible that during the sensing instant, the channel experiences a deep fade event and the primary signal may not get detected. This makes it necessary to develop a reliable technique for detecting the presence of primary services in the band. However, spectrum sensing solution has not been discarded as a potential solution for detecting primary services and it is generally proposed as a supplementary solution along with geo-location databases.

Some techniques for spectrum sensing include the following

- energy detection [21, 22],
- matched filtering [23, 24],
- covariance based detection [25, 26], and
- cyclostationary detection [27, 28].

Different spectrum sensing techniques, and their efficiency in detecting TV band signals have been described in [29].

2.1.3 Geolocation Databases

A more widely used technique for the detection of primary services is the use of geolocation databases. In order to protect the primary services, the TVBDs need to determine

their location (with sufficient precision) using Global Positioning System (GPS) or other suitable mechanism and then consult a ‘geo-location’ database [20] to determine the set of frequencies available at their location. In response, the database provides a list of channels that can be used by the secondary device to transmit. TVBDs are not allowed to transmit until they have obtained from the database, a list of channels (if any) that are available at its location. The database also (optionally) provides the transmitting power and the HAAT of the secondary device.

Database services are provided by private operators in the USA. Presently Spectrum Bridge and iConectiv are the most widely used database services in the USA. Figure 2.3 shows a snapshot of the list of available channels at Scott, PA as taken from the Telcordia (now iConectiv) TV White Space database.



Figure 2.3: Telcordia (now iConectiv) TV White Space database. [30]

2.1.4 Beacon

Besides Spectrum sensing and geolocation databases, there have are a few solutions proposed for detecting the presence of a primary device in the vicinity of the secondary transmitter, although these solutions are not widely used. 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 Availability of TV White Space in United States

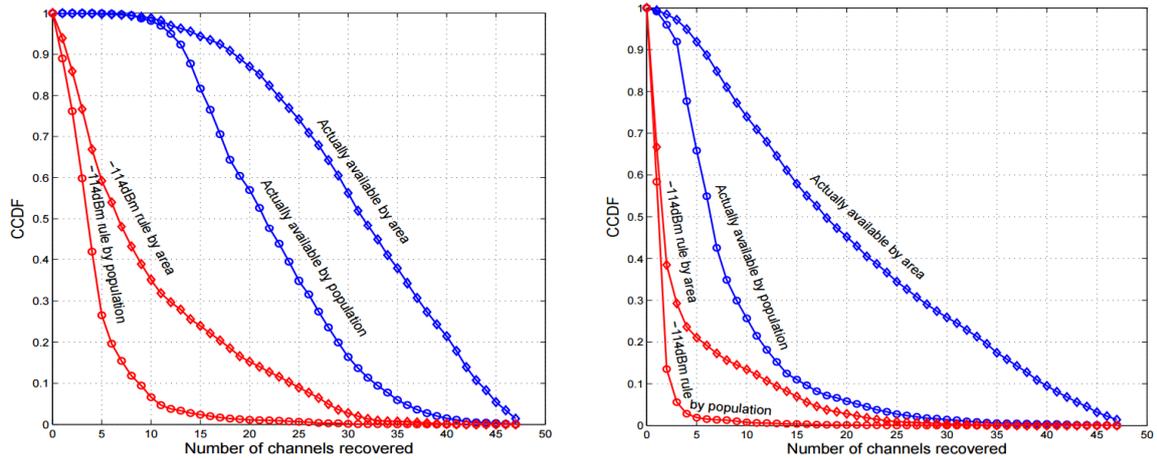
To quantify the amount of white space available and the capacity that can be achieved using these white spaces several studies have been carried out in USA [13], [14]. We look at the approach followed in [14]. The study assumes that all the TV transmitters in the FCC high power database and master low power database are transmitting. The analysis considers only fixed devices and assumes them to be operating in TV channels 2 (54 – 60 MHz), 5 – 36 (76 – 88 MHz, 174 – 216 MHz and 470 – 608 MHz) and 38 – 51 (614 – 698 MHz). 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 presented in [14] show that in the lower UHF channels (channels 14-51), approximately 15 channels are available per person for secondary applications. However, if we consider adjacent channel constraints, the available channels per person drop to approximately 5 channels. The complementary cumulative distribution function (CCDF) of the number of channels recovered by different methods is shown in Figure 2.4, which shows that the TV White Space area recovered using the -114 dBm sensing threshold is significantly lesser than the actual TV White Space available.

2.2 TV White Space in United Kingdom

2.2.1 Regulations

Following the FCC's regulations on TV White Spaces, Ofcom (regulator in UK) in 2007 released the Digital Dividend Review (DDR) Statement [31]. The UK Government decided to cease the operation of analog TV transmitters in 2012. This allowed the Digital



(a) Available TV channels without adjacent channel considerations (b) Available TV channels with adjacent channel considerations

Figure 2.4: CCDF of number of TV channels available as white space in USA using different methods. Adopted from [14]

TV Transmitters (DTT) to cover as much of the country as was due to the Analog TV transmitters. This changeover had two major consequences. Firstly, the number and range of services provided via terrestrial TV in UK increased significantly, and secondly, a large amount of spectrum became available. This was termed as Digital Dividend and could be usable for other services on a licensed or unlicensed basis. The DDR document proposes 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.

In 2009, Ofcom released a new consultation paper on license-exempting cognitive devices using interleaved spectrum [32]. Ofcom suggests the use of geo-location databases, sensing and beacon signals for detecting the presence of and avoiding interference to the primary device. The secondary devices are 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 United Kingdom is 8 MHz. Ofcom has set certain rules that need to be followed by the secondary devices while using TV White Space. Table 2.1 lists the parameters in the scenario where the secondary device uses only spectrum sensing, while



Figure 2.5: UHF Band channels in the UK after Digital Switchover. Adapted from [31]

table 2.2 lists the parameters when the secondary device uses only a geolocation database.

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 20 dBm
Transmit-power control	Required
Bandwidth	Unlimited
Out of band performance	less than −44 dBm
Time between sensing	less than 1 second
Maximum continuous transmission	400 milliseconds
Minimum pause after transmission	100 milliseconds

Table 2.1: Key parameters for sensing

As far as developing the geolocation database is concerned, there is a ‘master’ database that would contain the list of channels available for secondary 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

Location accuracy	100 meters
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 -44 dBm
Maximum continuous transmission	400 milliseconds
Minimum pause after transmission	100 milliseconds

Table 2.2: Key parameters for geolocation database approach

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.

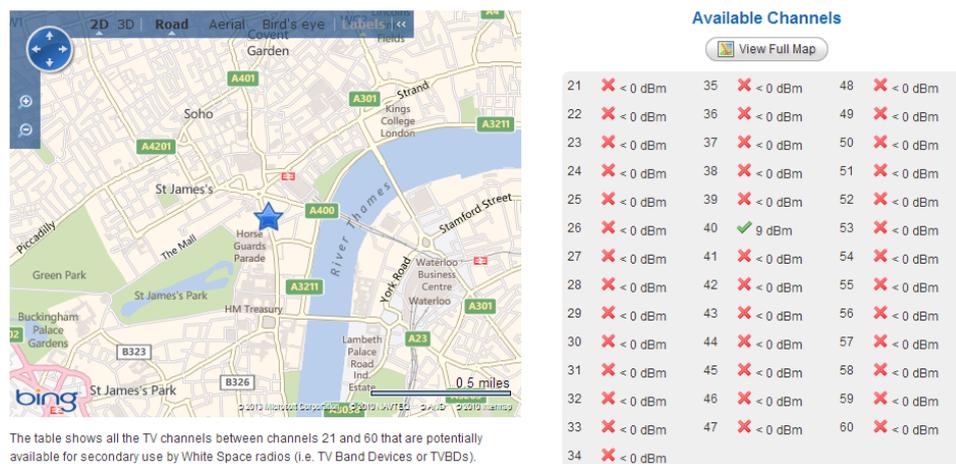


Figure 2.6: List of channels available in London as provided by Spectrum Bridge Inc.'s database [33]

2.2.2 Availability of TV White Space in United Kingdom

Each TV Channel in UK has a bandwidth of 8 MHz, and there are 32 such channels i.e. 256 MHz of spectrum. Ofcom decided to auction 2 channels for licensed usage. Hence, 240 MHz of spectrum is usable for TV transmissions. 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 [34]. 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 have been found to be occupied by Digital Television (DTV) transmission, and the green bars show the number of channels after the exclusion of the same.

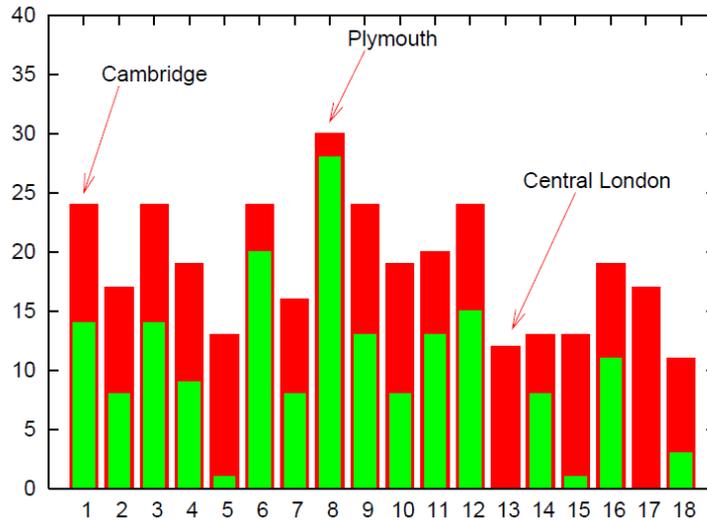


Figure 2.7: Available number of TV channels at 18 locations in UK. Adapted from [34]

2.3 TV White Space in Japan

2.3.1 Regulations

The analog TV transmissions in Japan have ceased to operate in most places by July 2013. The quantitative analysis of TV White Spaces in Japan has been carried out in [17]. However, since rules for TV White Spaces operation in Japan are still under discussion, 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 Information Service Bureau (ISB) Corporation for Japan.

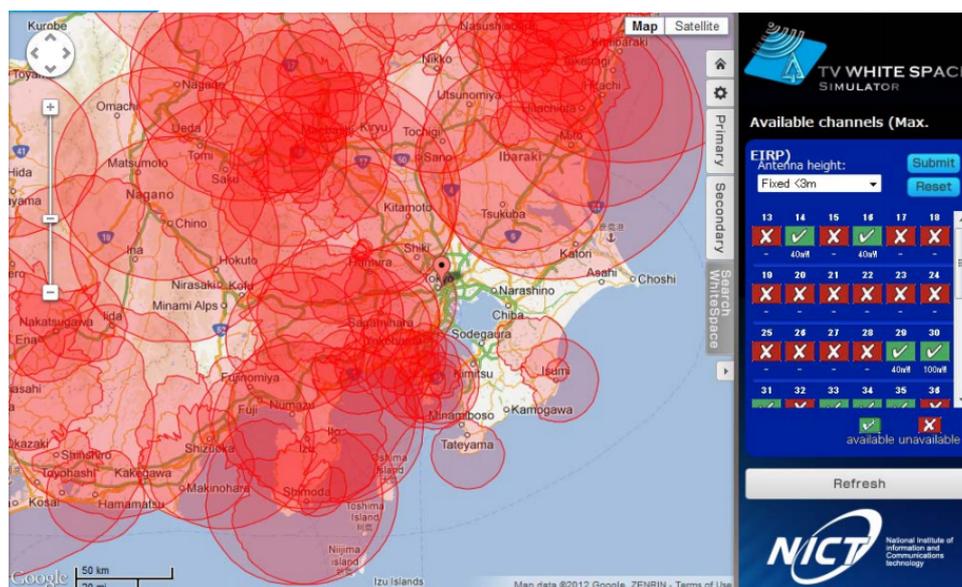


Figure 2.8: NICT White Space database for Japan [18]

2.3.2 Availability of TV White Space in Japan

The quantitative analysis of White Spaces in Japan has been carried out in [17]. In the 240 MHz spectrum from 470–710 MHz, 40 channels of 6 MHz each can be accommodated. These channels are numbered from channel 13 through 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 [19]. Figure 2.9 shows the number of available channels as TV White Space in the major cities of Japan for different values of separation distance (0 kilometers, 6 kilometers and 14 kilometers).

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 switch off (ASO) should be 2015 in all ITU Region 1 countries.

In Europe, a detailed report on the technical and regulatory work on cognitive radio has been published by Conference Europeen des Administrations des Poste et des Telecommunications (CEPT). The CEPT SE43 Project team has developed the Electronic Communications Committee (ECC) Report 159 [20] titled ‘Technical and Operational

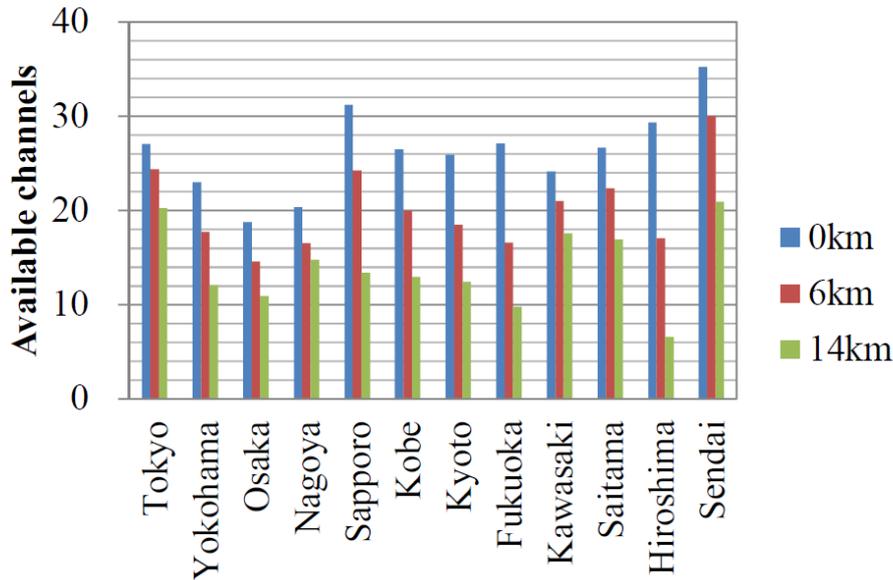


Figure 2.9: Expected available channels in Japanese metropolitan areas. Adapted from [17]

Requirements for Possible Operation of Cognitive Radio Systems in the ‘White Space’ of the Frequency band 470 – 790 MHz’. This report has been mainly developed to ensure the necessary level of protection to the primary services. Spectrum sensing and geolocation databases are the main techniques discussed for the protection of primary services. The threshold for the detection of primary services in the band was obtained to be in the range of -91 dBm to -155 dBm depending on various DTT receiver configurations. This report also to a large extent concludes that spectrum-sensing alone is not a reliable technology in order to guarantee the protection of nearby Digital Terrestrial Television (DTT) receivers operating on the same channel.

