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Spectrum Utilisation and Management
in
Cognitive Radio Networks

A DISSERTATION

SUBMITTED TO THE DEPARTMENT OF

ELECTRONIC SYSTEMS

OF

AALBORG UNIVERSITY

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

KISHOR PUNA PATIL



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This thesis has been submitted for assessment in partial fulfillment of the PhD degree. The thesis is based on the submitted or published scientific papers which are listed above. Parts of the papers are used directly or indirectly in the extended summary of the thesis. As part of the assessment, co-author statements have been made available to the assessment committee and are also available at the Faculty. The thesis is not in its present form acceptable for open publication but only in limited and closed circulation as copyright may not be ensured.

Dedicated

To my beloved parents Puna and Malti Patil

who ignited spark of knowledge in me

Abstract

In recent years, the demand for radio spectrum for wireless communication is growing due to increase in number of users and popularity of data and multimedia services. This has been observed in the recent auctions completed world wide for the vestige of radio spectrum. The radio spectrum has been assigned to different services and it is very much difficult for the emerging wireless technologies to get entry due to rigid spectrum policy and heavy opportunity cost. The inefficient prevailing spectrum management causes the artificial spectrum scarcity. The measurement campaigns conducted worldwide have confirmed this by showing that the considerable amount of radio spectrum is underutilized.

Dynamic Spectrum Access (DSA) and the spectrum refarming are the two viable solutions for the problem of spectrum scarcity. In DSA, unlicensed user opportunistically uses the vacant licensed spectrum with the help of Cognitive Radio. Cognitive Radio is a key enabling technology for DSA. In Cognitive Radio paradigm, secondary user (SU) i.e. unlicensed user locate the vacant licensed spectrum of licensed user i.e. Primary user (PU) and uses it without harmful interference to the PUs. The secondary use of licensed spectrum provides efficient use of spectrum. Spectrum refarming means the recovery of spectrum from its existing users for the purpose of re-assignment, either for new uses, or for the introduction of new spectrally efficient technologies. Spectrum refarming is a spectrum management tool that can satisfy new market demands and increase spectrum efficiency.

Evaluation of the spectrum usage is the first step toward the future deployment of cognitive radio. Several spectrum usage measurement campaigns have been performed mainly in USA and Europe. The results of these campaigns are not directly applicable to India since the geographical characteristics, and the social environment is different in India. The spectrum usage situation and therefore the Cognitive Radio in India are unclear. We address this in the thesis and present empirical work and modeling in the context of Cognitive Radio.

The empirical work include the design of the measurement setup and the short and longer time span measurement campaigns at different locations in India with practical scenarios of Cognitive Radio.

We evaluate the spectrum usage in different bands allocated to wireless services based on the real time data collected from the measurement. We find a significant amount of spectrum is underutilized and opportunities for the secondary use. We provide the temporal and spatial properties of the spectrum occupancy. From the extensive measurement we characterize the use of spectrum and identify the potential candidate bands for Cognitive Radio. We present the model which has ability to reproduces the statistical characteristics of the spectrum usage.

The cognitive access of unused TV band i.e. TV white spaces is the excellent opportunity to not only to counteract the spectrum scarcity problem but also for the new cognitive radio applications. Recently the secondary access to TV white spaces is allowed by American regulatory body FCC. From the occupancy measurement of TV band, we find a significant amount of spectrum is underutilized and opportunities for the secondary use in India. In this work, we address the technical and regulatory requirements for Cognitive Radio operation in TV white space band and its implications on spectrum regulation in the context of Indian scenario.

We point out the extensive use of spectrum in the mobile cellular services showing the popularity of these services. We suggest the demand of additional spectrum for these services can be meet through the digital dividend spectrum released from spectrum refarming in TV band. The developed spectrum sharing model derives some important statistics which are beneficial in analyzing the performance of the DSA systems.

Dansk Resume

I de senere år er efterspørgslen efter radiofrekvenser til trådløs kommunikation voksende på grund af stigningen i antallet af brugere og populariteten af data- og multimedietjenester. Dette er blevet observeret i de seneste auktioner afsluttede ord wide for levn af radiofrekvenser. Frekvensressourcer er blevet tildelt til forskellige tjenester, og det er meget svært for de nye trådløse teknologier til at få adgang på grund af stive frekvenspolitik og tunge offeromkostninger. Det ineffektive fremherskende frekvensforvaltning forårsager den kunstige knaphed på frekvenser. De målinger, der er gennemført på verdensplan har bekræftet dette ved at vise, at den betydelige mængde af radiofrekvenser underudnyttet .

Dynamic Spectrum Access (DSA) og spektret genopdyrkning er de to levedygtige løsninger for problemet af frekvensknaphed. I DSA, opportunistisk licensfri bruger anvender den ledige licenseret spektrum med hjælp af Cognitive Radio. Kognitiv Radio er en nødvendig teknologi for DSA. I Cognitive Radio paradigme , dvs licensfri bruger sekundær bruger (SU) lokalisere den ledige licens spektrum af licenserede bruger , dvs Primær bruger (PU) og bruger det uden skadelig interferens med pus . Sekundær anvendelse af licenseret spektrum giver en effektiv udnyttelse af frekvenserne. Spectrum genopdyrkning: nyttiggørelse af spektret fra de eksisterende brugere med henblik på re- opgave, enten til nye anvendelser, eller indførelse af nye spektralt effektive teknologier. Spectrum genopdyrkning er et spektrum management værktøj, der kan opfylde de nye markedskrav og øge frekvens effektiviteten.

Evaluering af frekvensanvendelsen er det første skridt mod den fremtidige udbredelse af kognitiv radio. Adskillige frekvensanvendelsen målekampagner er blevet udført primært i USA og Europa. Resultaterne af disse kampagner er ikke direkte anvendelig på Indien siden de geografiske karakteristika, og det sociale miljø er anderledes i Indien. Spektret brugssituation og derfor Cognitive Radio i Indien er uklare. Vi tage dette i afhandlingen og nuværende empirisk arbejde og modellering i forbindelse med Cognitive Radio.

Det empiriske arbejde omfatter design af målingen setup og de korte og længere tid span målekampagner på forskellige steder i Indien med praktiske scenarier for Cognitive Radio.

Vi vurderer brugen af radiofrekvenser i forskellige bands tildelt trådløse tjenester baseret på realtidsdata indsamlet fra målingen. Vi finder en betydelig mængde frekvenser underudnyttede og mulighederne for sekundær anvendelse. Vi leverer den tidsmæssige og rumlige egenskaber af spektret belægning. Fra den omfattende måling vi karakterisere brugen af frekvenser og identificere de potentielle kandidatlande bånd til Cognitive Radio. Vi præsenterer den model, som har evnen til at reproducere de statistiske karakteristika frekvensanvendelse .

Den kognitive adgang ubrugte tv band dvs TV hvide rum er den glimrende mulighed for ikke blot at modvirke knapheden på frekvenser problemet, men også for de nye kognitive radio applikationer. For nylig den sekundære adgang til tv hvide rum er tilladt af den amerikanske

tilsynsorgan FCC. Fra belægningsprocent måling af tv- band, finder vi en betydelig mængde frekvenser underudnyttede og mulighederne for sekundær anvendelse i Indien. I dette arbejde , tage vi de tekniske og lovgivningsmæssige krav til Cognitive Radio operation i TV hvide rum band og dets konsekvenser for frekvensregulering i forbindelse med indiske scenario.

Vi gør opmærksom på den omfattende brug af frekvenser i de mobile mobiltjenester viser populariteten af disse tjenester. Vi foreslår efterspørgslen af yderligere frekvenser til disse tjenester kan mødes gennem frekvenserne i digitaliseringsdividenden løsladt fra spektrum genopdyrkning i TV-band. Den udviklede frekvensdeling model udleder nogle vigtige statistikker, som er gavnlige i at analysere udførelsen af DSA -systemer.