2.5 TV White Space in India

We now look at the TV White Space scenario in India. Unlike in the US and the UK, there is only one terrestrial TV broadcaster in India — the Doordarshan. Doordarshan transmits only two channels (namely, DD1 and DD2) at any given location in the country. These channels occupy either a bandwidth of 7 MHz in the VHF band or a bandwidth of 8 MHz in the UHF band. Presently, Doordarshan has 1415 TV transmitters operating in India. Out of these, 8 transmitters operate in the VHF Band-I (54 – 68 MHz), 1034 transmitters operate in the VHF Band-III (174 – 230 MHz) and the remaining 373

transmitters¹ operate in the UHF Band-IV (470 – 582 MHz). Thus, a majority of the TV transmitters in India operate in the VHF band, and only a small portion of the total terrestrial TV transmitters operate in the UHF band. It is expected that the utilization of UHF TV band in India is sparse. A detailed quantitative assessment of spectrum in 470 – 590 MHz [35] has revealed that, *unlike in the developed countries, major portion of the UHF TV band is unutilized in India.* Moreover, digitization of broadcasting services in India by Doordarshan is under progress. After the completion of digitization, Doordarshan will operate within the frequency band 585 – 698 MHz, which has been exclusively earmarked for digital TV broadcasting in India. This will free up the full spectrum of 470 – 585 MHz for other potential applications.

2.5.1 How is the Indian Situation Different?

In the 470 – 585 MHz band, TV White Spaces have not been created in India in a manner similar to that were/are being dynamically created in the US, the UK, and other countries by digital TV switchover of terrestrial broadcasting. As seen in [35], in India, practically about 100 MHz spectrum is available in the 470 – 590 MHz band, which has been lying unutilized even by analog transmission. The TV White Space available in India using the Pollution viewpoint [14] is shown in Figure 2.10.

From the discussions in the previous sections, it is evident that the amount of TV White Space available in India is significantly larger than the available TV White Space in other countries. Moreover, this availability does not vary temporally in India.

¹Details of TV transmitters operating in the UHF TV band were obtained from Doordarshan through two separate Right to information (RTI) queries.

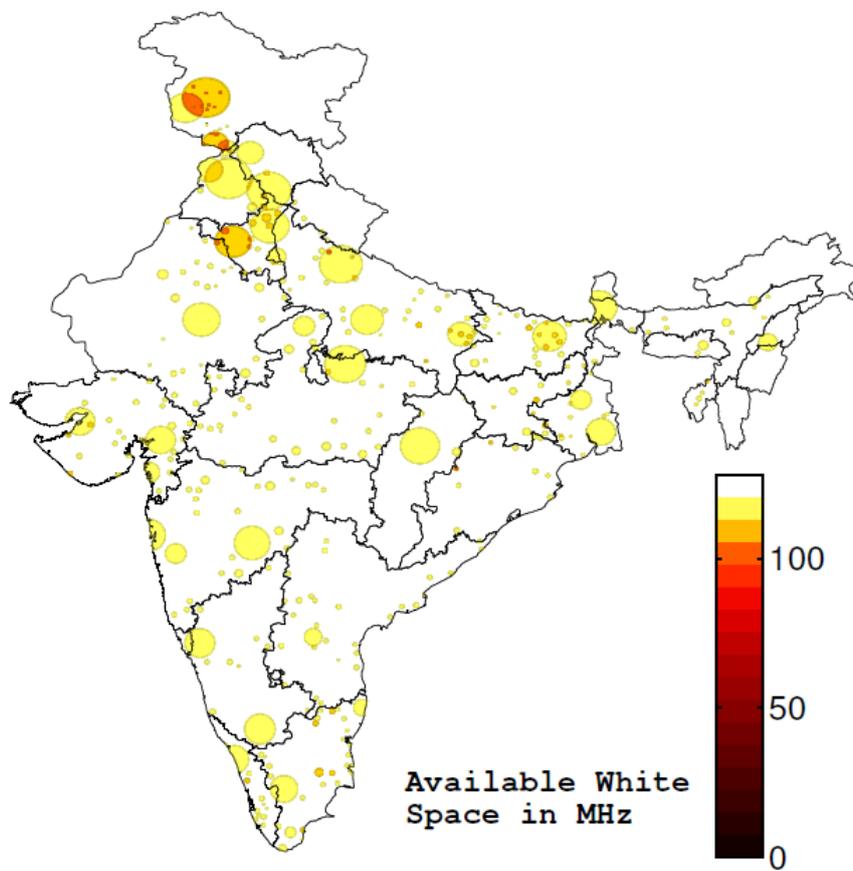


Figure 2.10: Available white space in India using Pollution method

Chapter 3

Architecture for Middle-mile Network for Providing Broadband Access Using TV White Spaces

The two most commonly discussed applications of TV White Space are (i) rural broadband using backhaul/access in TV White Space, and (ii) low-power Machine to Machine (M2M) communications using TV White Space [36]. In Chapter 2, we made two important observations about TV White Space in India,

- in the UHF TV band (470 – 590 MHz), at any given location in India, more than 100 MHz of spectrum is available as White Space, and
- the availability of this White Space does not vary temporally.

Thus, in the Indian context, there is a potential to develop applications that require large bandwidth at all times. In this thesis, we examine the feasibility of one such application — providing rural broadband services through backhaul in TV White Space.

As per the International Table of Frequency Allocations of the Radio Regulations Articles (Edition 2012) [37], the allocation of various radio services is done region-wise. For the purpose of allocation of frequencies, the world has been divided into three regions — 1, 2, and 3. In Region 3, where India belongs, the frequency band 470–585 MHz allows for Fixed, Mobile, and Broadcasting as Primary Services. Thus, in Region 3, apart from Broadcasting, the UHF TV band can additionally be considered for Fixed and Mobile services.

3.1 Proposed Solution for Rural Broadband and Associated TV White Space Backhaul

In order to reach the last mile access network, we propose a middle-mile network as a Fixed service in the UHF TV band that reuses the free spectrum available in the UHF TV band to provide connectivity to the distant habitat clusters. Figure 3.1 shows the schematic of such a middle-mile network. In the figure, the blue clouds represent a habitat cluster being provided connectivity using a local access network.

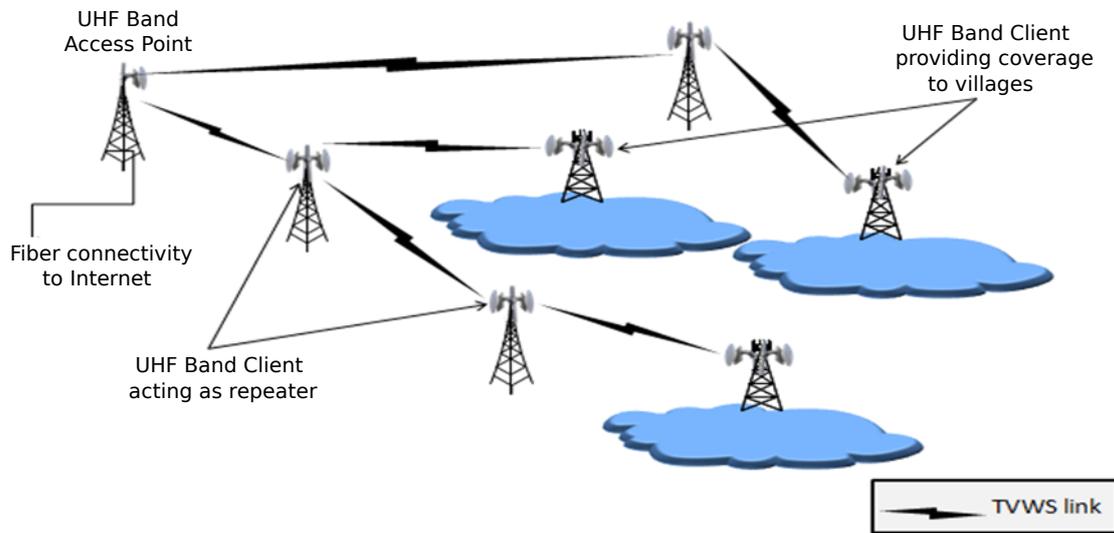


Figure 3.1: A middle-mile wireless network using TV White Space for backhaul connectivity

This middle-mile network may comprise of point-to-point links, multipoint-to-point links or a multi-hop wireless mesh network that is capable of providing coverage within a radius of one to five kilometers (in order to connect the surrounding habitat clusters as described in Chapter 1) to enable seamless connectivity from the access network to a backhaul point such as an NOFN node.

Within a particular region, 2.4 GHz unlicensed band Wi-Fi can be used as the connectivity option as shown in Figure 3.2. Wi-Fi access points can be connected in a multipoint-to-point manner to UHF band Clients (We define UHF band Client and UHF band Access Point in a later section). The UHF band Clients can then be connected as point-to-point or multi-hop link to the UHF band Access Point connected to the NOFN node. This will enable to extend the reach of NOFN to all village clusters.

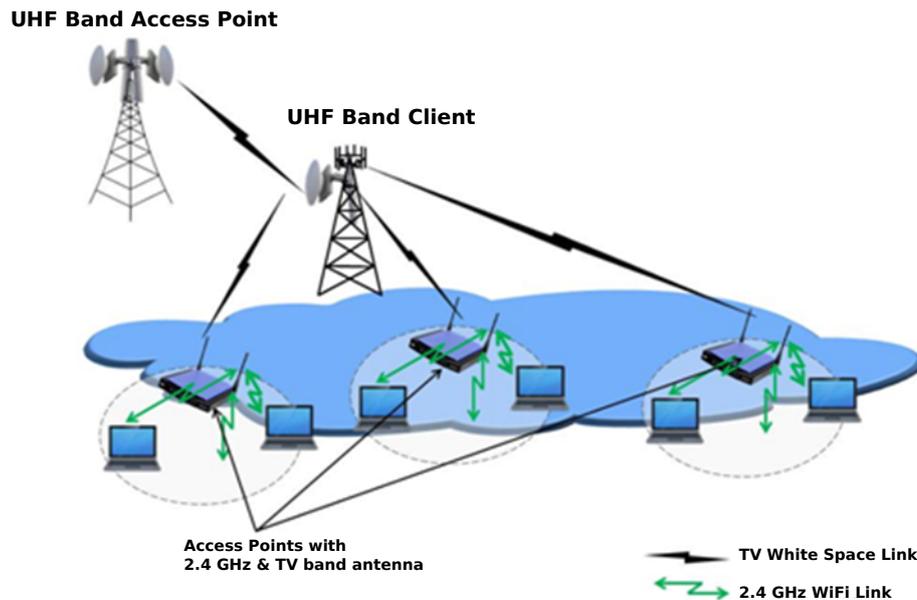


Figure 3.2: Rural area Wi-Fi connecting to TV band backhaul

3.2 Architecture for TV White Space Based Network Operations in India

In order to detect the presence of primary users in India, a spectrum sensing based approach is not required due to the following reasons¹,

- there is a single broadcaster — Doordarshan, which is using the spectrum;
- the usage of spectrum by Doordarshan is (nearly) static and has not changed for decades;
- at any given location, minimum 96 MHz will be available as unutilized frequency band in 470 – 585 MHz; and,
- information about free channels at any given location is also known and a geo-location database (See Section 3.4) can be used to ascertain these free channels.

Thus, in the rest of this thesis, we consider a geo-location database assisted approach for interference avoidance to the primary users. We describe the architecture of our proposed system next.

¹Some portions of this chapter have been used from a document submitted to the Department of Telecommunications by Prof. Abhay Karandikar.

3.2.1 Architecture for Database Assisted TV White Space Operations in India

The architecture for a TV White Space network supplementing the NOFN plan (described in Chapter 1) using a database is shown in Figure 3.3.

A secondary user having Internet connectivity to the database (referred to as Master node) can query the database and obtain a ‘free channel’ for operating at a certain maximum power level. In the Indian context, a village gram panchayat connected via the NOFN plan can qualify as this Master node.

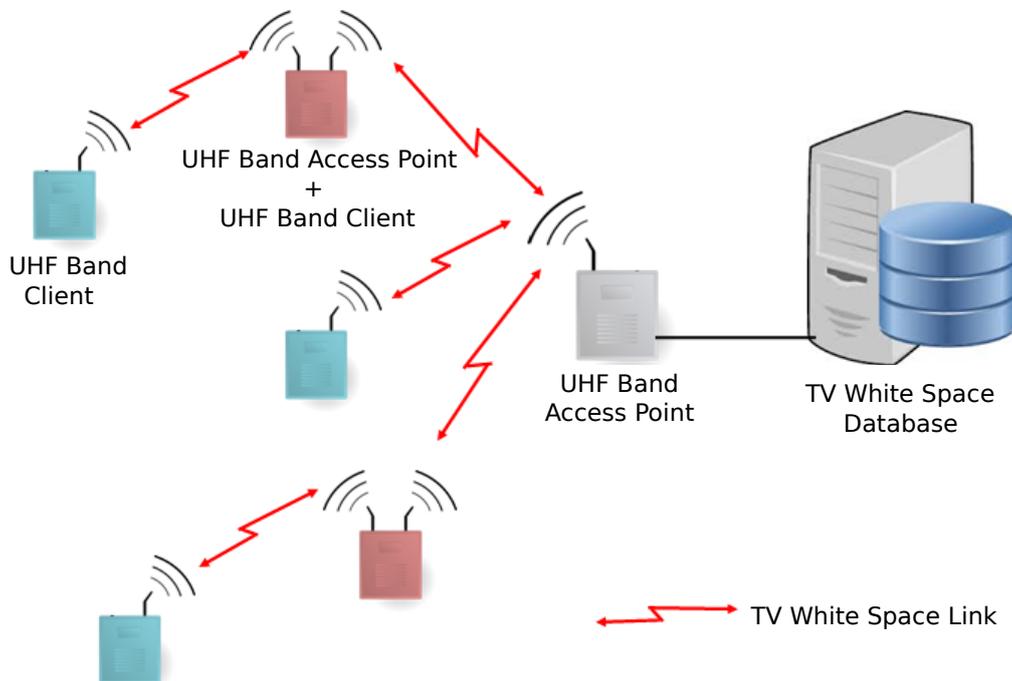


Figure 3.3: Architecture for database assisted operations

Villages without Internet connection cannot access the database directly. To obtain a ‘free channel’, a TV White Space node within a village without Internet connection (referred to as Slave node) must reach the database through the Master node. The Slave TV White Space device has two wireless interfaces. One of these interfaces is used for communication with the Master TV White Space node, while the other interface is used to serve client device or Customer Premise Equipment (CPE) and can operate at 2.4 GHz so that the end-clients can remain Wi-Fi devices such as smartphones, laptops, and tablets.

3.2.2 Regulatory Approach for the Use of TV White Space in India

The architecture described above allows for spectrum sharing with TV White Space nodes of different service providers. In this approach, the TV White Space nodes are susceptible to interference from other similar devices in their vicinity. This is not particularly favorable to services like fixed backhaul or middle-mile networks described above. An alternate spectrum sharing mechanism termed as *Licensed Shared Access* (LSA) [38] can effectively be used to facilitate rural broadband services using TV White Space nodes. The LSA mechanism is a complementary approach to the traditional exclusive licensing and the license-exempt approaches. In the LSA approach, additional users (termed as co-primary users or LSA licensee) are granted license to operate in a frequency band which is assigned (or will be assigned in future) to an incumbent user. The incumbent users agree to the terms of the LSA license, and the license is granted by the regulator.

A certain Quality of Service (QoS) is guaranteed to the incumbent users as well as the LSA licensees. The elements of the LSA framework are shown in Figure 3.4.

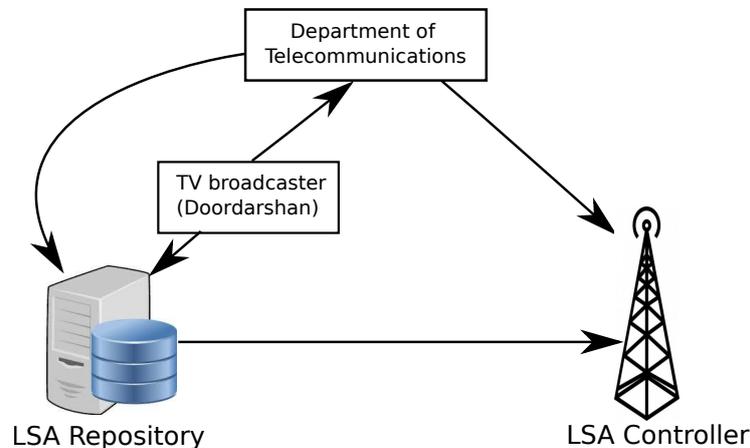


Figure 3.4: Elements of the LSA framework, adopted from [38], for Indian scenario

The TV White Space database is similar to the LSA repository, which interacts with the regulator and the incumbent user (which is the TV broadcaster in this case). The Master device is analogous to the LSA Controller, which queries the LSA repository in order to prevent any harmful interference to the incumbent user.

Presently, there are no regulations in India that allow operations for broadband services in the TV White Space. If such operations are allowed in India, the licensing

mechanism used could be an LSA approach where the UHF TV band devices can be considered as co-primary services operating along with the incumbent user. In this licensing regime, affordable rural broadband services can be provisioned using TV White Space middle-mile links.

3.3 Hardware Architecture - UHF Band Equipment

In this section, we describe the development of a prototype capable of operating in the UHF TV band. UHF band equipment are available off-the-shelf in countries like United States, United Kingdom and Japan. These equipment have been developed using Software Defined Radio (SDR) platforms, and, therefore, are expensive. (Each UHF band Base Station costs about \$4000-5000, while each UHF client device costs about \$1000-2000.) Since the objective of this thesis is to enable the provision affordable broadband services, a low cost prototype (\$650 per UHF band device) has been developed.

3.3.1 Block Diagram of UHF TV Band Device

The block diagram of a typical wireless device is shown in Figure 3.5.

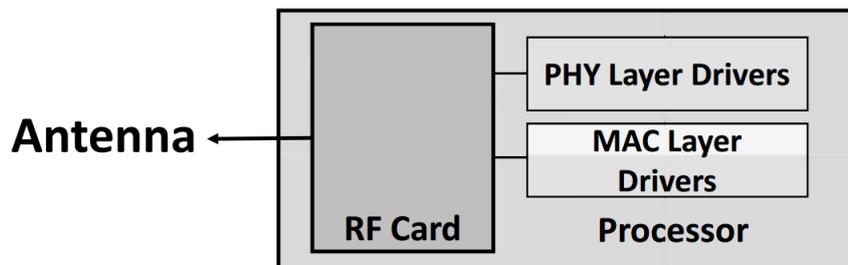


Figure 3.5: Block diagram of a wireless transceiver station

The component of a wireless device responsible for transferring data over the physical channel is the Radio Frequency (RF) card. The RF card takes care of functions like modulation/demodulation and converting the frequency of signals from baseband to frequencies that are suitable for wireless communication. Processing of baseband signals is carried out in the baseband processor. The RF card and the baseband processor communicate with each other using drivers that are device specific. The device drivers provide an abstract interface of the RF card to the baseband processor.

In order to develop a UHF band prototype, suitable components have been identified as baseband processor and RF card. The device drivers are implemented in software (within the operating system) running on the baseband processor. The baseband processor used in our UHF band prototype is the Mikrotik RouterBoard (model RB 433AH) [39]. The RouterBoard processor can operate with any RF card that provides a miniPCI interface [40]. The RF card used in our UHF band prototype is Doodle Labs DL535. This RF card was selected for the prototype for the following reasons.

- The RF card uses the same chipset (Atheros) as the one used in many standard IEEE 802.11g WiFi cards. As a result, the same set of drivers that are used with WiFi (namely ath5k or madwifi) can be used with DL535 RF cards.
- The open source wireless drivers make it possible to modify the drivers as per requirement and extract driver level information. This raw information can be used to characterize wireless links as needed. For example, the number of frames arriving at the Physical Layer every second can be printed, which gives the actual Physical Layer throughput in real-time.

An ideal RF card converts the baseband signal to the desired high frequency signal. However, the DL535 RF card is a modification of the standard IEEE 802.11g WiFi radios. As a result, the RF card first converts the baseband signal to 2.4 GHz, and a downconverter converts this to sub-GHz frequency (shown in Figure 3.6).

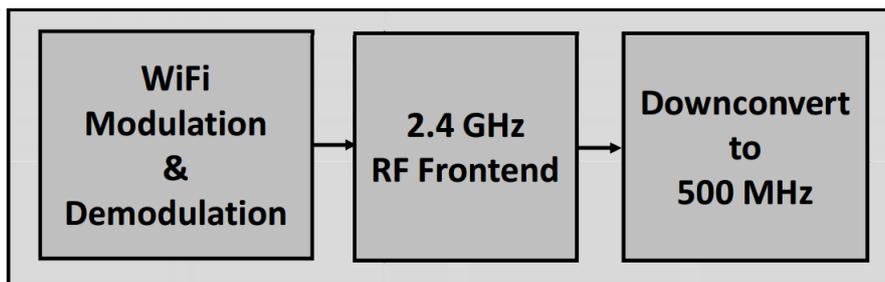


Figure 3.6: High-level architecture of the UHF TV band prototype

The prototype (comprising of the baseband processor and RF card) can operate in the UHF TV band with the following operational parameters.

An embedded linux kernel based operating system — OpenWrt [41] is ported on the prototype. The compilation and configuration of the operating system for the prototype involves several steps, all of which have been outlined in detail in Appendix A and B.

Parameter	Value
Center Frequency	510 – 560 MHz
Channel Bandwidth	5, 10, 20 MHz
Transmission Power	0 – 27 dBm
Physical Layer Data Rates	6, 9, 12, 18, 24, 36, 48, 54 Mbps

Table 3.1: Prototype Operation Parameters

3.4 Software Architecture - Implementation of Protocol to Access White Space (PAWS) Database on Hardware Platform

In this section, we describe the implementation of the geolocation database driven approach for interference avoidance to the primary users by a TV White Space network. In such a network, the TV White Space database, or simply a *database*, consists of mappings from location coordinates (latitude, longitude) and height to a list of channels and permissible transmit powers levels in each channel. Before transmitting in any TV channel, a secondary user in the network must query the database and obtain a list of available channels with the permissible power levels. In order to standardize this process of database query by the secondary devices, the Internet Engineering Task Force (IETF) has released the Protocol to Access White Space (PAWS) database [44].

3.4.1 OpenPAWS: Protocol Details

PAWS categorizes a TV White Space device as either a Master or a Slave device. The PAWS protocol defines a Master device as a “device that queries the database, on its own behalf and/or on behalf of a slave device, to obtain available spectrum information.” The Slave device, on the other hand, cannot connect to the database directly. As per the PAWS protocol, a slave device is a “device that queries the database through a master device.” One important assumption made while developing this protocol is that the Master device and the database, both have connectivity to the Internet.

The protocol specifies a sequence of procedures to be followed by the PAWS Master

device, PAWS Slave device and the database, which are as outlined below:

1. During bootstrapping, the Master device locates or discovers the regulatory domain for its location and the *Uniform Resource Locator* (URL) for the database to send subsequent PAWS messages.
2. The Master device then establishes an *Hypertext Transfer Protocol* (HTTP) session with the database.
3. An optional initialization message (INIT_REQ) is sent to the database by the Master device.
4. The database responds to the initialization message with an initialization response (INIT_RESP).
5. Based on the regulatory domain, the Master may have to register itself with the database using the registration request (REGISTRATION_REQ) message.

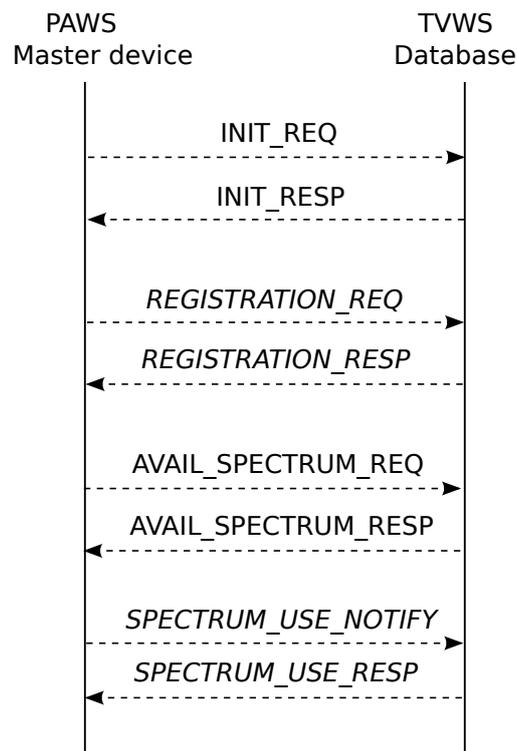


Figure 3.7: Messages exchanged between PAWS Master device and the database

6. If the database receives a registration request, it registers the Master device and sends a response (REGISTRATION_RESP) to the Master device.

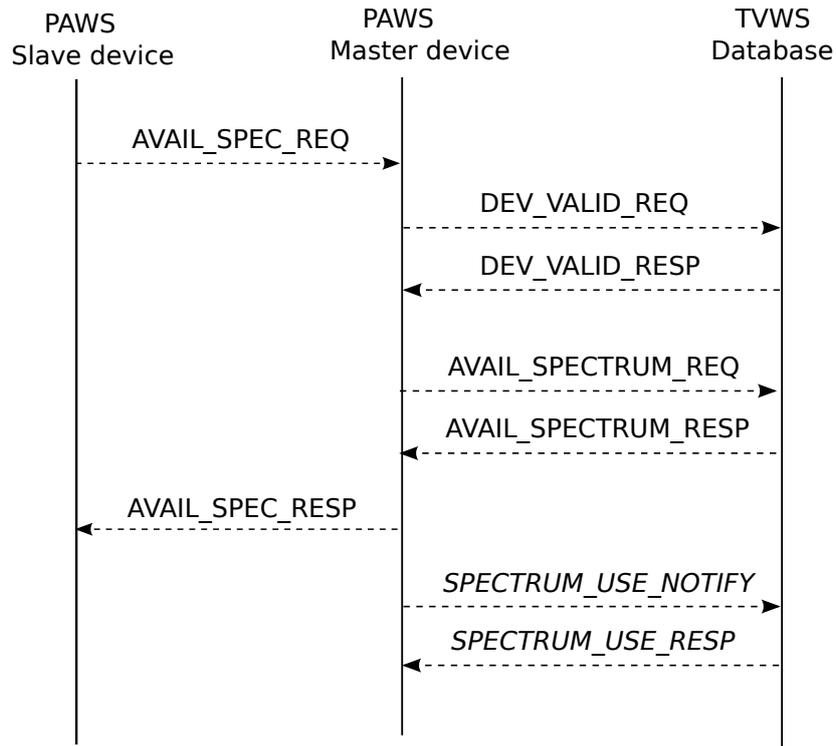


Figure 3.8: Messages exchanged between PAWS Slave device, PAWS Master device, and the database

7. Once the initialization and registration procedures are completed, the Master device can query the database for a list of available channels using an available-spectrum request (*AVAIL_SPECTRUM_REQ*) message to the database.
8. The database sends the list of available channels at the Master device's location using the available-spectrum response (*AVAIL_SPECTRUM_RESP*) message.
9. The Master can send the *AVAIL_SPECTRUM_REQ* message by itself, or for a Slave. If the Master queries the database for a Slave, the Slave device may be validated by the database using the *DEV_VALID_REQ* and *DEV_VALID_RESP* messages.
10. The Master device can use spectrum use notify (*SPECTRUM_USE_NOTIFY*) message to inform the database about its decision to operate on a particular channel. The database notes this and sends a spectrum use response (*SPECTRUM_USE_RESP*). This message is optional as PAWS does not concern the interference between secondary users.

The sequence of messages transmitted by the PAWS Master device and PAWS Slave

device are shown in Figure 3.7 and Figure 3.8, respectively. Messages shown in *italic* are optional messages specified by the PAWS protocol. These messages may be required by the regulatory domain of the database and are facilitated in our implementation of the protocol.

Format of PAWS Messages

All messages exchanged between the PAWS Master device, PAWS Slave device and the database are exchanged using *JavaScript Object Notation* (JSON) encoded strings. JSON strings have multiple parameters encoded in them. E.g., the AVAIL_SPECTRUM_REQ message has the latitude-longitude of the device, the height above average terrain, and the device ID specified. Response from the database contains parameters such as the operating frequencies, and transmit powers encoded. All the message formats are specified by PAWS [44].

The JSON encoded string for the INIT_REQ message used in OpenPAWS implementation is shown below:

```
1 {
2   "jsonrpc": "2.0",
3   "method": "spectrum.paws.init",
4   "params": {
5     "type": "INIT_REQ",
6     "version": "1.0",
7     "deviceDesc": {
8       "serialNumber": "D4:CA:6D:FF:06:15",
9       "rulesetIds": ["IITB-TvWhiteSpace"]},
10    "geo-location": {
11      "point": {
12        "center": {"latitude": 72.90, "longitude": 18.97}
13      }},
14 }
```

3.4.2 Implementation Details

An embedded Linux based operating system, OpenWrt, was used for the implementation of OpenPAWS. OpenWrt is a configurable open-source operating system that provides extensive functionality. Thus, the source code for OpenPAWS can be readily ported on any hardware platform supporting OpenWrt. The hardware platform used for our implementation is the prototype described in section 3.3.

Our implementation of PAWS has two components — one running on the OpenWrt platform and another running on the database. The OpenWrt component of OpenPAWS runs as a user space application, while the database side implementation is done on a desktop server using Apache2 Web Server running PHP scripts. We have released the OpenWrt-side as well as database-side source code under the GNU GPL version 2.0 [47]. Details of OpenPAWS implementation at the database and devices are discussed next.

3.4.3 TV White Space Database for India

In [35], the quantitative assessment of TV White Space was carried out in four zones of India. Subsequently, Doordarshan has provided data of North Zone and we have extended the analysis of [35] to include North Zone information. We briefly summarize the results of our analysis carried out for all the TV towers operating in India.

Considering the pollution viewpoint (viewpoint of the secondary user), with an allowable interference level (γ) of 15dB, 88.82% of the area in India has all the 15 channels available as white space, while in 99.99% of the area, 12 or more channels are available. On the other hand, if we consider the pollution viewpoint (viewpoint of the primary user) with (Ψ) a fading margin (an additional margin over the Signal to Interference plus Noise ratio that the regulator provides in case of deep fading events) of 1dB, in 78.82% of the area in India, all the 15 channels are available for TV White Space secondary operations, and in 99.61% of the area, 10 or more channels are available. Even with the FCC regulations, which is a conservative point of view, 94.97% of the area in India has all 15 channels available, while in 100% of the area 12 or more channels are available. The detailed noise effect is documented in [35].

The data obtained from Doordarshan contains operational parameters (except antenna patterns) of all towers operating the 470 – 590 MHz band in India. This data,

along with the computational model described in [35], have been used to create a TV White Space database for India. We discuss the implementation of the PAWS compliant TV White Space database next.