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List of Abbreviations

APD	Amplitude Probability Distribution
APT	Asia Pacific Telecommunity
ARNS	Aeronautical Radio Navigation Service.
ASO	Analogue Switch Off
ATSC	Advanced Television Systems Committee.
AUSPI	Association of Unified Telecom Service Providers of India.
BS	Broadcasting Service.
BWA	Broadband Wireless Access
CCDF	Complementary Cumulative Distribution Function
CDMA	Code Division Multiple Access
CEPT	European Conference of Postal And Telecommunications Administrations
COAI	Cellular Operator Association Of India.
CR	Cognitive Radio
CRN	Cognitive Radio Network
CRS	Cognitive Radio System
CTMC	Continuous Time Markov Model
DL	Downlink Band
DSA	Dynamic Spectrum Access
DSO	Digital Switch-Over.
DSP	Digital Signal Processor
DTT	Digital Terrestrial Television
DTTV	Digital Terrestrial TV
DVB-T	Digital Video Broadcasting – Terrestrial.
ECC	Electronic Communications Committee.
EIRP	Effective Isotropic Radiated Power.
EIRP	Equivalent Isotropic Radiated Power.
EU	European Union
FPGA	Field Programmable Gate Array

GDP	Gross Domestic Product.
GoF	Goodness of Fit Test
GPP	General Purpose Processor
GPS	Global Positioning System.
GSMA	GSM Association
GWSDB	Geolocation White Space Database.
IMT	International Mobile Telecommunications
INSAT	Indian National Satellite System
ISM	Industrial, Scientific and Medical band
ISO	International Organization For Standardization
ITU	International Telecommunication Union
K-S	Kolmogorov-Smirnov Test.
LR	Licensing And Regulation.
MANET	Wireless Mobile Ad-Hoc Network
MS	Mobile Service.
NFAP	National Frequency Allocation Plan.
NFAP-2011	National Frequency Allocation Plan 2011 of India.
NM	Noise Margin
NTG	New Technology Group.
NTIA	National Telecommunication and Information, and Administration
NTSC	National Television System Committee.
OFDM	Orthogonal Frequency Division Multiplexing.
PDF	Probability Density Function
PFA	Probability of False Alarm
PLMR	Public Land Mobile Radio
PLMRS/CMRS	Private Land Mobile Service/ Commercial Radio Service.
PMRTS	Public Mobile Radio Trunked Service
PMSE	Program Making and Special Event
PMSE	Program Making And Special Event.
PPDR	Public Protection And Disaster Relief.
PSD	Power Spectral Density

PU	Primary User
QoS	Quality-of-Service.
RAS	Radio Astronomy Service.
RFID	Radio Frequency Identification
SDO	Standard Organizations.
SDR	Software Defined Radio
SoC	Programmable System on Chip
SPDT	Single Pole Double Throw
STPF	<i>Spectrum Task Policy Force</i>
SU	Secondary User
TEMA	Telecom Equipment Manufacturers Association.
TRAI	Telecom Regulatory Authority of India
TVWS	TV White Space
UL	Uplink Band
UWB	Ultra Wide Band
WF	WiMAX Forum.
WG	Working Group.
WLAN	Wireless Local Area Network
WPC	Wireless Planning And Coordination
WRAN	Wireless Regional Area Networks
WRC-07	World Radiocommunication Conference 2007
WS	Whitespaces
WSD	White Space Devices.

1

Introduction

This chapter first explains the background and motivation of the presented work. Research objectives are elucidated in this chapter. The scientific contributions of this thesis are explained. Finally, the outline of the thesis is provided to give an overview of the individual chapters.

This thesis deals with radio spectrum utilization in India, empirical modeling of spectrum utilization, Cognitive access of TV white spaces and Digital dividend in India, spectrum management in the context of Cognitive Radio (CR) Systems and spectrum sharing in Cognitive Radio Networks.

1.1 Background

The number of users for wireless devices is increasing rapidly along with their increased use of data and multimedia applications results in increasing need of higher data rates. It puts heavy demand for the radio spectrum for wireless communication systems. The demand for spectrum has been clearly reflected in the auction concluded in the countries [1-3] where exorbitant prices paid to obtain licenses for the small vestige of the radio spectrum. The government of India earned a total revenue of over Rs.106262 crore (US\$19.23 billion) from the auction of the spectrum for 3G, and Broadband wireless services [1], which is approximately, 10% of the expenditure budget of India for the year 2009-2010. The other reason for this is the spectrum shortage due to limited natural frequency spectrum. The entire radio spectrum is already allotted to various wireless services thus the emerging wireless technologies could not get the spectrum for its operation. This increases the opportunity cost of the spectrum. The spectrum scarcity is not real but artificial and due to inefficient static spectrum allocation policies [4]. The early spectrum measurement campaigns conducted in USA showed the shocking result of under utilization of spectrum [5-6] which further confirms the claim of the inefficient spectrum allocation. These studies show that a large portion of the allocated spectrum is rarely used and spatial variations in spectrum usage of assigned spectrum vary from 15% to 85% with high variation in time [7]. The outcome of studies put question mark on the prevailing spectrum allocation policy to fulfill the growing demand of spectrum for the future wireless services. The current spectrum management system is excessively rigid system. It provides license, which offers slow, cumbersome, and inefficient access to the spectrum. The five spectrum access barriers which are described by Buddhikot in [8] are given below.

1.1.1 Spectrum Access Barriers

FlexUse-Barrier

In this case, a technology- specific license is issued in the assigned band by the regulatory body. Thus, the license holder has to use specified technology even though the better technology

options are available. License terms are so rigid to prohibit the license owner to switch to improved technology. It is always desirable to offer licenses on technology neutrality basis.

Service-Silo Barrier

In the current spectrum management, assigning of specific services to fixed bands is called as Service-Silos. In such case if particular wireless service is underutilizing the assigned spectrum, the license conditions do not allow to use the spectrum to other services which uses the spectrum of the fullest.

License-Scope Barrier

The current licenses are issued for a very longer time span, and large geographical regions considering the present demand. The demand for the spectrum over the period of time varies within the geographical region, but the license terms, and conditions prohibit adapting according to change. Thus, the license scope barrier ensures that the other entities will not get access to the unused spectrum of a specific geographical region.

License-Granularity Barrier

The present cellular licenses are for a large slot of spectrum. For example, in India GSM cellular operators currently have 50 MHz spectrum (890-902.5 paired with 935-947.5 MHz, & 902.5-915MHz paired with 947.5-960MHz). During traffic peaks or big events or events, the need of additional spectrum in a smaller lot is always arises, to meet the traffic demand, but there is no such provision for a service provider to acquire a smaller amount of spectrum in small spatial, and a temporal dimension. As the popularity of bursty data traffic increases compared to voice traffic, the spatial-temporal dimension of traffic in a network varies suddenly. To cope up with the variation of traffic, it is necessary to acquire spectrum on small spatial-temporal granularity.

Secondary-usage Barrier

The present license regime permits only certified devices of spectrum licensees to access the assigned spectrum bands. The spectrum license does not allow the secondary use of licensed spectrum, though it is possible without harmful interference to the incumbent users. There is also spatially, unused license spectrum, but it is prevented from secondary use in this barrier.

The current spectrum management is successful in achieving the harmful interference but failed to achieve easy access to spectrum and the efficient spectrum utilization. In the current scenario of fast increasing use of mobile devices has almost everywhere led to a need for efficient usage of spectrum.

1.1.2 Dynamic Spectrum Access

The concept of Dynamic Spectrum Access [7, 9] is to break the secondary user barrier, and provide access for secondary use of licensed spectrum for efficient spectrum utilization. An overview of the different dynamic spectrum access models, specifically, open sharing, hierarchical access, and dynamic exclusive usage models, is presented in [9]. DSA facilitates flexible spectrum use through Software Defined Radio (SDR) [10-12]/Cognitive Radio (CR) [13] and can significantly improve spectrum utilization. Frequency agile operation is the main requirement of the DSA devices. The concept of CR is first coined by Mitola in his first seminal work. The CR has ability to sense the spectrum environment, locate the unused frequencies and adapt accordingly to use these frequencies opportunistically without harmful interference to the licensed users. The cognitive radio dynamically optimizes the operating parameters like frequency and bandwidth according to RF environment variations [14].

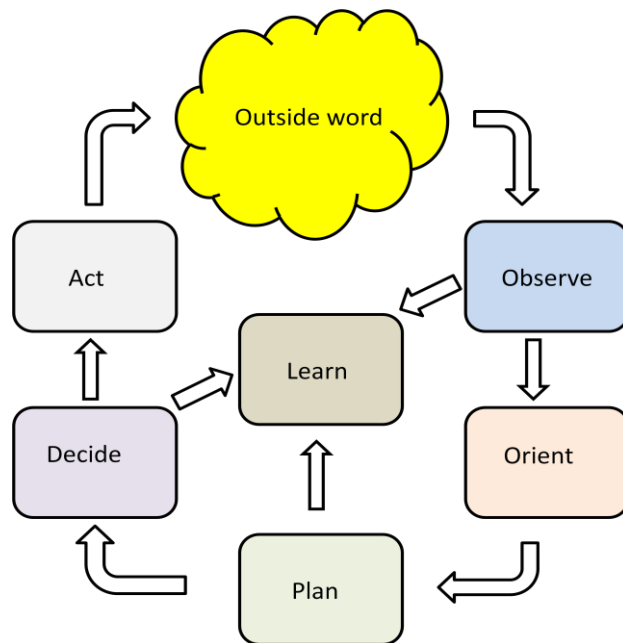


Figure 1.1: Cognition Cycle (from [15])

The definitions of CR are still being developed by Industry, Regulatory body, and Academia. The functionality of CR is highlighted through different definitions of CR found in literature [13], [16], [17], [18].

The cognition cycle [15] by, which the CR interacts with the environment, is shown in the figure 1.1. It depicts the functionality of the CR. In the cognition cycle, a radio receives information about its wireless communication environment (Outside world) through direct observation or through signaling. This information is then evaluated (Orient) to determine its significance. Based on this assessment, the radio finds out its alternatives (Plan), and chooses an alternative (Decide) in a way that probably would improve the valuation. Assuming a waveform change was deemed necessary, the radio then implements the alternative (Act) by adjusting its resources, and performing the appropriate signaling. These changes are then reflected in the interference profile presented by the cognitive radio in the Outside world. As part of this process, the radio uses these observations, and decisions to improve the operation of the radio (Learn), perhaps by creating new modeling states, generating new alternatives, or creating new valuations.

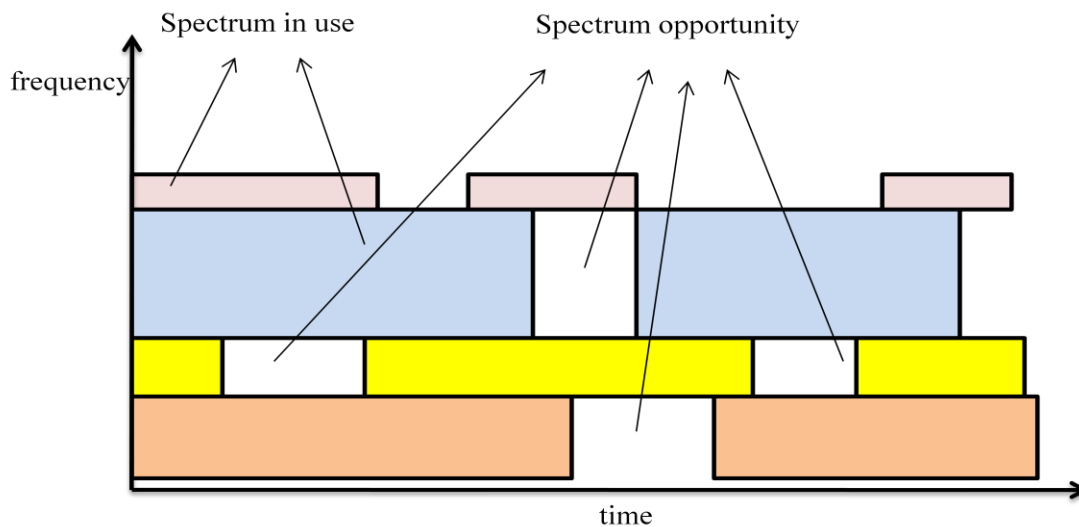


Figure 1.2: Spectrum Opportunity

In DSA, SUs form a CR network (CRN), and are allowed to opportunistically, utilize the spectrum bands of PUs as long as the SUs do not cause any harmful interference to the PUs. The

time period when SUs can reuse a licensed band is called spectrum opportunity or spectrum whitespaces (WS) [16]. The concept of spectrum opportunity is illustrated in Figure 1.2.

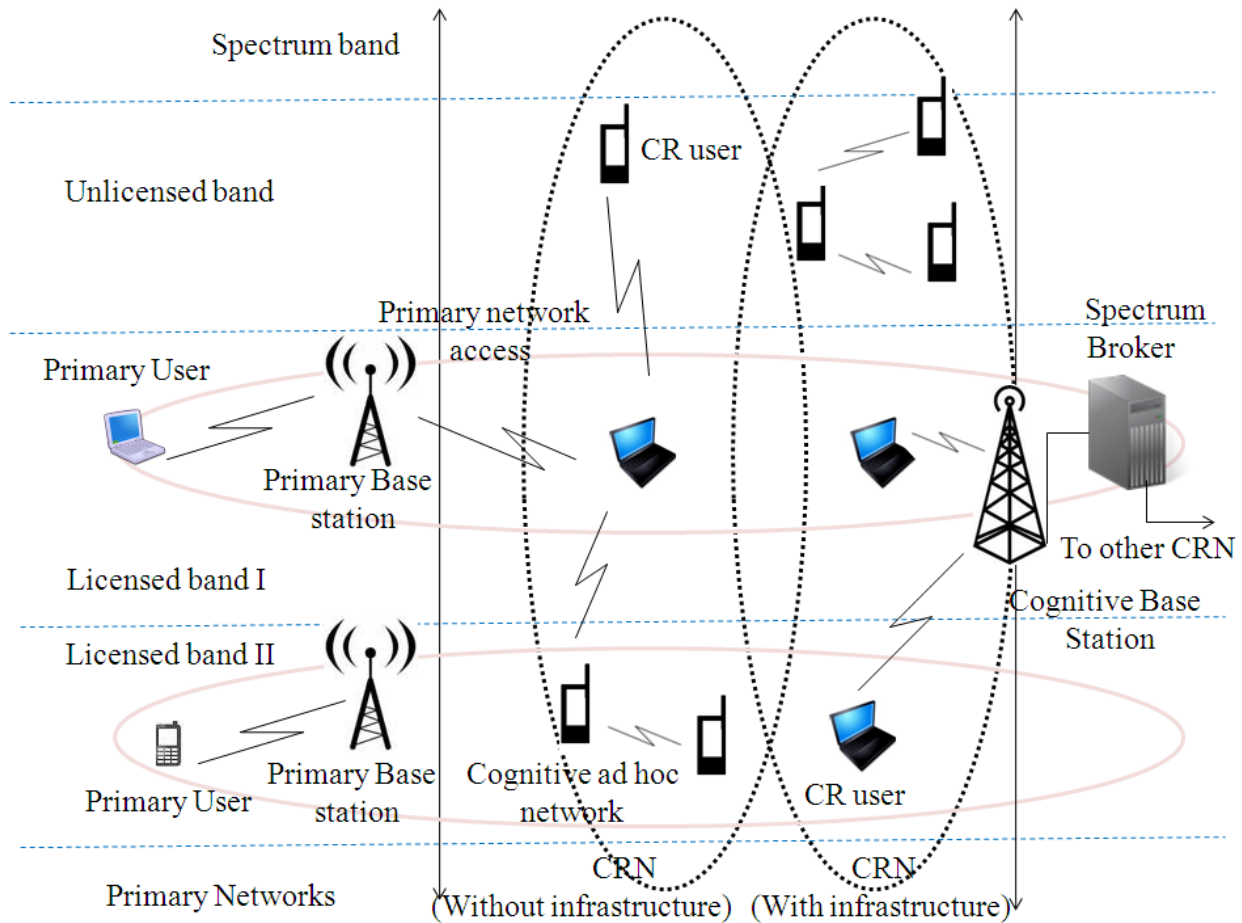


Figure 1.3: CRN Architecture (from [19])

1.1.3 Cognitive Radio Network

The CR network architecture, as shown in figure 1.3, consists of two networks: the primary network and the CR network. The primary user is legitimate user to operate in the primary network (or licensed network) since he has license to operate in certain band. If primary networks have an infrastructure, primary user activities are controlled through primary base stations. Primary users have priority in operation over unlicensed users. The CR network (also called the dynamic spectrum access network, secondary network, or unlicensed network) does not have a license to operate in a desired band. Hence, additional functionality is required for CR users to share the licensed spectrum band. CR networks have its separate infrastructure to control

the activities of secondary users. Finally, CR networks may have spectrum brokers for allocation of the spectrum resources among different CR networks [20]. Cognitive Radio Networks can provide unlicensed users large bandwidth through the heterogeneous wireless architecture, and dynamic spectrum sharing techniques in the era of spectrum crunch. The CR users have to find out the channels for the secondary use then it has to decide the best channel from the available channels for secondary communication, and further coordinate the access of this channel with other users, and during the secondary use if the primary user detected then vacates the channel for the primary user. This can be achieved through the spectrum management functions: spectrum sensing, spectrum decision, spectrum sharing and spectrum mobility [19]. The spectrum management in CRN has these four functionalities to address the challenges like avoid the harmful interference to legitimate users, quality of service, and seamless secondary communication.

Spectrum Sensing: Generally, spectrum sensing techniques classified as transmitter detection, cooperative detection, and interference detection. In this section, we focus on transmitter detection, which is commonly used to detect the primary user. There are three techniques usually, used to detect the primary transmitter signal. These are: energy detection, matched filter detection, and feature detection [21]. A secondary user has to monitor the available spectrum bands, and detect the spectrum holes for opportunistic use. The reliable detection of spectrum hole is a crucial step in spectrum management of the CR to avoid harmful interference to primary users.

Spectrum Decision: Spectrum decision is another required functionality of CRN. It is the ability to opt for the best channel amongst the available channels for the application, which will fulfill the QoS requirement. The allocation of the channel is resolute by internal, and external policies. The spectrum decision is closely related to channel characteristics, and operation of the primary users. The spectrum decision has two steps - 1.Characterize each available spectrum band 2. Choose the appropriate channel based on characterization. The channel characterization is derived from the statistical information of the primary network and activities of the CR users. The channel characteristics include an interface path loss wireless link error, and link layer delay, which are briefed in [19].

Spectrum Sharing: Spectrum sharing in CRN requires coordination of transmission from CR users. The spectrum sharing is possible by including the functionality in MAC protocol. The challenges associated with spectrum sharing in CRN are coexistence of a CR user with license users, and a wide range of spectrum for operation. The classification of spectrum sharing is based on architecture, spectrum allocation behavior, spectrum access technique, and scope and associated challenges are described in [19].

Spectrum Mobility: While using the best available channel by a CR user, if primary presence is detected in the same channel then the CR has to move it from this channel, and look for the other best option. This is known as spectrum mobility or spectrum hand off. This frequency agile operation requires modification in a network protected parameter to ensure a swift switching operation without degradation of the link performance. A very important aspect of the spectrum mobility management is the spectrum handoff time. The available channels for spectrum mobility vary with time, and thus, provide a challenge of maintaining the QoS. Also, the movement of the CR users creates a problem like continuous allocation of the same channel at a new location.