PAWS Server Implementation

The PAWS server is a web-server located at a remote location. This server hosts the White-Space database. This is a MySQL database listing out all possible channels available for transmission corresponding to a particular geolocation. The PAWS master device must have an external connectivity to the PAWS server over a wired or wireless channel. All communications between the PAWS Master, Slave and the database is carried on over the HTTP protocol. In our implementation, we have used the Apache2 server as the HTTP web-server to host the database. A PHP script runs at the database and keeps listening for incoming PAWS request messages. On receiving the initialization request from Master, PHP script at the server detects parses the request to obtain the coordinates provided by the Master. If the coordinates are not found in the database, the Master device is not within the regulatory domain of the database, and server sends an Error message to the Master and stops communication. If the coordinates are found in the database, the server decides that the point is within its regulatory domain, i.e. in India. The database sends a response message with a ruleset information and records a unique device identifier (MAC address in our implementation) in a repository within the database. Though not the main aim of this work, the repository keeps record of all the channels being used in a particular location. In case, multiple secondary users start operating in that location, this repository resolves the issue of interference between them. The ruleset information is a guideline with parameterized-rule values which has to be followed by the radio devices while connected to the database. The Master device then queries the channels available at the geolocation. This query may be on behalf of itself or any Slave device connected to the Master. If a match for the coordinates is found, the server looks up for the coordinates in the database and gets the list of available channels with permissible power levels. The server encodes this list in the JSON format and sends it to the Master device through the response message. It must be noted that the PAWS protocol does not specify any particular implementation of the TV White Space database. It only defines the *Application Program Interfaces* (APIs) required at the TV

White Space database and the messages exchanged between the PAWS Master device and the database.

OpenWrt Master device

The PAWS Master is configured to operate as an Access Point (AP) with a single wireless interface. A wired connectivity to the database is provided using an Ethernet cable connected to the Internet backhaul. The Ethernet interface of the OpenWrt hardware is bridged to the Wireless interface, which can be configured using the *Command Line Interface* (CLI) of OpenWrt. Detailed configuration procedure for OpenWrt Attitude Adjustment is available in OpenWrt forum. Once the OpenWrt hardware device is configured to operate as an AP in the bridged-local area network mode, the device is ready to be configured as a Master device, which is done using a configuration script *install.sh*. This configuration script checks for all pre-requisites, and installs the required executables for OpenPAWS. All PAWS Master device scripts are set up in the PAWS root directory and a PAWS *User Interface* (UI) is set up. At this stage, the device is configured to operate as a PAWS Master device.

The operational parameters required in order to connect to the database and obtain a list of channels are listed below.

- IP Address of the PAWS Server,
- Coordinates of Master device (latitude, longitude),
- Height of the Master device antenna,
- MAC Address of the Master device.

These parameters can be set up using the PAWS UI as well as the OpenWrt CLI. When all the above parameters are provided and a request is sent to the database, the user space application runs at the Master device. This application initializes and registers the Master device with the database and sends a query to the database. The HTTP connection with the database is established using the bash command ‘cURL’. The JSON encoded string consisting of the above mentioned parameters is sent to the database using an HTTP POST request. This procedure is followed for all messages sent by the Master device to the database. To each of these messages, the database responds

with the corresponding response message which decides the action to be taken by PAWS Master device.

The TV White Space availability at any location may change over time. The PAWS protocol specifies a parameter ‘maxPollingSecs’ which denotes the maximum interval in seconds after which a secondary device must query the database. In India, TV tower operations do not vary largely over time. Hence, we set this parameter to 86400 seconds, i.e. a secondary device running OpenPAWS must send the AVAIL_SPECTRUM_REQ message to the database once every 86400 seconds. This is done using a PAWS daemon which runs at the Master device and sends the channel request periodically.

The state diagram of the Master device is shown in Figure 3.9. Once the Master

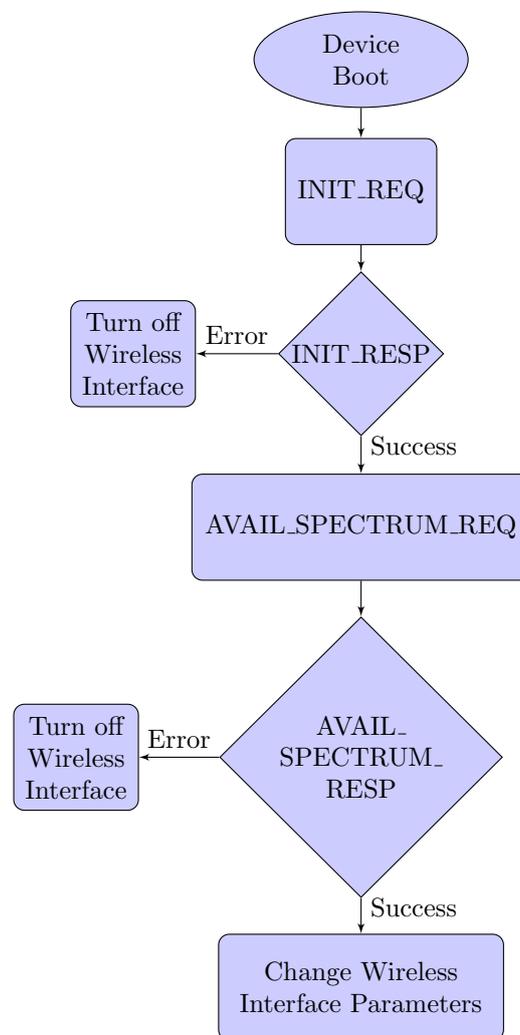


Figure 3.9: PAWS Master device state diagram

device obtains the list of available channels and corresponding transmission powers, it

selects a channel from the list and sets its wireless interface to operate at the channel and transmit at a power lower than the permissible level. In any of the responses from the database, if an Error message is received, the secondary device turns off its wireless interface. The fixed wireless node (Master or a Slave), as shown in Figure 3.3 is expected to be set up at a remote location in a rural area. At such remote locations, there is a possibility of power failure. In order to avoid user intervention in the event of a power failure, all PAWS request and response parameters are stored in a local configuration file *config.cfg*. Using this file, the Master device can be set to operate at parameters provided by the database in the event of power failure. All instances of spectrum query requests are stored in a PAWS update file and can be viewed remotely to check the operational parameters of the Master device as well as Slave devices.

OpenWrt Slave Device

Configuration and setup of the PAWS Slave is done using the configuration script (*install.sh*). In case of the Slave device, the most important requirement is the presence of a PAWS Master device in its radio coverage area. PAWS does not specify the protocol for communication between the Master device and the Slave device. In our implementation, we assume that there are two wireless interfaces available at the PAWS Slave device. One of these interfaces is used for communication with the Master device (Master-side interface), while the second interface is used to serve the CPEs (CPE-side interface). The architecture of the PAWS Slave device described above is designed taking into consideration the Indian conditions. If there is no Master device present in the vicinity of the Slave device, the Slave device turns off its CPE-side wireless interface. The following parameters are required for Slave device operation and can be set using the PAWS UI or the OpenWrt CLI.

- IP Address of the PAWS Master,
- Coordinates of Slave device (latitude, longitude),
- Height of the Slave device antenna,
- MAC Address of the Slave device.

Once the Slave device is connected to the Master, rest of the PAWS messages are exchanged in a manner similar to the Master-database communication. The state diagram of the Slave device is shown in Figure 3.10.

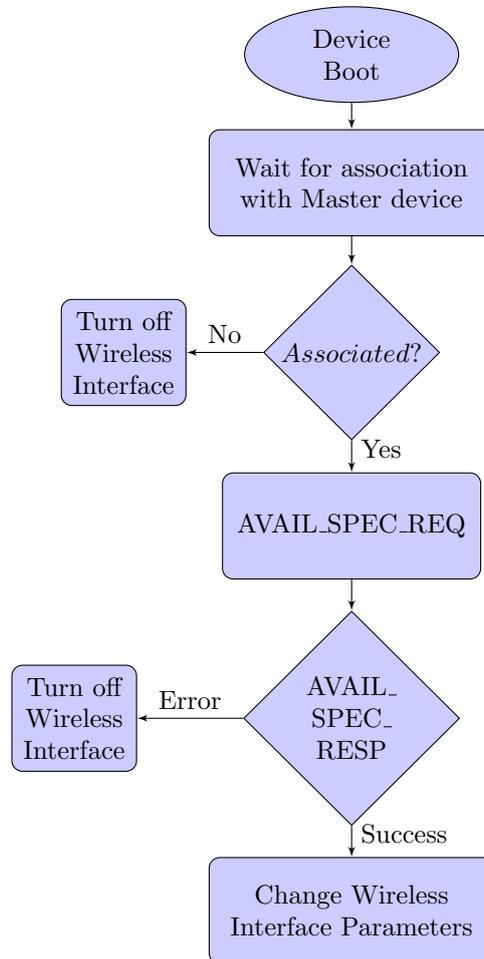


Figure 3.10: PAWS Slave device state diagram

Post Script

The Agreement in Principle for grant of the Experimental Radiating License for setting up the pilot test-bed was issued on June 12, 2015. The pilot test-bed has been set up after the License was issued. The plan for setting up the test-bed was presented during the M. Tech defense. The implementation of test-bed was carried out after the defense. The next chapter has, therefore, been written and included in the thesis after the defense.

Chapter 4

Implementation Details of the Proposed Experimental Test-bed in Palghar

4.1 Details of the Proposed Test-bed

As a part of this thesis, we propose and implement a pilot test-bed at selected locations in the Palghar district of Maharashtra state. The proposed test-bed consists of one base stations and ten clients. These UHF band equipment (comprising of UHF band Access Point connected to several UHF band Clients) have been set up at remote locations situated within a small distance of each other as shown in Figure 4.1 and 4.2.

4.2 Selection of Sites for Test-bed

The test-bed sites for the pilot test-bed have been selected considering the following criteria,

1. Distance between the tower with fiber connectivity and any other tower should be approximately 4 – 5 kilometers. and tower height should be about 30 meters from ground.
2. Some Government owned school/ hospital/ office must be present in the vicinity (say 200 – 300 meters) in order to provide services.

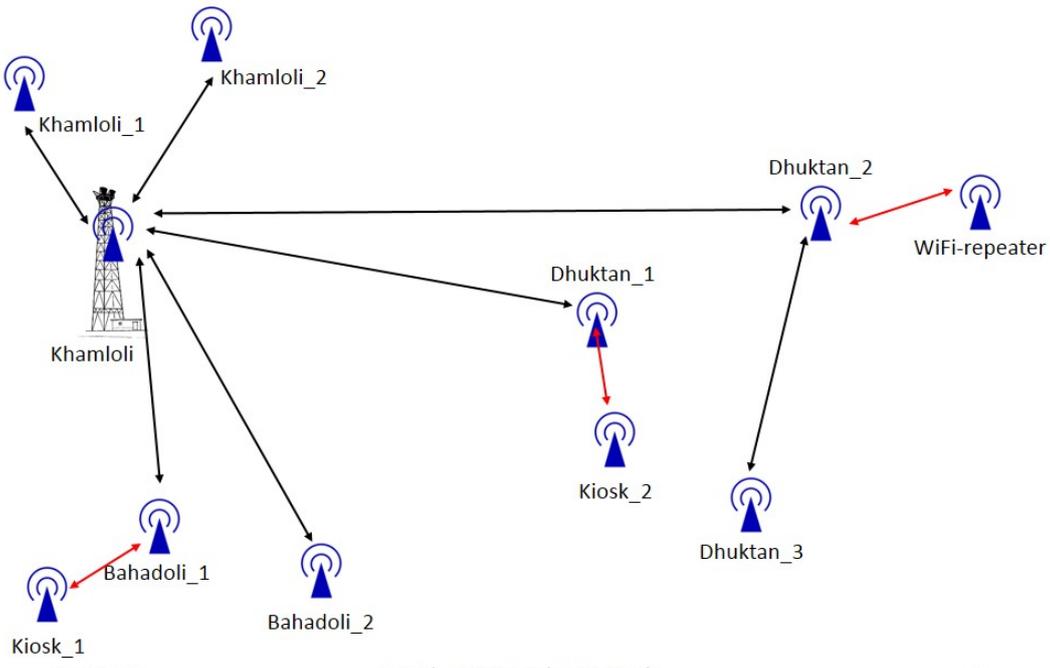


Figure 4.1: Detailed layout of Khamloli test-bed (Short distance links)

3. The objective of the test-bed is to provide high-speed access to rural areas. Therefore, the selected locations must not be heavily populated with high rise buildings.
4. Suitable space to install antenna, radio and other accessories.

The details of locations selected for the pilot testbed are listed in Table 4.1.

The TV band radios are configured to operate either as an Access Point (AP), or a Client. The Ground Based Tower (GBT) at Khamloli has an Omnidirectional antenna and the UHF TV band radio (operating in the AP mode) mounted at a height of 140 feet. At the Khamloli tower, access to the Internet is provided through a fixed 20 Mbps Ethernet line. All other towers and village nodes are connected to the Khamloli tower over UHF TV Band links, and the respective radios are configured to operate in the Client mode.

At each location, a suitable space is identified for setting up the UHF TV band radios and associated accessories including power supply. At every location within a test-bed, Wi-Fi routers have been installed to test the Internet connectivity. The customer premises equipments or CPE are Wi-Fi enabled devices such as tablets or low-cost smart phone.

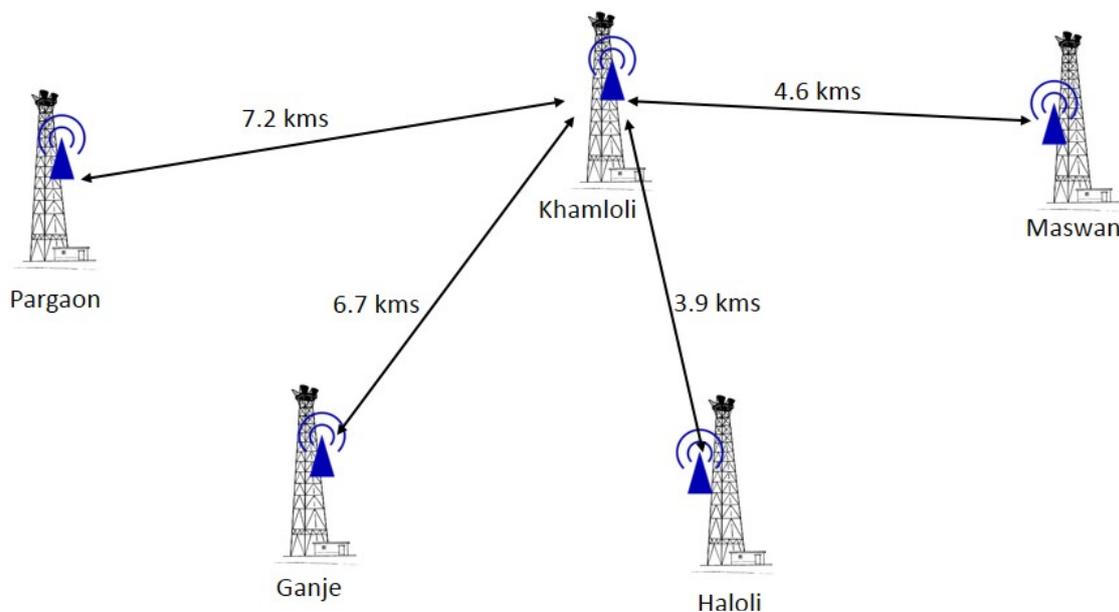


Figure 4.2: Detailed layout of Khamloli test-bed (Long distance links)

4.3 Topographic Details of Wireless Nodes

The test-bed is proposed to be set up in a primarily rural area. There are significant differences in the topographic settings between Khamloli tower (Gateway) and each of the other towers. Table 4.3 describes these settings.