1.2 Motivation

Cognitive radio has considered being a promising solution for the current problems like spectrum underutilization and spectrum scarcity. There are many difficulties in realization of cognitive radio concept in practice. There are many challenges are still open. It includes reliable sensing of spectrum opportunities, interference free spectrum sharing, efficient spectrum handoff, and coordination among CR users for secondary use of licensed spectrum. The empirical measurement of the radio environment to understand the current spectrum usage of the different wireless services is the first step towards deployment of future CR network. Many measurement campaigns [22]-[33] conducted worldwide in the context of cognitive radio. The result shows underutilization of the licensed spectrum temporally and spatially. The CR research got further momentum from the outcome these spectrum occupancy measurement campaigns. The results of above mentioned campaigns are not directly applicable to any other location since the geographical characteristics, and the social environment have an impact on the spectrum use. The occupancy situation, and therefore, the case for cognitive radio is far from clear in India. The empirical work in India is therefore, timely considered the international situation. Most of

the measurement campaigns were conducted for short time durations (two days) to estimate the spectrum occupancy but have not studied the spectrum usage for longer time duration. The statistical characteristics of spectrum usage can be determined from the longer span measurements which are beneficial to identify the potential candidate frequency bands for the cognitive radio. Empirical modeling of spectrum utilization in the context of Cognitive Radio is the research area that still requires much more effort. It has wide applications such as design of CR networks, development of spectrum allocation algorithms and spectrum sharing techniques. The knowledge of the spectrum usage of licensed bands from the measurement campaign will be the input for the regulatory body to adapt spectrum refarming in certain bands and motivation to introduce emerging technologies like Cognitive radio for efficient spectrum utilization.

1.3 Research Objectives

The project includes three main working areas: 1) reference empirical spectrum occupancy measurements in India; 2) modelling and analyses of cognitive radio potentials; 3) potentials of deployment of cognitive radio in India including specific technical and regulatory requirements.

1) The main goal of the empirical research work is to conduct spectrum occupancy measurement in India to identify the low occupancy bands suitable for deploying cognitive radio technology. The occupancy situation and therefore the case for cognitive radio is far from clear – in India or internationally. The empirical work is therefore timely considered the international situation.

2) The modelling and analytical research work includes discussion of the potentials in ‘cognitive’ based on measurement and the resulting need for spectrum for the addressed services. Overall this activity is intended to contribute to counteract spectrum scarcity.

3) The goal of this part of the research is to analyze the specifics of technical and regulatory requirements for the deployment of the cognitive radio technology in Indian scenario. These include overview of the current spectrum management problems and study the implications of deploying Cognitive Radio on spectrum regulation in India.

1.4 Thesis Contributions

The main contribution of the presented work in this thesis is study of the spectrum usage variation in frequency, time and special domain within India through the extensive empirical spectrum measurement campaigns. This is to the best of our knowledge the first spectrum

occupancy evaluation in the context of Cognitive radio in India to identify the underutilized frequency bands for opportunistic use. First measurement campaign we have conducted for two days in Mumbai, India. The second measurement campaign we have conducted in Pune, India at four locations for two days. From these campaigns we have estimated the spectrum occupancy of the frequency bands allocated to the different wireless services and also investigated the impact of location on spectrum usage. The third measurement campaign conducted in Pune for seven days. We have presented the stochastic duty cycle model based on spectrum measurement to find spectrum opportunities for secondary use. We have identified the potential frequency bands for the cognitive radio applications. We have presented the spectrum opportunities in GSM bands in indoor and outdoor scenarios from the measurement results including statistical as well as spectral occupancy details. Also we discussed about the wireless services that can be considered in the bands which are probable for dynamic spectrum sharing. The primary users' arrival and departure in the licensed band is random in nature and this poses the problem in modeling the spectrum occupancy or availability of channel. Existing research literature has assumed the Beta distribution in modeling spectrum occupancy of primary user in licensed band. We validated the beta distribution assumption of channel occupancy using our real time measurement. The validation of assumption of beta distribution is done with the Kolmogorov-Smirnov (K-S) test.

We have discussed the current spectrum management problem such as spectrum scarcity, spectrum allocation, and inefficient spectrum utilization in this thesis. The fourth measurement conducted specially in TV band to understand current TV band scenario for CR operation. The spectrum occupancy of TV band in India and current scenario of TV band is presented. The overview of the operation of Cognitive Radio in the TV white spaces in USA is presented. Further we discussed the about TV white spaces in India and requirements for cognitive access of TVWS in India. The generic technical and regulatory requirements for the operation of Cognitive Radio in TV white spaces are presented in this thesis. The major ongoing CR/TVWS standardization activities are briefed. We have proposed wireless broadband access to rural areas as a potential use of TV White Spaces (TVWSs) in India. Cognitive radio deployment implications with reference to spectrum regulation are also presented.

According to International Telecommunication Union (ITU) and Telecom regulatory Authority of India (TRAI), there is a huge demand of the spectrum for the mobile telecom services since the penetration of mobile telecom services is rapidly increasing in India. This we

have confirmed through the spectrum occupancy results of frequency band of 2G services. We have observed highest spectrum occupancy in these bands. With reference to this we have presented the comprehensive study of digital dividend in India and suggested for the allocation of this spectrum to mobile services. The need of global harmonization in IMT band in the line of ITU efforts is stressed in this thesis. The views of the different stakeholders about 700 MHz band and the two harmonized frequency arrangement for IMT systems agreed by the Asia Pacific Telecommunity (APT) for 700 MHz band is presented. A Continuous Time Markov Chain (CTMC) based spectrum sharing scheme is also presented in this thesis. A CTMC analysis model developed and some important statistics are obtained.

Publications

C. Journal Publication

1. **Kishor Patil**, Ramjee Prasad, Knud Skouby, “**Frequency Usage and Digital Dividend in India,**” in monograph series of Scientific Journal of the University of Szczecin, No. 767, vol. no. 1, page 537 – 553, June 2013.**(Published)**

D. Conference Publications

9. **Kishor Patil**, Madhukar Deshmukh, Horia Cornean, “**CTMC based spectrum sharing scheme for Cognitive Radio Networks,**” in Proc. of 8th International Conference on Communications (COMM 2010), pp.509-512, Bucharest, Romania, June 10-12, 2010.
10. **Kishor Patil**, Ramjee Prasad, Knud Skouby, “**A Survey of Worldwide Spectrum Occupancy Measurement Campaigns for Cognitive Radio,**” in Proc. of International conference on Devices and Communication (ICDeCom 2011), pp. 89-83, Ranchi, India, February 24-26, 2011.
11. **Kishor Patil**, Knud Skouby, Ashok Chandra, Ramjee Prasad, “**Spectrum Occupancy Statistics in the Context of Cognitive Radio**”, in Proc. of 14th International Symposium on Wireless Personal Multimedia Communications (WPMC’11), pp. 486-490, Brest, France, October 3-7, 2011.
12. **Kishor Patil**, Ramjee Prasad, Knud Skouby, “**Stochastic Duty Cycle Model Based on Measurement for Cognitive Radio,**” in Proc. of 15th International Symposium on Wireless Personal Multimedia Communications (WPMC’12), pp.128-132, Taipei, Taiwan, September 24-27, 2012.
13. **Kishor Patil**, Ramjee Prasad, Knud Skouby, “**Cognitive Access to TVWS in India: TV Spectrum Occupancy and Wireless Broadband for Rural Areas,**” in Proc. of Global Wireless Summit (GWS 2013) Special Session, New Jersey, USA, June 24-27, 2013. **(Accepted and presented)**

14. **Kishor Patil**, Ramjee Prasad, Knud Skouby, “**Spectrum Measurement and Analysis of TV Band in Support of Cognitive Radio Operation in India,**” in Proc. of 3rd International conference on Wireless VITAE 2013, New Jersey, USA, June 24-27, 2013. (Accepted and presented)
15. **Kishor Patil**, Snehal Barge, Ramjee Prasad, Knud Skouby, “**Evaluation of Spectrum Usage for GSM band in Indoor and Outdoor Scenario for Dynamic Spectrum Access,**” in Proc. of International Conference on Advances in Computing, Communications and Informatics (ICACCI-2013), Mysore, India, August 22-25, 2013. (Accepted and presented)
16. Madhukar Deshmukh, **Kishor Patil**, Flemming Frederiksen, Knud Skouby, Ramjee Prasad, “**Wireless Broadband Network on TVWS for Rural Areas: an Indian Perspective,**” in Proc. of 16th International Symposium on Wireless Personal Multimedia Communications (WPMC’13), New Jersey, USA, June 24-27, 2013. (Accepted and presented)
17. **Kishor Patil**, Knud Skouby, Ramjee Prasad, “Resource Allocation During Efficient Spectrum Handoffs in CR Network” (Submitted to Supervisors)

1.5 Thesis outline

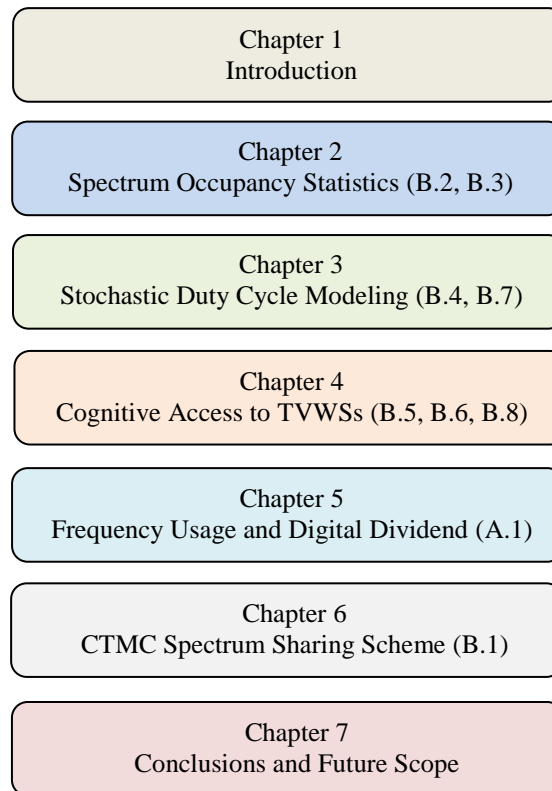


Figure 1.4: Thesis Organization

This thesis is structured as follows. In Chapter 2, we start with measurement challenges and methodological aspects. Then we review the other worldwide measurement campaigns. We present the measurement set-up and the spectrum utilization results of Mumbai campaign are in Chapter 2. In addition, we discuss potential candidate bands for cognitive Radio. We focus on the impact of measurement location and decision threshold on spectrum occupancy in Chapter 3. We present the measurement set up and the spectrum utilization results of Pune campaign for different locations this Chapter 3. We also identify the probable frequency bands for secondary use with the help of stochastic duty cycle modeling based on the measurement. We present general characteristics of traffic density along with occupation details at GSM bands. Beta distribution is intuitive fit for the channel occupancy is shown in this chapter.

In Chapter 4, we start with the introduction to the concept of TV white spaces. We present the current scenario TV band in India and its spectrum occupancy. Next, we provide overview of the operation of cognitive radio in TV white space band in USA. We propose generic technical and regulatory requirements for the operation of cognitive radio in TV white space band in the context of Indian scenario. Finally, we present implications of Cognitive Radio on spectrum regulation.

In Chapter 5, we focus on the spectrum usage in the frequency band of GSM mobile service to show the demand for mobile services in India. We introduce the concept of Digital dividend. We point out the need of spectrum refarming in TV band to meet the demand of the spectrum for mobile services. We present different stakeholder's view about 700 MHz band plan of India, and the two harmonized frequency arrangement for International Mobile Telecommunications (IMT) systems agreed by Asia Pacific Telecommunity (APT) for 700 MHz band in this chapter. We also stress on the global harmonization in International Mobile Telecommunications (IMT) band in the line of ITU efforts. In chapter 6, we present CTMC spectrum sharing model for cognitive radio network.

Finally, we summarize the thesis and give an outlook on future work in Chapter 7.

Spectrum Occupancy Statistics in the Context of Cognitive Radio

This chapter reports the spectrum occupancy measurements conducted in the frequency band from 700 MHz to 2700 MHz in an outdoor environment in the suburban of Mumbai, India. Measurement challenges and methodological aspects are discussed. The measurement results of two weekday's campaign presented showing considerably low occupation in licensed spectrum with great potential for cognitive radio operation. Further CR potentials based on the measurement results are discussed.

2.1 Introduction

The fast increasing use of mobile devices has almost led to a need for efficient usage of spectrum. Cognitive radio is a promising technology for the efficient spectrum utilization due to its ability to modify operating parameters such as transmits power, operating frequency and modulation schemes etc. The spectrum utilisation of the bands assigned to different wireless services is not clear in India. Therefore it is essential to evaluate the frequency usage of different bands for cognitive radio operation to counteract the problem of spectrum scarcity. With reference to this, previous measurement campaigns are studied along with the methodological aspects. The spectrum measurement was performed in Mumbai for 48 hours to investigate the extent to which the wireless services are utilizing their frequency bands. This empirical work was performed to identify the underutilized frequency bands for cognitive radio operation.

2.2 Related Work

There were many spectrum measurements conducted by Industry, academia and research groups in different parts of the world with goals varying from general analysis of spectrum utilization to specific individual wireless technologies. The first large spectrum occupancy measurement campaign was performed in USA by the National Telecommunication and Information, and Administration (NTIA) in 1998 [22]. The main purpose of this survey was to understand the spectrum usage in the allocated spectrum at several locations in the USA. The results indicate large differences mainly, caused by geographic differences. The spectrum utilization was found to be higher in coastal cities than Midwest cities due to the presence of naval radars. The next large scale spectrum occupancy measurement was done by Marc McHenry *et.al.*, which was initiated by NSF [6], [23]. The goal for the measurements was to gain a better understanding of the actual utilization of the spectrum in the dense urban environment with the potential to identify the spectrum bands with low occupancy. The high dynamic range measurement system, a data collection, and processing system was used for spectrum occupancy measurement. The spectrum occupancy for the two-day measurement period was found 17.4% in Chicago.

The main objective of the New Zealand campaign [24] was to study of the availability of the temporarily, unoccupied spectrum resource in terms of frequency, time, and space for future secondary use. The measurement conducted during weekdays in the morning, and afternoons over a 12-week time span in the frequency range from 806 MHz to 2750 MHz at indoor and

outdoor locations in Auckland, New Zealand. This band was further divided into 19 frequency sub bands according to the type of wireless service, and the bandwidth of the signal. The measurement set-up consisted of a dipole antenna (806~1000MHz), and a discone antenna (1000~2750MHz) connected to a Rohde & Schwarz ESVN40 Test Receiver. The decision threshold for deciding occupancy was selected at 5 dB above the mean noise power in each spectral channel. The noise power was estimated by replacing the antenna with matched load. The statistical analysis of the measurement results shows that the actual spectrum utilization in the band is only about 6.21% for an outdoor location and 5.72% for an indoor location. As suggested in [24], a Cognitive Radio should have the ability for diversity reception, and cooperative spectral sensing, thereby, reducing the probability of a false alarm due to the wireless channel characteristics.

An extensive measurement campaign conducted in Aachen, Germany by Matthias Wellens *et.al.* for comparing indoor, and outdoor location measurement results over the frequency range 20-6000 MHz [25]. A highly sensitive measurement system was used in this campaign. A high performance spectrum analyzer Agilent E4440A, which supports up to 8192 measurement points, is used in the measurement set-up. A wide band antenna system is used, which avoids further reconfiguration of the measurement set-up to cover all possible directions. The antenna system includes a large discone antenna of type AOR DA-5000 to cover frequency range between 20 MHz, and 1.52 GHz, a smaller discone antenna of type AOR DA-5000JA for frequency range 1.5 GHz up to 3 GHz, and random antenna of type Antennentechnik Bad Blankenburg AG KS 1-10 for the frequency range between 3 GHz, and 6 GHz. The frequency span of 1.5 GHz wide with a resolution bandwidth of 200 kHz was chosen considering the new technologies. The decision threshold was chosen 3 dB above the measured noise floor throughout the investigated band. A very high occupancy evaluated in outdoor scenario and significantly less in an indoor scenario due to less ambient noise. In addition, a case study was presented about the use of Amplitude Probability Distribution (APD) along with detailed regulatory information to gather additional information about the spectrum usage. This information is useful for optimizing the sensing process, and identifying the potential candidate bands for possible secondary usage in the context of cognitive radio. The next measurement campaign conducted in Aachen, Germany, and the Netherlands at three different locations. The

various aspects of the measurement set up, and lessons learned through the measurement activities described in [17].

In the Singapore campaign [26], the 24 hour measurement has been taken at an outdoor location on the roof top of the Institute for Infocomm Research building over 12 weekday period. The objectives of this campaign were to evaluate the spectrum usage of different services in Singapore, and identify the potential candidate bands for future opportunistic use. The occupancy was measured as the amount of spectrum detected above the threshold. The spectrum measurement results revealed that the average spectrum occupancy in Singapore was found to be only 4.54%. Also highest occupancy has been observed in the broadcasting bands, and GSM 900 bands. The bands which are allocated for aeronautical radio navigation, radiolocation, primary radar, and secondary radar have found very low utilization, and therefore, suggested for secondary usage. Almost all of 614-790 MHz TV band was found unoccupied most of the time, so considered for opportunistic use.

The Radio Communications Group of the Technical University of Catalonia has carried an initial phase spectrum measurement in an outdoor urban environment of Barcelona that covers the frequency range from 75 MHz to 3 GHz for two days [28]. The objective of the campaign was to determine the spectrum occupancy, and compares the results with the official spectrum regulation fixed by the Government. The average spectrum occupancy was found 22.72% for the frequency range from 75 MHz to 3 GHz. The result showed TV bands are considerably populated. The cellular GSM 900 band for the uplink appears to be the potential candidate for the cognitive radio. Very low activity was recorded in the UMTS uplink about 2.86%, and this band considered for future CRNs. The finding of the campaign showed a significant amount of spectrum available in the 1-3 GHz band for the future deployment of the Cognitive Radio.