Link	Topographic Settings
Maswan Tower	There is no line-of-sight between Khamloli and Maswan tower. The connecting area is hilly and has moderate vegetation. The Received Signal Strength varies between -65 dBm and -90 dBm. Connectivity at the Medium Access Control (MAC) Layer is intermittent.
Haloli Tower	There is complete line-of-sight with Khamloli tower. The in-between area has moderate vegetation and a highway.
Ganje Tower	The connecting area has heavy vegetation and a hilly terrain. There is no line-of-sight visibility to the Khamloli tower. Connectivity is highly intermittent.

Continued on next page

Table 4.2 – continued from previous page	
Link	Topographic Settings
Pargaon Tower	There is line-of-sight visibility with the Khamloli tower. There is very little vegetation in between. However, being the farthest tower from Khamloli, the Received Signal Strength is low (order of -80 dBm) and connectivity is intermittent.
Khamloli Node-1	The UHF band radio has been deployed on a single-storey house, and there is complete line-of-sight with the Khamloli tower. The connecting area has small houses with 4 – 6 meter height.
Khamloli Node-2	The UHF band radio has been deployed on a single-storey house, and there is complete line-of-sight with the Khamloli tower. The connecting area has small houses with 4 – 6 meter height.
Bahadoli Node-1	The UHF band radio has been deployed on a two-storey building, and there is complete line-of-sight with the Khamloli tower. The connecting area has small houses with 4 – 6 meter height.
Bahadoli Node-2	The UHF band radio has been deployed on a single-storey house, and there is complete line-of-sight with the Khamloli tower. The connecting area has small houses with 4 – 6 meter height.
Dhuktan Node-1	The UHF band radio has been deployed on a single-storey house, but there is no line-of-sight visibility. There are small hillocks in between, with moderate vegetation.
Dhuktan Node-2	The UHF band radio has been deployed on a 10 – 15 meter high hillock. There is partial line-of-sight with Khamloli tower. The area in between has hillocks, small houses with moderate vegetation.
Dhuktan Node-3	This node connects with Khamloli tower through Dhuktan Node-2. The UHF band radio has been deployed on a single-storey house. There is no line-of-sight with Dhuktan Node-2. There is a height mismatch, and large vegetation and small houses in between.

Node	Distance from Khamloli Tower (kilometers)	Latitude	Longitude	Altitude of Installation (ft)
Khamloli Tower		19°39'40.01"	72°52'17.04"	140
Maswan Tower	4.6	19°42'0.38"	72°51'22.23"	150
Haloli Tower	3.9	19°40'18.28"	72°54'24.39"	150
Ganje Tower	6.75	19°36'59.22"	72°54'.86"	160
Pargaon Tower	7.2	19°35'45.95"	72°52'34.99"	140
Khamloli Node 1	0.34	19°39'40.10"	72°52'5.50"	50
Khamloli Node 2	0.27	19°39'37.29"	72°52'8.10"	42
Bahadoli Node 1	0.73	19°39'54.76"	72°52'36.49"	46
Bahadoli Node 2	1.38	19°40'11.29"	72°52'51.11"	64
Dhuktan Node 1	2.3	19°40'53.78"	72°52'9.11"	34
Dhuktan Node 2	2.5	19°40'59.40"	72°52'7.31"	51
Dhuktan Node 3	2.2	19°40'48.62"	72°52'38.33"	53

Table 4.1: Location details of test-bed sites

4.4 IP Connectivity Details

Tata Teleservices has provided 5 publicly accessible IP addresses to help us in conducting our experiments and provide broadband Internet access to the villagers. A single WAN port has been made available at the Khamloli site with a 20 Mbps TCP throughput connectivity. Details of the IP scheme are as follows.

Public IP: 114.143.217.58-62

Gateway: 114.143.217.57

Subnet: 255.255.255.248

4.4.1 Private IP-addresses to Enable Networking within the Wireless Local Area Network

Since limited IP addresses are available for the test-bed, it is necessary to use a private addressing scheme inside the network. In order to enable Internet access to the village nodes, we have used Network Address Translation (NAT) at the Gateway node. On the other hand, to access the village nodes through the Internet (from IIT Bombay campus), port forwarding has been used. In this section, brief steps for enabling a private-IP based network have been listed.

Overall, a combination of Routed-Access Point (AP) and Routed-Client configurations have been used.

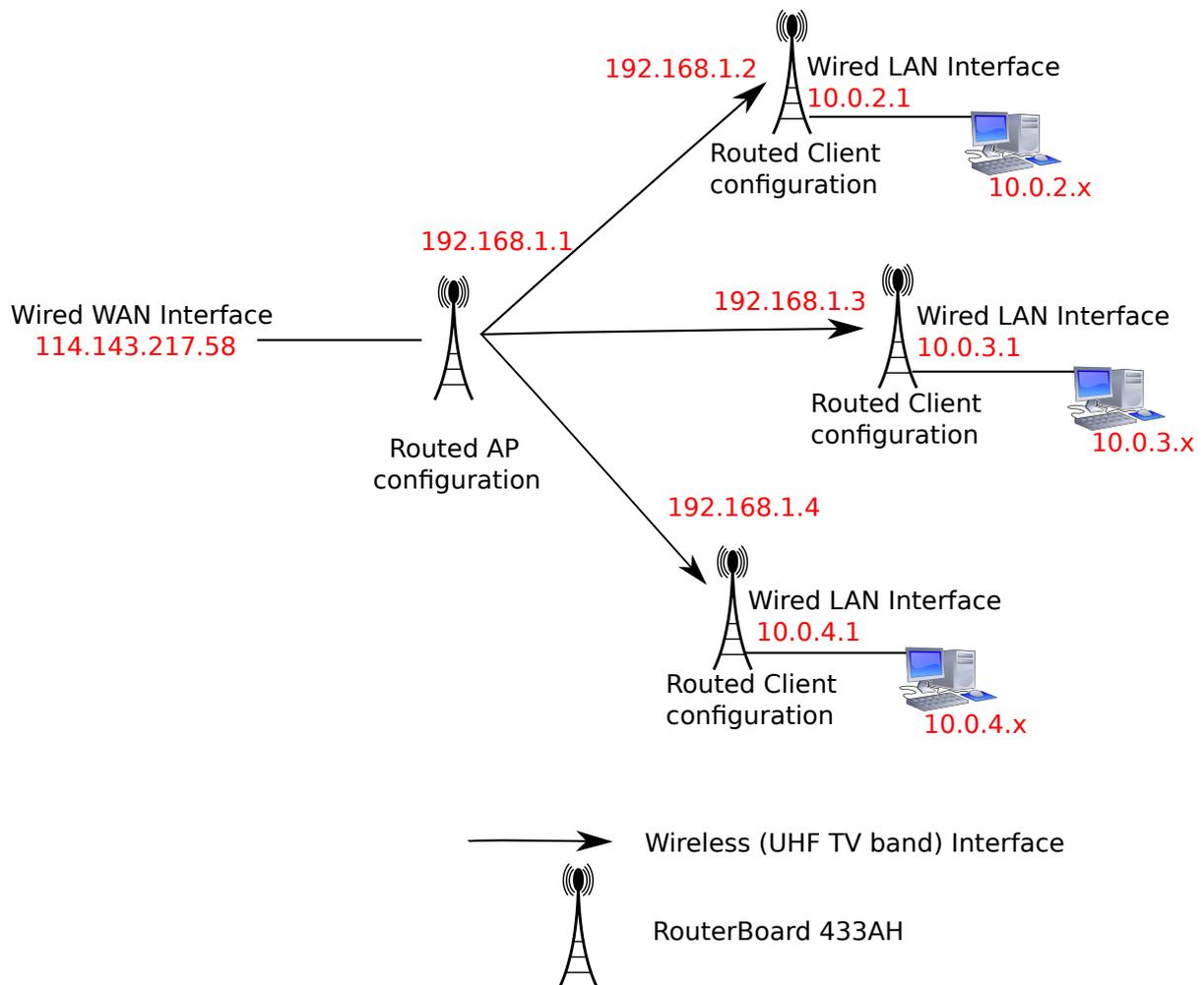


Figure 4.3: Network configuration of wireless nodes in the pilot test-bed

As shown in Figure 4.3, the UHF band equipment at Khamloli village serves as the Gateway to the public Internet. Here, a Routed-AP configuration was used. The Ethernet

or wired (eth0) interface used the public IP address 114.143.217.58 and the wireless (wlan0) interface used the IP address 192.168.1.1.

Access Point Configuration

Enabling the Routed-AP configuration involved the following steps,

- Create a WAN interface with IP address 114.143.217.58. This was done using the configuration file `‘/etc/config/network’`.
- Create a Wireless Interface using the configuration files `‘/etc/config/network’` and `‘/etc/config/wireless’`. At this stage, the wireless device was configured to operate as an AP. Following are the details of various operation parameters.
 - SSID: IITB-TVWS
 - Channel: 1 (500-520 MHz)
 - Transmission Power: 27 dBm
 - Hardware mode: IEEE 802.11g
- Start a DHCP server at the AP in order to lease IP addresses to any UHF band wireless client trying to connect to the AP. Configuration files used: `‘/etc/config/dhcp’`.
- Implement firewall rules through the file `‘/etc/config/firewall’` to enable routing between the WAN interface and the Wireless interface. This step involves implementing a Network Address Translation (NAT) through Masquerading at the WAN interface of the OpenWrt device.

The detailed configuration of the OpenWrt device in Routed-AP configuration has been provided in [43]. The complete configuration parameters are given in Appendix B.

Routed-Client Configuration

Enabling the Routed-Client configuration involved the following steps,

- In case of the Routed-Client, the wireless interface (wlan0) acts as the WAN interface, i.e. interface to Internet.

- Using ‘/etc/config/network’ and ‘/etc/config/wireless’ create a WAN interface at the wireless radio, and a LAN on the ethernet (eth0) interface.
- Make sure that the wireless parameters at the client are the same as that at the AP, i.e.
 - SSID: IITB-TVWS
 - Channel: 1 (500-520 MHz)
 - Transmission Power: 27 dBm
 - Hardware mode: IEEE 802.11g
- The end users connect to the Internet through the LAN interface. Therefore, a DHCP server is enabled at the LAN interface using the file ‘/etc/config/dhcp’
- Implement firewall rules through the file ‘/etc/config/firewall’ to enable routing between the WAN (wireless) interface and the ethernet (LAN) interface. This step involves implementating a Network Address Translation (NAT) at the WAN (wireless) interface of the OpenWrt device.

At the Customer Premise Equipment (CPE) side, the wireless interface is the WAN interface. Each CPE radio is statically assigned an IP address in the 192.168.1.0/24 subnet. NAT is also performed at the CPE side. The CPE with wireless interface IP 192.168.1.y has the IP 10.0.y.1 for its LAN interface. The LAN interface has a DHCP server enabled. Thus, any end-user that sends a DHCP query for an IP address gets an address in the 10.0.y.0/24 subnet.

4.4.2 Experimental Results

Testing of the OpenPAWS System

In this section we first test the OpenPAWS architecture described in Chapter 3. The performance of the UHF band devices in the test-bed is described later.

The TV White Space Database was configured on a desktop server running an Apache2 server within the lab. Figure 4.4 shows a sample response to an Error message. Such an error message can occur when (i) the hardware device is outside the regulatory domain of the TV White Space database, (ii) the hardware device sends an AVAIL_SPECTRUM_REQ

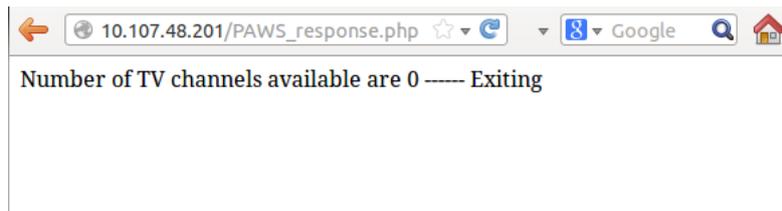


Figure 4.4: PAWS Failure Response

before initialization and registration or (iii) there are no channels available at the location of hardware device. In case of Figure 4.4, the Error message occurs because the location sent by the hardware device is outside the regulatory domain of the TV White Space database. Figure 4.5 shows a Success message response. The coordinates provided to the TV White Space database are (19.6614, 72.8641) corresponding to the Khamloli village in our pilot test-bed. At this location, all the TV Channels are available. Table 4.3 shows

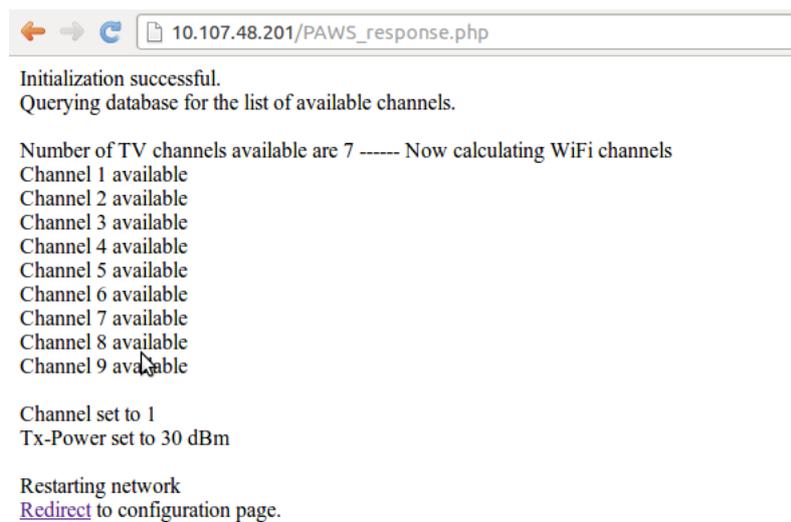


Figure 4.5: PAWS Success Response

the channels available at the six test-bed sites in the Palghar district. At each of the locations, all the TV Channels are available for secondary user transmission. Consequently, all channels are available for the RF card DL535. OpenPAWS, thus, selects Channel 1 for the operation the devices at each of these locations.

Once the channel and power values are set, the OpenWrt network is restarted and the updated channel and power values take effect. The database created is open for public access [46] and can be used to view the list of all TV towers operating in India in the UHF TV band along with all operational parameters. It also displays TV towers operating on

Site Name	TV Band Available	Channel selected by OpenPAWS	Tx Power
Khamloli	470-590 MHz	Channel 1	30 dBm
Haloli	470-590 MHz	Channel 1	30 dBm
Pargaon	470-590 MHz	Channel 1	30 dBm
Ganje	470-590 MHz	Channel 1	30 dBm
Maswan	470-590 MHz	Channel 1	30 dBm
Khamloli-1	470-590 MHz	Channel 1	30 dBm
Khamloli-2	470-590 MHz	Channel 1	30 dBm
Bahadoli-1	470-590 MHz	Channel 1	30 dBm
Bahadoli-2	470-590 MHz	Channel 1	30 dBm
Dhuktan-1	470-590 MHz	Channel 1	30 dBm
Dhuktan-2	470-590 MHz	Channel 1	30 dBm
Dhuktan-3	470-590 MHz	Channel 1	30 dBm

Table 4.3: Channel availability predicted by our Database at the test-bed sites

any particular channel along with the tower’s coverage area calculated in [35].