The next wide band campaign by Miguel López-Benítez et.al has been conducted for 24 hours over the frequency range from 75 to 7075 MHz with the perspective of Cognitive Radio user, and the impact of different locations on spectrum utilization determined, analyzed, and quantified [29]. The wide band measurement set-up was employed for the campaign. A Single Pole Double Throw (SPDT) switch to select the desired antenna, several filters to remove undesired overloading (FM), and out of band signals, a low noise preamplifier to enhance the overall sensitivity used in the set up. The decision threshold was set such that the false alarm

probability will get only 1%. The result showed the occupancy level perceived by the cognitive user strongly depends on its location. A theoretical duty cycle model for TV band is presented and validated. Several methodological aspects and the impact of different factors while evaluating spectrum occupancy in the context of cognitive Radio are discussed in [30]. The results of the measurement campaigns described in [31] also show the inefficiency of the current static spectrum regulation. The overview of worldwide measurement campaigns in the context of CR is presented in [47]. A generic spectrum surveying framework has introduced standardisation and automation to spectrum surveying [34].

All above mentioned campaigns have shown significant amount of spectrum is unused confirming that the current spectrum regulations are somewhat inefficient and motivating further research work on improved spectrum utilization.

Shortcomings of Existing Campaigns

Many measurement campaigns have conducted for few hours or maximum one or two days. With the limited data collected in the duration, it is not possible to characterize the use of limited spectrum in remaining days of week. Few measurement campaigns were conducted for longer duration one week or more than a one week. Some of the measurement campaigns focused on single locations or services. CR implementation requires not only temporal properties of spectrum use but also require knowledge of how spectrum use varies spatially. When we have started the work of measurement campaigns in India, most of the spectrum measurement campaigns were conducted in USA and Europe and there was lack of detailed result for the occupancy situation in India. We have planned measurement campaigns in India. First measurement campaign conducted in Mumbai for two days. The other campaigns conducted in Pune at different locations which includes one longer duration measurement campaign.

Almost all the earlier measurement campaigns have used spectrum analyzer as a measuring instrument in measurement set up. No measurement campaigns have used spectrum monitoring system which is compliant with ITU-R recommendation SM1537 and the spectrum monitoring Handbook editions 2002. We have addressed the shortcomings in our measurement campaign. We have used ESMEALDA integrated spectrum maintain system which is compliant with ITU.R recommendation SM1537 and the spectrum monitoring Handbook editions 2002.

2.3 Measurement Challenges

The primary signal detection is very important functionality of any measurement system. Efficient sensing of primary signal is essential for reliable measurement system. There are three techniques usually, used to detect the primary transmitter signal. These are: energy detection, matched filter detection, and feature detection. After we introduce the general problem formulation in next section, we investigate the characteristics of the energy detector, matched filter detection, and feature detection.

Problem Formulation

Spectrum Sensing ascertains the PU signal presence or absence in the channel. The detection of the primary signal is the test of the binary hypothesis [35]-[37].

$$\begin{aligned}
 H_0 & : Y(n) = W(n) \quad \text{PU signal absent} \\
 H_1 & : Y(n) = X(n) + W(n) \quad \text{PU signal present}
 \end{aligned} \tag{2.1}$$

Here, $X(n)$ are samples of the primary signal of interest. $W(n)$ are samples of the noise signal. $Y(n)$ are the received signal samples at the CR. The hypothesis H_0 state is the absence of PU signal, and the hypothesis H_1 state is the presence of PU signal. The binary spectrum occupancy of channel, $O_{t,i}$, specifies the state of channel i at time t .

$$O_{t,i} = \begin{cases} 0, & H_0 \\ 1, & H_1 \end{cases} \tag{2.2}$$

Where H_0 or H_1 is the output of the algorithm used for sensing the spectrum. The binary spectrum occupancy of channel i at any time t , $O_{t,i}$, is either 0 or 1 indicating the channel state as idle or occupied respectively. The duty cycle, δ_i , is the most common metric used to indicate channel occupancy is given by the equation

$$\delta_i = \frac{1}{N_i} \sum_{t=1}^{N_i} O_{t,i} \tag{2.3}$$

Where N_i is the total number of samples considered for channel i .

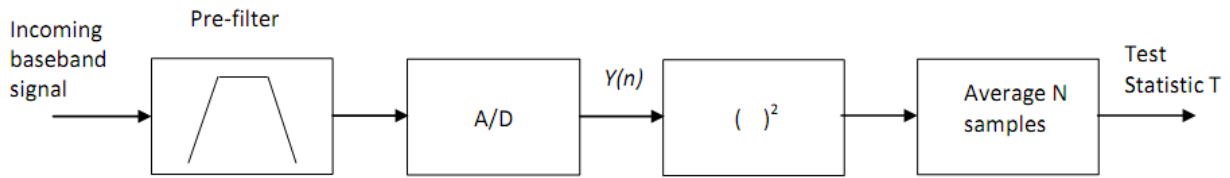


Figure 2.1: Conventional Implementation of Energy Detector [36]

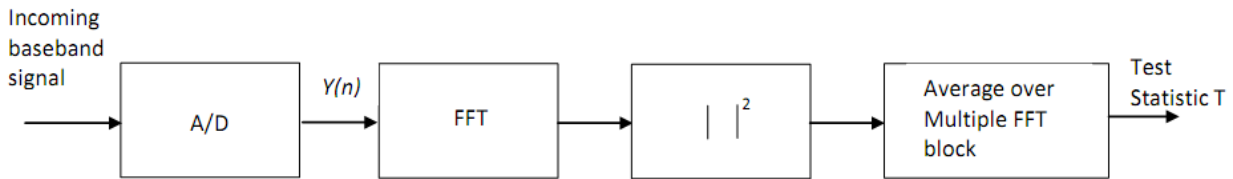


Figure 2.2: Implementation of Energy Detector Using Periodogram [36]

Energy Detection

Energy detection [38] is the simplest spectrum sensing technique, which can be applied to any signal type. It is robust to the variation of the primary signal since it does not require prior knowledge of the primary signal. Moreover, it does not involve complicated signal processing, and has low complexity. Energy detection is especially, suitable for wide-band spectrum sensing. The energy detection method senses the received signal energy in a certain frequency band, and compares it with a predefined threshold limit, which depends on the noise floor for primary user occupancy [39]. The challenges of the energy detector method are choice of the threshold for detecting primary users, inability to discriminate interference from primary users, and noise, and poor performance under low signal-to-noise ratio (SNR) values [40]. Also, it is difficult to set the threshold for the frequency selective fading channels. Energy detectors do not work efficiently for detecting spread spectrum signals: direct sequence, and frequency hopping signals [21]. The energy detection method does not give detailed information about the signal.

As only power measurement is available for frequency usage, the energy detection is the choice left offering benefits of low computational, and the implementation of complexities. We study the energy detector in more detail because it is the detection technique that we apply throughout the remaining thesis. Figure 2.1 shows the structure of the conventional implementation of the energy detector which performs signal processing in time domain. The conventional energy detector consists of a low pass filter to reject out of band noise, and adjacent

signals, Nyquist sampling A/D converter, square law device, and integrator. The output at integrator at any time is the energy of the input to the square law device over the period of interval T in the past.

A test statistics for the energy detector is given by,

$$T(y) = \frac{1}{N} \sum_{n=1}^N |Y(n)|^2 \quad (2.4)$$

Where, $Y(n)$ is the vector of incoming samples, and N is the number of considered samples. Note that, for a given signal bandwidth B, a preamplifier matched to the bandwidth of the signal needs to be applied. This implementation is quite inflexible particularly in case of narrow band signals, and sine waves

Here, we are now considering the detection of a single frequency channel by comparing the detected energy with the threshold of the energy detector. The test statistics is compared with the decision threshold of the energy detector, γ , of the energy detector to decide the binary occupancy O_t .

$$O_t = \begin{cases} 1, & T(y) \geq \gamma \\ 0, & T(y) < \gamma \end{cases} \quad (2.5)$$

An alternate approach of implementation of the energy detector is shown in figure 2.2. It performs signal processing in frequency domain. The incoming baseband signal is Nyquist sampled, and transformed to the frequency domain using FFT. Then, the power spectrum is averaged over multiple FFT blocks. The above implementation provides the flexibility to process wider bandwidths, and sense multiple signals simultaneously. As a consequence, an arbitrary bandwidth of the modulated signal could be processed by selecting the corresponding frequency bins in the periodogram.

Matched Filter Detection

Matched filter detection provides an optimal way of coherent detection of any primary user signal in the presence of additive Gaussian noise since it maximizes the signal to noise ratio [41]. The matched filter effectively, performs demodulation of a PU signal, which requires the prior knowledge of the PU signal at both the PHY and MAC layers. Thus cognitive radio must

have exact knowledge of the modulation scheme employed by the primary transmitter, time synchronization of arriving symbols, and the channel parameters for detection. Such information might be pre-stored in the CR memory, but the difficult part for demodulation is to achieve coherency with the primary user signal by performing timing, and carrier synchronization, and even channel equalization. The detection is still achievable since most primary users have pilots, preambles, synchronization words or spreading codes that can be used for coherent detection. The main advantage of a matched filter is that it requires less time to achieve high processing gain due to coherency since only $O(1/\text{SNR})$ samples are needed to meet a given probability of detection constraint [42]. The main drawback of matched filter detection is that a cognitive radio would need a dedicated receiver for every primary user class [21].

Cyclostationary Feature Detection

Modulated signals have built in periodicity, and characterized as Cyclostationary since their statistics mean, and autocorrelation, exhibit periodicity. This periodicity is typically, introduced intentionally in the signal format so that a receiver can exploit it for parameter estimation such as carrier phase, pulse timing, or the direction of arrival. This can then be used for the detection of a random signal with a particular modulation type in a background of noise, and other modulated signals. Cyclostationary feature detection is introduced by Gardner [43] for the detection of signal features. Cyclostationary features of the received signal are utilized for the detection of the primary user in Cyclostationary feature method [21], [44]. Instead of power spectral density (PSD), cyclic correlation function is used for detecting signals present in a given spectrum. This method has the ability to extract primary signals on the background of interference, and noise. The sensing is focused to the specific feature, and other parts of the signal can be used for noise calibration lowering the impact of noise uncertainty, and giving improved detection performance. However, similarly as in the case of the coherent detector, the limited coherence time of the channel between primary transmitter, and the secondary receiver builds a SNR wall also for feature detectors. The gain of feature detection compared to energy detection is dependent on the channel coherence time, but will always be lower than the coherent processing gain achievable by the coherent detector [45].

2.4 Methodological Aspects

The spectrum occupancy measurement campaigns conducted in context to the cognitive radio have adapted a similar approach, but they used different evaluation methodologies. Due to this the results of these campaigns cannot be compared directly. With reference to this a comprehensive and in-depth discussion on the different methodological aspects to be considered while evaluating spectrum occupancy is presented in [30]. Also, this section includes a discussion on the design of the measurement setup as well as several aspects related to the frequency, and time dimensions. There are various factors to be considered while defining strategy for specific radio spectrum occupancy measurement, which are mentioned in [46]. These are frequency band (frequency span, and frequency points to be measured), time (sampling rate, and measurement period), geographical location, Direction (antenna pointing angle), polarization of the antenna used for reception. The radio spectrum under measurement should be divided into smaller blocks to get better frequency resolution. To get the first impression about the spectrum occupancy of spectrum bands initially, the frequency blocks can be kept wide [25]. Then the spectrum for, which some activity detected can be divided into smaller bands. The narrow frequency bin size than the signal bandwidth can give better accuracy in the results. The lower resolution bandwidth of the spectrum analyzer decreases the noise floor, and thus, improves signal detection capability, but increases the measurement time. A resolution bandwidth of 10 KHz is a good compromise between detection capability, and measurement time [30].

The time dimension is the important aspect of the spectrum measurement, which includes the sampling rate, and measurement period. The sampling rate is automatically, adjusted in some spectrum analyzers. As suggested in [30], a 24 hour measurement option is good compromise between the reliability of the obtained results, and the time required to complete the measurement. For the limited measurement period for the measurement campaign, the required reconfiguration of the measurement set-up reduces either the number of technology or shortens the available measurement time per technology. To overcome this problem, Aachen measurement campaign inspected multiple technologies in parallel with partially suboptimal measurement campaign [28]. Another very important component of the measurement system is the antenna selected for the measurement. The parameters considered for the selection of the antenna are frequency range, radiation pattern gain, polarization etc. For the small frequency

range one antenna is sufficient, but for the large range multiple antennas are required. Large discone antenna, which has vertical polarization and an omni-directional radiation pattern, is preferred for the measurement. The Singapore measurement campaign has used long periodic antenna, which has better sensitivity, but increased measurement complexity [26]. A preamplifier can be used to enhance the sensitivity of the measurement system. In addition, the length of the interconnecting cables can be limited to improve the sensitivity of the set-up further.

A very important parameter in data processing is the decision threshold, which has a great impact on spectrum occupancy results. The selection of a high decision threshold may lead to under-estimation of spectrum occupancy, and over-estimation for the low decision threshold. There are three criteria for the selection of the decision threshold maximum noise, m-dB, and Probability of False Alarm (PFA) Criterion, which are analyzed, and compared in [30]. The maximum noise criterion takes the maximum noise level recorded for each frequency point as the decision threshold. This method assures that no overestimation of occupancy occurs, but may result in underestimation due to weak samples, which are a blow to the maximum noise level. The m-dB criterion adds m decibels in to the average noise floor for getting the decision threshold. The drawback of this method is that the noise floor slightly, increases with the frequency. One of the ITU recommendations [48, page 168] suggests setting the threshold 10 dB above the ambient noise floor. In the PFA criterion, the decision threshold at each frequency point is selected such, that only a fraction of the measured noise samples having value above the threshold. Thus, the PFA can be fixed in this method. The 1% false alarm probability is the reasonable compromise between the ability to detect weak signals, and overestimation errors in bands occupied by high power transmitters [30].

2.5 Mumbai Measurement Campaign

In this section, we describe the Mumbai spectrum occupancy measurement campaign conducted in the month of December 2010 in economic capital of India, Mumbai. To the best of our knowledge, this campaign was the first of its kind to estimate the spectrum usage in India. The details of the measurement campaign are previously, described in [49].

2.5.1 Measurement Description

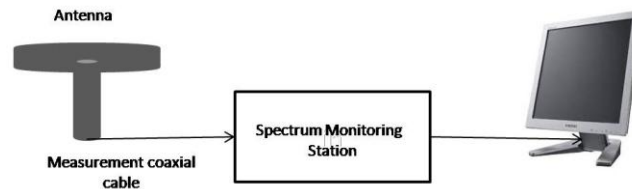


Figure 2.3: Measurement Configuration



Figure 2.4: Measurement set-up

Following are the list of requirements for measurement that we have set from shortcomings of existing work and research objectives.

- Accurate and reliable measurement of primary signals.
- The measurements system should be able to capture spectrum usage across a very wide bandwidth 700 MHz to 2700MHz
- The frequency resolution should allow detecting popular wireless services signals such as GSM, Digital cellular, ISM and 3G cellular services.
- The measurement system should not support the signal analysis and transmission identification. Do not use this feature if it is available in measurement system.
- The system should not allow the analysis of communication content in order to prevent the privacy issue.

- The emission from any part of measurement system should not alter the measurement reliability.
- The measurement control software should support the offline testing and enable quick and flexible adaption of measurement configuration at the measurement site.
- The setup should be capable of working autonomously in outdoor locations.
- The measurement set up should be deployable at the different locations with easy installation.

Above mentioned set of requirements are fulfilled during design of measurement set up. This project is basically a data collection campaign, in which spectrum monitoring station is installed at fixed location in Mumbai city. The monitoring station interfaced with computer system and programmed to save real-time information about the spectrum in the computer system's hard disk. The data is processed and analyzed. The stored data is processed using in built software package according to mission set. The project uses the data to drive conclusions about the percentage of the bandwidth used in measurement location.

The research project scope is defined by the following:

- Space diversity: Measurements is to be taken at different locations in India, so that the variation of the spectrum usage due to location can be examined.
- Time diversity: Rather than taking a measurement at one single time, the data is collected for 2 and 7 days to examine the behavior of the spectrum over time. The timing was chosen so that data includes weekdays and weekends, day and night.
- Frequency diversity: In each reading, a sweep includes data in the 700MHz - 2700MHz band. This band is the one of interest for this project, because it includes GSM, 3G, Wi-Fi and several other transmissions.

The selection of measurement device was crucial for accuracy and reliability of measurement of primary user signals. Several options were present such as spectrum analyzer, a vector signal analyzer, a spectrum Monitoring station, and a technology-specific receiver. The requirements for measurement setup narrowed down the selection to spectrum monitoring station because a vector signal analyzer do not support wideband analysis in the range of hundreds of MHz. Since

the spectrum range of measurement included a very large variety of different services a set of technology-specific receivers was also not sufficient. Since the Integrated Spectrum Monitoring station has fixed installation at Mumbai we have opted spectrum analyzer for Pune Campaign

We have used ESMERALDA integrated spectrum monitoring system which provides highly reliable and accurate technical measurement. It provides a unique solution for automatic spectrum monitoring (9 KHz – 3 GHz). The monitoring system is compliant with latest ITU-R recommendation and the spectrum monitoring Handbook edition 2002. Automatic spectrum monitoring missions is possible in this monitoring station. The station is multipurpose and modular and remotely controlled. Antennas used in system are perfectly adapted to each configuration. Signal analysis and transmissions identification is also possible in the monitoring station. It has high sensitivity and linearity allowing processing of distant low-level signals in a dense radio electric environment. ESMERALDA system offers a unique solution integrating every spectrum monitoring functions, in full compliance with Chapter 3.3 and 3.4 of ITU-R Spectrum Monitoring Handbook Edition 2002. We have used in our campaign the mission occupancy rate by frequency.