PAWS server scalability was tested by concurrent database queries from 5 Master devices a hundred times. All the incoming requests were handled seamlessly, and channel list was given to all the Master devices successfully. The execution time of the PAWS application at the Master device was calculated. The hardware device operating at 680 MHz clock took an average of 0.9 seconds to complete the process of initialization and spectrum querying. Restart of wireless network took an additional 3 seconds on an average. Thus the entire process of querying the database, obtaining and processing the list of channels and setting up the wireless interface takes an average of 3.6 seconds in our trial. The worst results found in this process are as follows: (i) real: 4.10 seconds, (ii) user: 0.95 seconds, and (iii) sys: 0.75 seconds. Real time measurement is higher as it includes other processes and boot up time of the device. User time is time for executing only the initialization and the query process. System time is time for execution of these processes in the kernel only.

Link Characterization

In this subsection, we describe the experiments performed on the testbed, and the results obtained. In order to determine the quality of different links in the network, we performed the following experiments.

- TCP Throughput 5, 10 and 20 MHz bandwidth at transmit power 0 dBm, 10 dBm and 27 dBm.
- UDP Throughput 5, 10 and 20 MHz bandwidth at transmit power 0 dBm, 10 dBm and 27 dBm.

The two operating parameters that were varied during the experiments are - channel bandwidth and transmission power. We represent these two parameters as a (i,j) tuple, where i is the channel bandwidth in MHz, and j is the transmission power in dBm. TCP and UDP throughputs were tested over each link using the network testing tool - iperf. TCP and UDP throughput were computed over 1 second intervals for 500 seconds over each link. Thus, 500 samples were taken for TCP and UDP throughputs over each link.

Link	Bandwidth (MHz), Tx-Power (dBm)	Mean TCP Throughput (Mbps)	Mean UDP Throughput (Mbps)
Haloli	(5, 0)	4.22547	4.81739
	(5, 10)	4.92972	6.46496
	(5, 27)	5.05754	6.85669
	(10, 0)	8.61719	11.0046
	(10, 10)	9.05413	12.088
	(10, 27)	9.3816	11.4964
	(20, 0)	1.44898	1.631
	(20, 10)	12.3573	12.9867
	(20, 27)	13.8705	19.0532
Bahadoli Node-1	(5, 0)	2.79553	4.34944
	(5, 10)	4.5478	5.9962
	(5, 27)	5.35349	7.15839
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Table 4.4 – continued from previous page			
Link	Bandwidth (MHz), Tx-Power (dBm)	Mean TCP Throughput (Mbps)	Mean UDP Throughput (Mbps)
	(10, 0)	10.4924	12.344
	(10, 10)	8.95731	10.2318
	(10, 27)	10.5354	11.9964
	(20, 0)	12.8225	17.4324
	(20, 10)	18.0082	23.9144
	(20, 27)	21.2162	26.6176
Bahadoli Node-2	(5, 0)	3.03872	3.99966
	(5, 10)	4.74094	6.10532
	(5, 27)	4.85643	6.33319
	(10, 0)	5.64116	7.95169
	(10, 10)	9.79519	11.6073
	(10, 27)	9.34904	10.4776
	(20, 0)	9.21279	12.7363
	(20, 10)	11.2953	14.468
Dhuktan Node-1	(20, 27)	11.9705	18.1926
	(5, 0)	2.88409	3.89643
	(5, 10)	4.74908	6.44512
	(5, 27)	5.04509	6.73147
	(10, 0)	4.43671	7.05167
	(10, 10)	7.78523	9.90485
	(10, 27)	9.38749	10.5829
	(20, 0)	2.31768	2.42076
(20, 10)	11.8024	17.0448	
	(20, 27)	11.3246	14.3376
	(5, 0)	4.16866	5.37884
	(5, 10)	3.56659	4.43287
	(5, 27)	4.66114	6.5312
Continued on next page			

Dhuktan Node-2

Link	Bandwidth (MHz), Tx-Power (dBm)	Mean TCP Throughput (Mbps)	Mean UDP Throughput (Mbps)
	(10, 0)	7.38828	9.90536
	(10, 10)	8.92427	10.1758
	(10, 27)	8.60459	8.90942
	(20, 0)	4.07018	5.10066
	(20, 10)	15.8271	23.3578
	(20, 27)	13.8529	19.0866

Table 4.4: Average TCP and UDP throughputs for different operating parameters

Figures 4.6 through 4.10 show the variation in TCP and UDP throughput over time for each link over the 500 seconds interval for (20 MHz, 27 dBm) tuple.

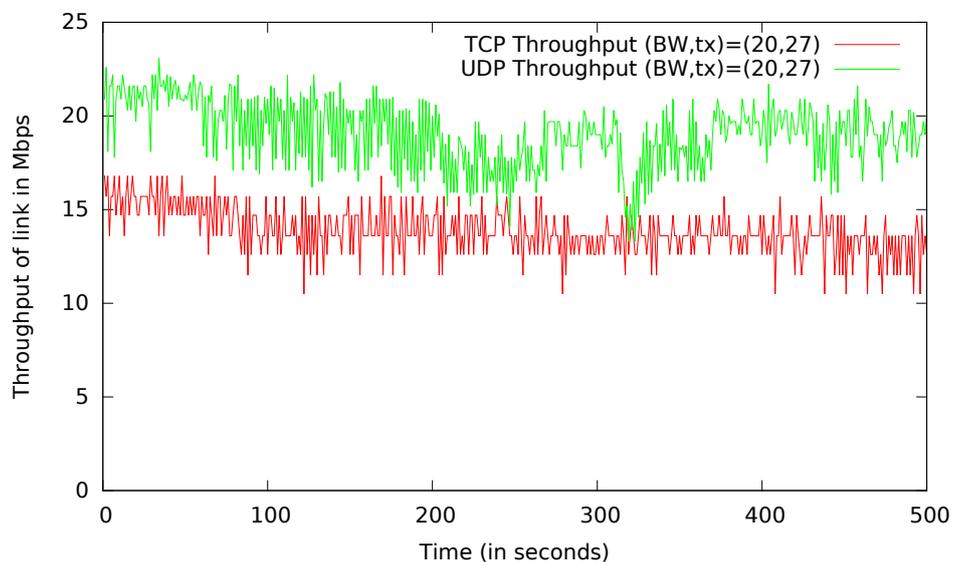


Figure 4.6: TCP and UDP Throughput on Khamloli Tower-Haloli Tower link

Some observations that follow from Table 4.4 are as below,

- For a particular link, it is expected that with an increase in the channel bandwidth, the TCP and UDP throughputs increase. This is, however, true only for higher

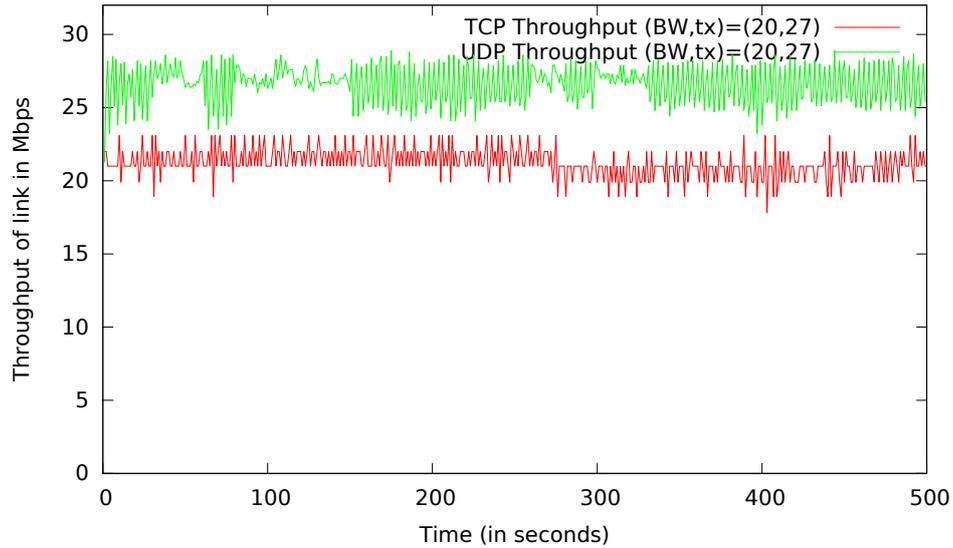


Figure 4.7: TCP and UDP Throughput on Khamloli Tower-Bahadoli Node-1 link

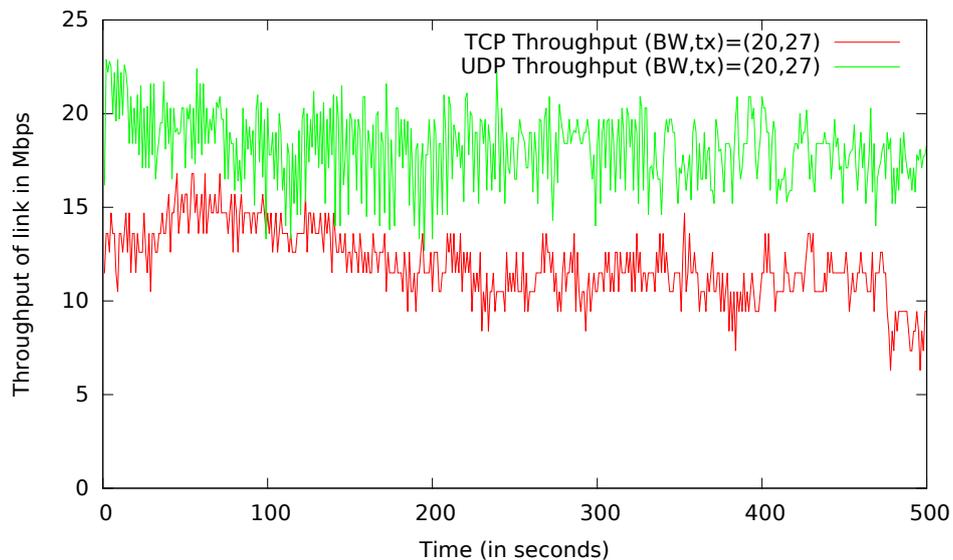


Figure 4.8: TCP and UDP Throughput on Khamloli Tower-Bahadoli Node-2 link

transmission powers. In all the links that were studied, for transmission power 10 dBm and 27 dBm, an increase in the channel bandwidth caused an increase in the throughput. However, when the transmission power was set to 0 dBm, there were some interesting observations.

- For links shorter than 1 kilometer (Bahadoli Node-1 and Bahadoli Node-2), throughputs increased with increase in channel bandwidth. This is shown in Figure 4.11.

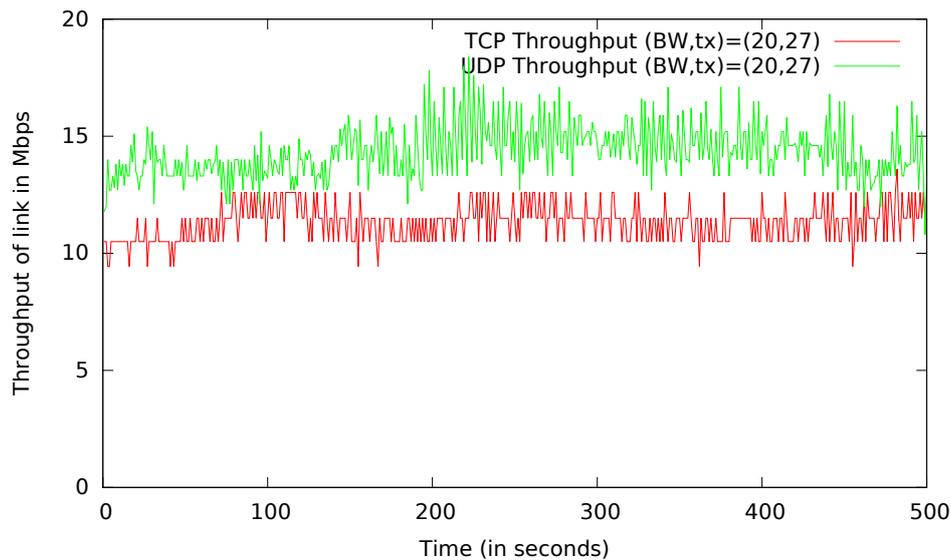


Figure 4.9: TCP and UDP Throughput on Khamloli Tower-Dhuktan Node-1 link

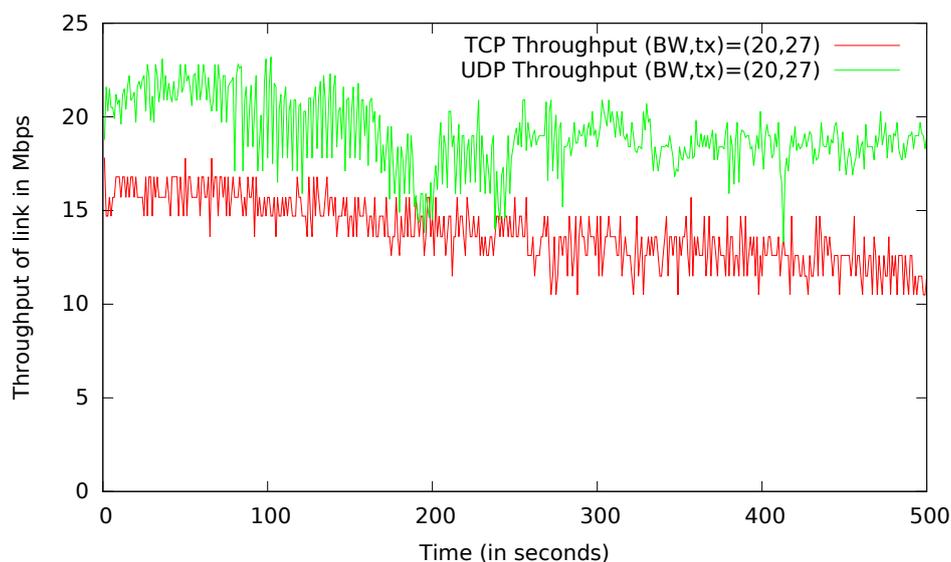
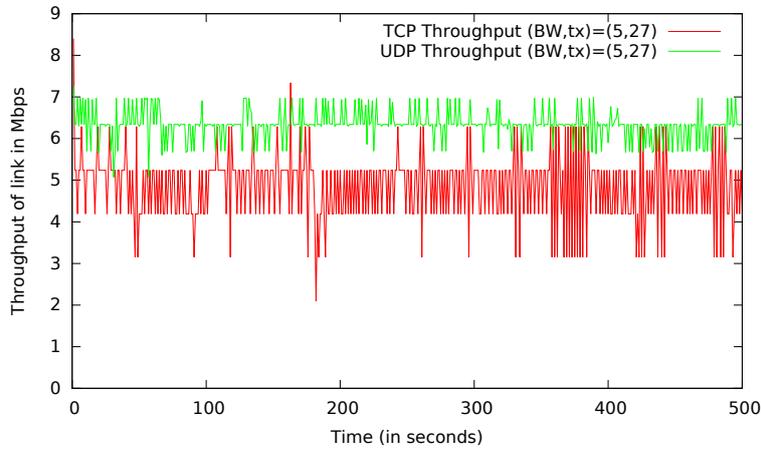


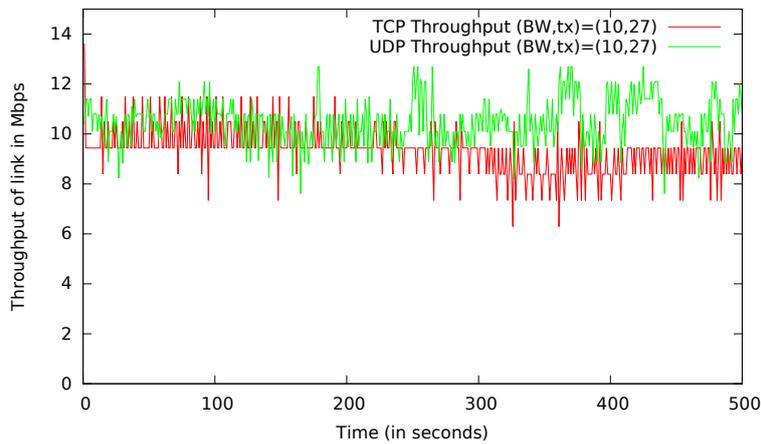
Figure 4.10: TCP and UDP Throughput on Khamloli Tower-Dhuktan Node-2 link

- For longer links (Haloli, Dhuktan Node-1 and Dhuktan Node-2), the performance was poor at 20 MHz as compared to 5 MHz, and 10 MHz channel bandwidth. This is shown in Figure 4.12.
- For distances as long as 2.3 kilometers with complete non line-of-sight, transmission power of 0 dBm provided TCP throughput of 2.88 Mbps at 5 MHz channel bandwidth and 4.436 Mbps at 10 MHz channel bandwidth.
- In case of line-of-sight between towers, at a distance of 3.9 kilometers, transmis-

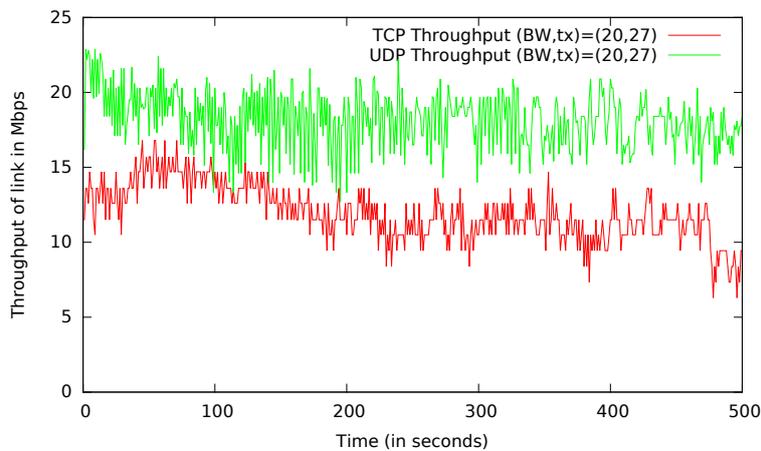
sion power of 0 dBm provided TCP throughput of 4.22 Mbps at 5 MHz channel bandwidth and 8.617 Mbps at 10 MHz channel bandwidth.



(a) Throughput at Bahadoli Node-2 for (5,27)

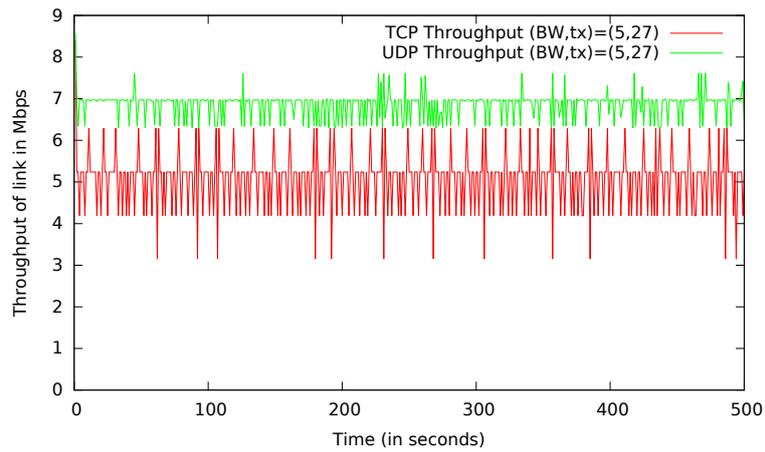


(b) Throughput at Bahadoli Node-2 for (10,27)

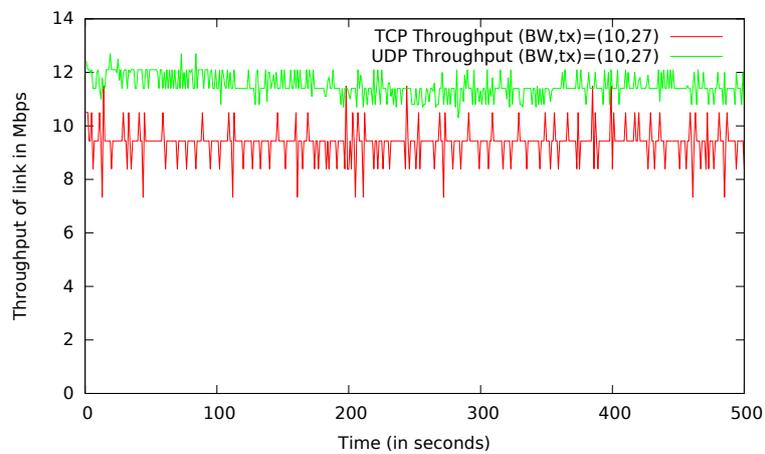


(c) Throughput at Bahadoli Node-2 for (20,27)

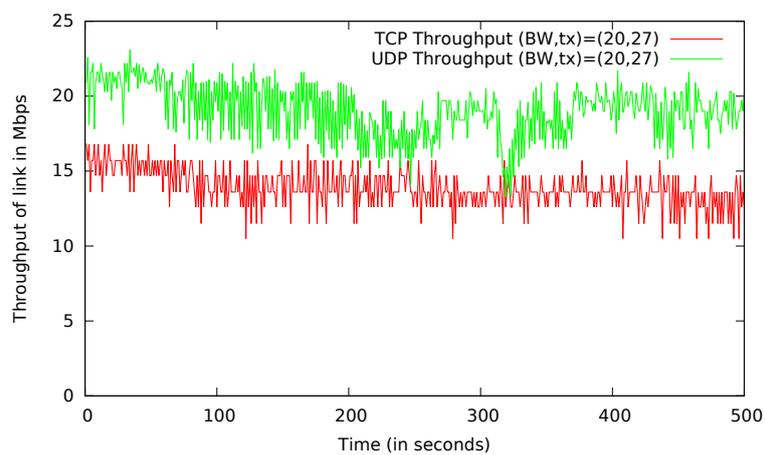
Figure 4.11: TCP and UDP throughputs at Bahadoli Node-2



(a) Throughput at Haloli Node-2 for (5,27)



(b) Throughput at Haloli Node-2 for (10,27)



(c) Throughput at Haloli for (20,27)

Figure 4.12: TCP and UDP throughputs at Haloli

4.5 Images of Test-bed Setup



Figure 4.13: UHF TV band Access Point deployed at Khamloli tower



Figure 4.14: UHF TV band Client in Khamloli Village (Khamloli-1)



Figure 4.15: UHF TV band Client in Khamloli Village (Khamloli-2)



Figure 4.16: UHF TV band Client in Bahadoli Village (Bahadoli-1)



Figure 4.17: UHF TV band Client in Bahadoli Village (Bahadoli-2)



Figure 4.18: UHF TV band Client in Dhuktan Village (Dhuktan-1)

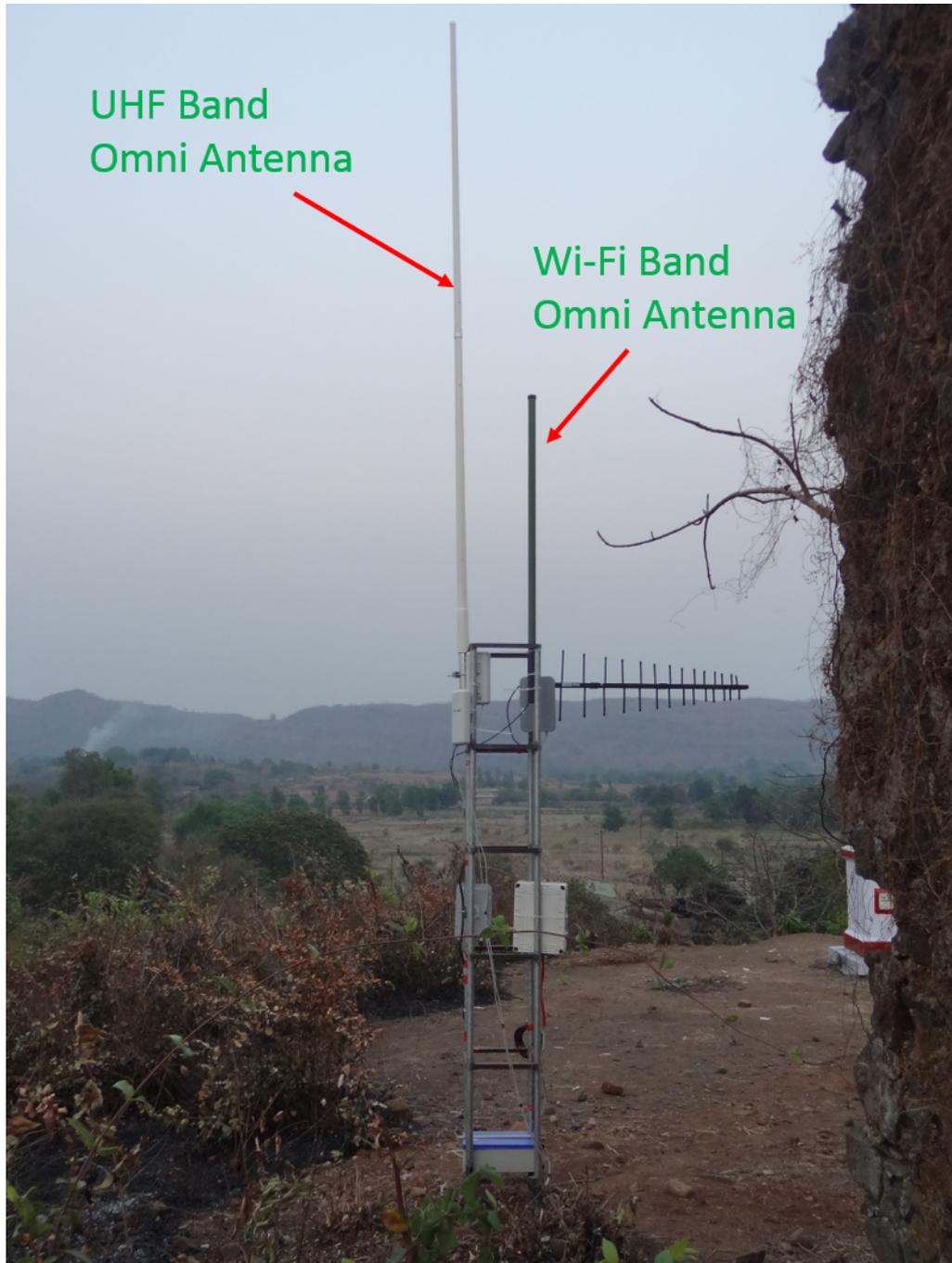


Figure 4.19: UHF TV band Client in Dhuktan Village (Dhuktan-2)

Chapter 5

Conclusions

5.1 Summary

The TV White Space scenario in India is unlike those in other countries. While the availability of underutilized spectrum in TV band is significant in many countries, in India, we have ascertained that more than 100 MHz in the frequency band from 470 – 590 MHz remains underutilized using a computation tool. Measurements on spectrum utilization of the TV band in three different cities validate the results of our computation tool. Additionally, at any given location, the usage of TV band is more or less static in India. Thus, in India, there is a potential for developing applications that require fixed bandwidth at all times. In this report, we have explored one such application.

We have discussed the feasibility of providing affordable broadband services in India with focus on rural areas using backhaul in TV White Spaces. In order to demonstrate the usefulness of the UHF TV band for this application, and to study the characteristics of sub-GHz spectrum, we have proposed to set up a pilot test-bed comprising of multiple UHF band Access Points and UHF Band Clients in a rural environment. As a part of the planning for the pilot test-bed, we have identified sites for the deployment of UHF TV band equipment. The implementation of test-bed could not be carried out due to delay in the grant of experimental radiating license by the Wireless Planning & Coordination Wing (WPC).

5.2 Future Work

Wireless Link Characterization

The next step to the work in this thesis involves setting up the pilot test-bed by deploying UHF band equipment at the selected sites. Once the UHF band Access Point and Clients are deployed, it is necessary to characterize the performance of each link, and relate this performance to the topographic conditions. The possible metrics to characterize the link performance are Transmission Control Protocol (TCP) and User Datagram Protocol (UDP) throughputs, jitter and error rates.

Technical Parameters for Target Quality of Service

The proposed broadband backhaul network has to guarantee certain Quality of Service (QoS) requirements, such as TCP and UDP throughputs, error rates etc. Based on the experiments conducted using the UHF band equipment, we must determine the various technical parameters for provisioning target QoS. These parameters include

- transmission power,
- transmitter and receiver antenna heights,
- channel bandwidth,
- modulation and coding schemes, etc.

Implementation of Scheduling Algorithms

In the current plan for the implementation of the pilot test-bed, the UHF band equipment operate with Carrier Sense Multiple Access (CSMA) based Medium Access Control (MAC) protocol. However, since CSMA is a contention based protocol, the performance is expected to be poor in the presence of multiple UHF band clients. To address this problem, we have identified a user-space application that schedules the packet from all UHF band clients to the UHF band Access Point in a round-robin fashion and ensures fair-scheduling between the different UHF band clients. This package, known as Frottle [50], must be cross-compiled for the UHF band equipment and used in the pilot test-bed.

Development of Network Management System

An Element Management System (EMS) and control server needs to be developed to enable remote management of the pilot test-bed network. Different parameters that can be remotely monitored and configured are as follows,

- UHF band device status (CPU usage, on/off status etc.),
- channel bandwidth,
- operating frequency,
- transmission power,
- IP address, etc.

Propagation Models in the 470 – 585 MHz Band for Indian Terrain Conditions

The measurements on spectrum utilization of TV band must be carried out at more locations, and at each location, the readings must be averaged over a sufficiently large interval of time to obtain accurate results. These results must be compared against the predictions of different propagation models, to determine a suitable model for Indian terrain conditions. The quantitative assessment of TV White Space in India was carried out using the Okumura Hata model; this assessment must be carried out using suitable propagation models to obtain more accurate results for the quantitative assessment.

Appendices

Appendix A

Compilation of RouterBoard 433AH in Bridged AP and Routed AP/Client modes

The process for completing the setup of a wireless node (Access Point or Client) with Attitude Adjustment OS to operate using the standard CSMA MAC protocol can be broken down into the following steps.

1. Make kernel and rootfs files for the desired OS
2. Flash these files into the RouterBoards
3. Configure relevant files and install selected tools

The following section describe each of these steps in detail.

A.1 Make kernel and rootfs files for the desired OS

- Go to the directory where you wish to download the source code
- Download Attitude Adjustment 12.09 source using the following command

```
$ svn co svn://svn.openwrt.org/openwrt/branches/  
attitude_adjustment
```

- Untar the file and copy it in home folder

- Go to the openwrt folder

```
$ cd openwrt
```

- We now need to configure the OS to include the relevant tools and drivers. This can be done using the make menuconfig command

```
$ make menuconfig
```

- This will open a User Interface. (If it does not, there might be some dependencies missing. Install them and try the command again). In order to install the Operating System in the NAND Memory of the Routerboard, we first need to get the board running using network boot. To this, we must prepare the ramdisk image file.
- Select the following components:

```
Target System: AR71XXX
Subtarget: Devices with NAND flash (mostly Mikrotik)
Target Profile: Atheros WiFi (ath5k)
Target Images: ramdisk
Kernel Modules -> Wireless Drivers: kmod-ath5k
(Make selected as '*' and not 'm')
Network: wpa-supPLICANT
Base System: wireless-tools
```

- Once this is completed, compile the OS using the command

```
$ make V=99
```

- If there are no errors in the compilation, the ramdisk image file will be formed in the following directory

```
$ <build_dir>/openwrt/bin/ar71xx
```

Rename this ramdisk file as 'vmlinux'.

A.2 Flash kernel and rootfs files into the RouterBoard

- Using this image, the RouterBoard will boot from the network. However, for field deployments, we want the OS to be installed permanently into the NAND Memory of the RouterBoard. To do this, we first need to create the kernel image file and the rootfs file. This can be done using follows.

```
$ make menuconfig
```

Keep all other configurations the same as before and change the Target Images

```
Target Images: tar.gz , jffs2 , squashfs
```

Exit the configuration screen and compile the OS using the command:

```
$ make V=99
```

- The ramdisk file has to be first loaded onto the RouterBoard using network boot. To do this, we first need to create an TFTP and DHCP server in the local host system. This is done as follows.

Install and Configure DHCP & TFTP Server

```
$ sudo apt-get install atftpd
$ sudo apt-get install dhcp3-server
$ sudo mkdir /tftpboot
$ cd <build_dir>/openwrt/bin/ar71xx
$ sudo cp vmlinux /tftpboot/vmlinux
$ sudo atftpd --bind-address 10.107.48.210 --daemon /tftpboot
```

Configure file `/etc/dhcp/dhcpd.conf` file appropriately, and then start dhcpd via the command

```
$ sudo dhcpd -cf /etc/dhcp/dhcpd.conf --no-pid eth0
```

- Now, switch on the RouterBoard, and enable network boot. Connect the RouterBoard to the local host system using serial cable. To gain access to the system, minicom needs to be installed in the local host system. Install minicom using the following command.

```
$ sudo apt-get install minicom
```

Now, to run minicom, type the following.

```
$ sudo minicom
```

If the above configurations are correctly done, the Routerboard will transfer the ramdisk file into its RAM and boot using network boot. Once the device boots, execute the following.

```
$ ifconfig br-lan down
$ brctl delbr br-lan
$ ifconfig eth0 10.107.48.50
$ passwd
$ <Set Password>
```

Now, in a new terminal go the directory containing the kernel image file and the rootfs file

```
$ cd <build_dir>/openwrt/bin/ar71xx/
$ scp openwrt-ar71xx-nand-rootfs.tar.gz -ar71xx-nand-vmlinux.elf
  root@10.107.48.50:/tmp/
```

At this point, the RouterBoard has the kernel image and rootfs file in its /tmp/ directory. To install OpenWrt on the RouterBoard run following set of commands.

```
$ mount /dev/mtdblock1 /mnt/
$ mv /tmp/ openwrt-ar71xx-nand-vmlinux.elf /mnt/kernel
$ umount /mnt
$ mount /dev/mtdblock2 /mnt/
$ cd /mnt/
$ tar -xzvf /tmp/ openwrt-ar71xx-nand-rootfs.tar.gz
$ cd ..
$ umount /mnt/

$ sync
```

Both, the kernel image and the utilities have been mounted on the RouterBoard. Reboot the system now.

```
$ reboot
```

- When the system reboots, make sure you change the boot option from netboot to Boot from NAND. If this is not done, then all the steps described above (From ifconfig br-lan down onwards need to be redone.)
- If the process described above has been done correctly, then the RouterBoard will boot without any errors. We now need to configure the boards to communicate with each other and enable performing throughput measurements using the boards.

A.3 Configure Relevant Files and Install Selected Tools

- Once the board reboots, we first need to set the network parameters in the following files

```
$ /etc/config/network
$ /etc/config/wireless
$ /etc/config/dhcp
```

In the ‘network’ file, we change the lan interface as follows

```
config interface lan
option ifname eth0
option proto static
option ipaddr 10.107.48.10*
option netmask 255.255.240.0
option gateway 10.107.63.250
```

We then add a new network interface for the radio interface as follows.

```
config interface wlan
option ifname wlan0
option proto static
option ipaddr 192.168.1.*
```

In the ‘wireless’ file, we first need to enable the wireless interface. Delete or comment the following line.

```
option disable 1
```

Make sure you comment the above line corresponding to the correct wireless interface. This problem will not arise in case of RB433AH boards. However, in case of RB411AR, the board has an internal 2.4GHz WiFi card. The first wireless interface in the file corresponds to this internal WiFi card and need not be enabled.

A sample configuration of the wireless interface is as follows.

```
config wifi-device radio0
option type mac80211
option channel 7
option hwmode 11g
option path pci0000:00/0000:00:14.0

config wifi-iface
option device radio0
option network wlan
option mode sta
option ssid OpenWrt
option encryption none
```

Note:

The option `network` must contain the name of the network interface which was created for the wireless interface in the `/etc/config/network` file above.

Make sure all nodes have the same `ssid` and channel numbers. Also, if the nodes are to operate in AP-Client mode, then one of the nodes is to be configured in the AP mode and the remaining in client mode. To configure a node in the AP mode, simply replace the option `mode sta` by option `mode ap`. All other configuration values remain the same.

- At this stage, the basic configuration of the nodes is done. Reboot the system, connect the antenna to the card and check if the nodes connect to each other.
- If the nodes are configured in the AP-Client mode, then all clients associate to the AP. This can be seen in the kernel logs, which can be viewed using

```
$ dmesg
```

It can also be verified by using the `iwconfig` command

```
$ iwconfig
```

A sample output of the command at a client is as shown below.

```
wlan0
IEEE 802.11bg ESSID: 'OpenWrt'
Mode:Managed Frequency:2.462 GHz Access Point: 00:30:1A:46:09:5B
Bit Rate=24 Mb/s Tx-Power=27 dBm
RTS thr:off Fragment thr:off
Encryption key:off
Power Management:off
Link Quality=61/70 Signal level=-49 dBm
Rx invalid nwid:0 Rx invalid crypt:0 Rx invalid frag:0
Tx excessive retries:98 Invalid misc:951 Missed beacon:0
```

Since the client is associated to the Access Point, we see the MAC address of the Access Point. Note that the Frequency shown by this command is 2.462GHz, which is the frequency corresponding to channel 7 for a normal WiFi card. However, the card operates at 570MHz.

- If all clients are associated to the AP, then we can start communication between the clients and the AP. Simply ping any of the node in the network.

```
$ ping 192.168.1.1
```

If the above command returns an output, the nodes are connected to the AP and can communicate with one another.

- If the nodes communicate with each other (ping each other), then we can run iperf server at any node and measure the throughput of any link by running an iperf client at the desired node and connecting the the iperf server.

Appendix B

Compilation of OpenWrt Attitude Adjustment 12.09 from source-code

Once the OpenWrt OS is installed on RB, all that remains in order to get the RB working as a Wireless AP is configuration of its network and wireless parameters. This is done using two files

```
/etc/config/network  
/etc/config/wireless
```

Disable DHCP Server

OpenWrt, by default, leases DHCP on its LAN interface. First and foremost, we need to disable this:

In the file,

```
/etc/config/dhcp
```

make the following changes:

```
...  
config dhcp lan  
    option interface      lan  
    option start         100  
    option limit          150  
    option leasetime     12h  
    option ignore        1  
...
```

B.1 Operation mode of RouterBoard 433AH

B.1.1 Bridged AP

Basic explanation of what the Bridged AP mode is and the configuration of RB in Bridged AP mode is given [48]. Configuration specific to our network is given below.

File: /etc/config/network

```
config interface loopback
    option ifname lo
    option proto static
    option ipaddr 127.0.0.1
    option netmask 255.0.0.0

config interface lan
    option ifname eth0
    option type bridge
    option proto static
    option ipaddr 10.107.91.232
    option netmask 255.255.224.0
    option gateway 10.107.95.250

config interface wan
    option ifname eth0
    option proto dhcp

config switch
    option name switch0
    option reset 1
    option enable_vlan 1

config switch_vlan
    option device switch0
    option vlan 1
    option ports 1 2 5
```

Here, it is assumed that the IP addresses are assigned in a static manner. If a DHCP server can lease IP addresses to the RB, then replace 'option proto static' with 'option proto dhcp' and delete (or comment) the next three lines.

File: /etc/config/wireless

```
config wifi-device radio0
    option type mac80211
    option channel 1
    option hwmode 11g
    option path 'pci0000:00/0000:00:14.0'
    # REMOVE THIS LINE TO ENABLE WIFI:
    #option disabled 1

config wifi-iface
    option device radio0
    option network lan
    option mode ap
    option wds 1
    option rts 0
    option ssid Openwrt
    option encryption none
```

Note:

- Wireless Distribution System (WDS) has been enabled (option wds 1). This is necessary in the Bridged AP mode.
- The RB is configured as an AP (option mode ap). The RB can instead be configured as a client or station (option mode sta).
- The option rts 0 works only for madwifi based system. We have used ath5k drivers. So, though RB does not throw an error, RTS mechanism doesn't actually work.

B.1.2 Routed AP

Routed AP

The Routed AP mode requires changes at the AP side, as well as the Client side. Basic explanation of what the Routed AP mode is and the configuration of RB in Routed AP mode is given [43].

Configuration specific to our network is given below.

File: /etc/config/network

```
config interface loopback
    option ifname lo
    option proto static
    option ipaddr 127.0.0.1
    option netmask 255.0.0.0

config interface wan
    option ifname eth0
    option proto static
    option ipaddr 114.143.217.58
    option netmask 255.255.255.248
    option gateway 114.143.217.57
    option dns 8.8.8.8

config interface wifi
    option proto static
    option ipaddr 192.168.1.1
    option netmask 255.255.255.0

config switch
    option name switch0
    option reset 1
    option enable_vlan 1
    config switch_vlan
    option device switch0
    option vlan 1
    option ports 1 2 5
```

File: /etc/config/wireless

```
config wifi-device radio0
    option type mac80211
    option hwmode 11g
    option txpower 27
    option path pci0000:00/0000:00:14.0
    option country US
    option channel 1

config wifi-iface
```

```
option device radio0
option network wifi
option mode ap
option ssid IITB-TVWS
option encryption none
```

File: /etc/config/dhcp

```
config dnsmasq
    option domainneeded 1
    option boguspriv 1
    option filterwin2k 0 # enable for dial on demand
    option localise_queries 1
    option rebind_protection 1 # disable if upstream must serve RFC1918
        addresses
    option rebind_localhost 1 # enable for RBL checking and similar
        services
#list rebind_domain example.lan # whitelist RFC1918 responses for
        domains
    option local /lan/
    option domain lan
    option expandhosts 1
    option nonegcache 0
    option authoritative 1
    option readethers 1
    option leasefile /tmp/dhcp.leases
    option resolvfile /tmp/resolv.conf.auto

config dhcp lan
    option interface lan
    option start 100
    option limit 150
    option leasetime 12h
    option ignore 1

config dhcp wan
    option interface wan
    option ignore 1

config dhcp wifi
```

```
option interface wifi
option start 100
option limit 150
option leasetime 12h
```

File: /etc/config/firewall

```
config defaults
    option syn_flood 1
    option input ACCEPT
    option output ACCEPT
    option forward REJECT

config zone
    option name lan
    list network lan
    option input ACCEPT
    option output ACCEPT
    option forward ACCEPT
    option masq 1
    option mtu_fix 1

config zone
    option name wan
    list network wan
    list network wan6
    option input ACCEPT
    option output ACCEPT
    option forward REJECT
    option masq 1
    option mtu_fix 1

config zone
    option name wifi
    list network wifi
    option input ACCEPT
    option output ACCEPT
    option forward REJECT

config forwarding
```

```
option src lan
option dest wan

config forwarding
option src wifi
option dest wan

config redirect
option name Dhuktan-1
option src wan
option proto tcpudp
option src_dport 8006
option dest_ip 192.168.1.6
option dest_port 80
option target DNAT
option dest wifi
```

Routed Client

File: /etc/config/network

```
config interface loopback
option ifname lo
option proto static
option ipaddr 127.0.0.1
option netmask 255.0.0.0

config interface lan
option ifname eth0
option proto static
option ipaddr 10.0.1.1
option netmask 255.255.255.0
option dns 8.8.8.8

config interface wan
option proto static
option ipaddr 192.168.1.6
option netmask 255.255.255.0
option gateway 192.168.1.1
```

```

config switch
    option name switch0
    option reset 1
    option enable_vlan 1
    config switch_vlan
    option device switch0
    option vlan 1
    option ports 1 2 5
    
```

File: /etc/config/wireless

```

config wifi-device radio0
    option type mac80211
    option channel 1
    option hwmode 11g
    option path 'pci0000:00/0000:00:14.0'
    
```

REMOVE THIS LINE TO ENABLE WIFI:

option disabled 1

```

config wifi-iface
    option device radio0
    option network wan
    option mode sta
    option ssid IITB-TVWS
    option encryption none
    
```

File: /etc/config/dhcp

```

config dnsmasq
    option domainneeded 1
    option boguspriv 1
    option filterwin2k 0 # enable for dial on demand
    option localise_queries 1
    option rebind_protection 1 # disable if upstream must serve RFC1918
        addresses
    option rebind_localhost 1 # enable for RBL checking and similar
        services
    #list rebind_domain example.lan # whitelist RFC1918 responses for
        domains
    
```

```
option local /lan/
option domain lan
option expandhosts 1
option nonegcache 0
option authoritative 1
option readethers 1
option leasefile /tmp/dhcp.leases
option resolvfile /tmp/resolv.conf.auto

config dhcp lan
option interface lan
option start 100
option limit 150
option leasetime 12h
option ignore 1

config dhcp wan
option interface wan
option ignore 1

config dhcp wifi
option interface wifi
option start 100
option limit 150
option leasetime 12h
```

File: /etc/config/firewall

```
config defaults
option syn_flood 1
option input ACCEPT
option output ACCEPT
option forward REJECT

config zone
option name lan
list network lan
option input ACCEPT
option output ACCEPT
option forward REJECT
```

```
option masq 0

config zone
option name wan
list network wan
list network wan6
option input ACCEPT
option output ACCEPT
option forward REJECT
option mtu_fix 1
option masq 1

config forwarding
option src lan
option dest wan

config forwarding
option src wan
option dest lan
```

Publications

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Gaurang Naik

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