We report the spectrum occupancy in the several bands after the conclusion of the spectrum occupancy measurement campaign in the frequency band 700-2700 MHz. The measurement configuration for the campaign is shown in figure 2.3. The measurement set-up shown in figure 2.4 is used in this campaign. It consists of an Esmeralda integrated spectrum monitoring station from the Thales group, bi-conical Omni-directional passive antenna with vertical polarization having a frequency range of 300-3000 MHz, and a computer system. Esmeralda system control technical parameters of licenses of radio electrical spectrum usage, thus ensuring accuracy of data stored in the data base. The signals reach at the antenna from the users who follow multipath characteristics so the direction of the arrival of the signal cannot be predicted. Hence, the Omni-directional antenna is preferred. The antenna is connected to the monitoring station with a low loss coaxial cable. The station used is in digital receiver (UHF/VHF) mode having a frequency range of 20 to 3000 MHz. The measurement frequency range has been divided into eight sub-bands as shown in table 3.2. The continuous sub band scanning step size, which is selected in this campaign, is 200 KHz thus, giving 10001 measurement points in the frequency range under measurement. Thus, the chosen frequency resolution is not fine enough to differentiate very narrowband primary user signals. We chose resolution bandwidth 200 KHz as a compromise

between frequency resolution and the maximum supported span and to satisfy the requirement 3 i.e. to identify the popular services such as GSM 900 and 1800. The channel scanning speed of the digital receiver is 1000 channels per second. Thus, on an average, each scan to cover the entire band takes 10 seconds. The spectrum survey is performed over two weekdays as suggested in [30] for a more realistic estimate of spectrum occupancy. A measurement of 48 hours results in a measurement trace of about 17280 scans.

2.5.2 Measurement Location

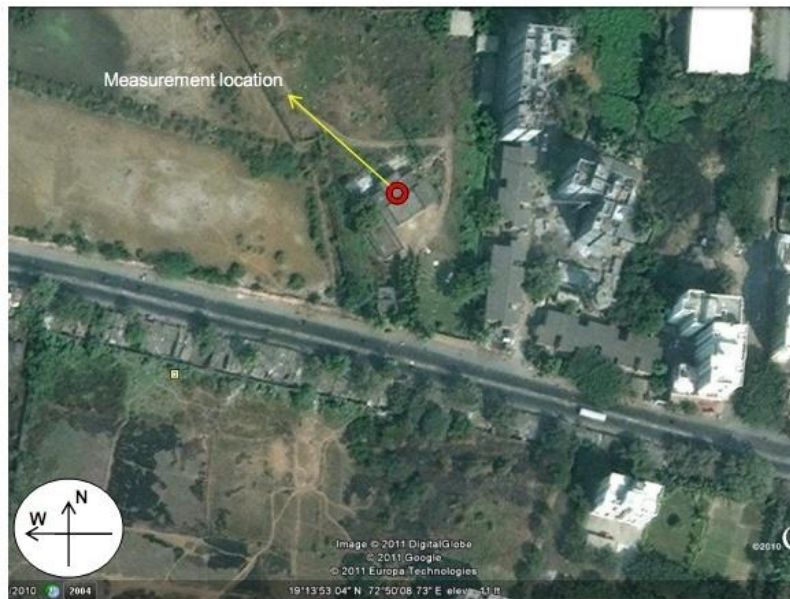


Figure 2.5: Location of the Measurement

The measurement campaign was performed at The International Wireless Monitoring Station Campus, Wireless Planning and Coordination Wing of The Ministry of Communication, and IT, Borivli (West), Mumbai (Longitude: $72^{\circ} 50' 09''$ - East, Latitude: $19^{\circ} 13' 55''$ - North). The location of measurement is shown in figure 2.5. This location is near to the beach, and in the residential zone not having any business center or industrial zone. The location has a fixed measurement setup. The scenario defined for this measurement campaign includes an outdoor high point location. The antenna placed for this measurement is on a tower having a height of 25 meters. The antenna has a strategic location with a direct line of sight to many nearby transmitters so that it provides realistic information about the spectral activity of primary transmission. The database of the spectrum occupancy should be reliable for the deployment of

some opportunistic spectrum access scheme in future since one of the components of the cognitive radio structure is the experimental database containing knowledge gathered in past about spectrum occupancy [50].

2.6 Measurement Results and Analysis

Spectrum Occupancy and Decision Threshold

Spectrum occupancy, also referred to as the duty cycle, is an important parameter for the spectrum regulatory body in the assignment of frequency bands, and further monitoring their usage. It shows at what degree the frequency band is occupied over the observation period. The most widely used definition of spectrum occupancy in the measurement campaigns is the one, which is given by Splauding, and Hagn in their pioneer work. They defined the spectrum occupancy for a channel as a fraction of time the received signal power exceeds a threshold [51]. In our work, the spectrum occupancy is defined as the fraction measured in time, and frequency dimensions where the received signal strength exceeds a decision threshold [23]. In the literature [21], various spectrum sensing techniques are described to sense the primary user activity. Since no prior information is available of the licensed user signal only power measurement is available, the energy detection is the only choice left offering benefits of low computational, and implementation complexities. The energy detection method senses the received signal energy in certain frequency band, and compares it with the predefined threshold limit, which depends on the noise floor for the primary user occupancy [52]. When the received signal strength of a channel at any instant in the measurement equipment is above a decision threshold then the channel at that time said to be occupied. If it is below, it is said to be free or idle. The decision threshold is a very important parameter, which has a great impact on the evaluation of spectrum occupancy. The selection of a high decision threshold may lead to the under-estimation of spectrum occupancy, and over-estimation for the low decision threshold. The existing literature survey shows that most of the measurement campaign has kept the decision threshold at certain dB above the noise level of the measurement equipment. The instrument noise level is measured by terminating the equipment by a 50 ohms resistor. The decision threshold in this work is taken as per the ITU recommendation i.e. 10 dB above the ambient noise level [48, page168]. The measurement study in New Zealand shows that the noise margin of 10 dB above the mean noise power level produces only 0.0005% false alarm rate [30]. The back-ground noise varies with the

frequency so the decision threshold is not fixed for the entire band of the measurement. In this work we use a different threshold in order to address the different background noise levels, and also to achieve a realistic estimate of spectrum utilization. The entire band of 700-2700 MHz is divided into eight different bands, and the corresponding threshold is given in table 2.1.

The frequency occupancy rate mission of spectrum monitoring system is used to determine the occupancy rate of list of frequencies or subbands over period of time as per set in mission file. The results of the frequency occupancy rate are get stored in excel file hourly.

$$\text{Occupancy rate per hour} = \frac{\text{Number of detections per hour}}{\text{Number of scanning turns per hour}} \times 100$$

The data of hourly occupancy rate of frequencies get stored in excel file over the measurement period. We have determined the average duty cycle of a band from this data. The occupied spectrum of a band is calculated as the product of the average duty cycle and the bandwidth. The overall occupancy is obtained by dividing the sum of the occupied spectrum by the total spectrum in consideration. The summary of spectrum occupancy by band is given in Table 2.2.

Table 2.1: Detection Threshold for the Band

Band	Frequency span	Average ambient noise level (dBm)	Decision threshold (dBm)
1	700-960 MHz	-111	-101
2	960.2-1215 MHz	-112	-102
3	1215.2-1515 MHz	-112	-102
4	1515.2-1710 MHz	-112	-102
5	1710.2-1880 MHz	-111	-101
6	1880.2-2250 MHz	-111	-101
7	2250.2-2500 MHz	-109	-99
8	2500.2-2700 MHz	-113	-103

Table 2.2: Summary of Spectrum Occupancy By Band

Band	Services	Average duty cycle day1	Average duty cycle day 2	Average of two days	Occupied spectrum (MHz)	Average percentage occupancy
700-806 MHz	UHF TV, Fixed, and Mobile services	0.00429	0.00373	0.00401	0.42	0.40%
806-890 MHz	PMTRS, Cell Phone, RFID	0.27828	0.27749	0.27781	23.33	27.78%
890-960 MHz	GSM 900, Cordless Phones	0.37141	0.37264	0.37202	26.04	37.20%
960-1429 MHz	Aeronautical Radio Navigation, Radio Navigation Satellite, Earth Exploration Satellite, Radio Location, Space Research	0.01779	0.01704	0.01741	8.16	1.74%
1429-1525 MHz	Fixed/Mobile, Mobile Satellite	0.01823	0.01780	0.01802	1.73	1.80%
1525-1710 MHz	Mobile Satellite, Meteorological Satellite Aeronautical Radio Navigation	0.01523	0.01491	0.0150	2.78	1.50%
1710-1880 MHz	GSM 1800	0.30735	0.32702	0.31718	22.20	31.71%
1880-2400 MHz	TDD, 3G, Fixed/ Mobile, BWA	0.03081	0.03227	0.03154	16.40	3.15%
2400-2700 MHz	ISM, BWA, INSAT	0.00618	0.00209	0.004140	1.24	0.41%
Total					132.35	
Total available bandwidth(MHz)					2000	
Average spectrum usage (%)					6.62%	

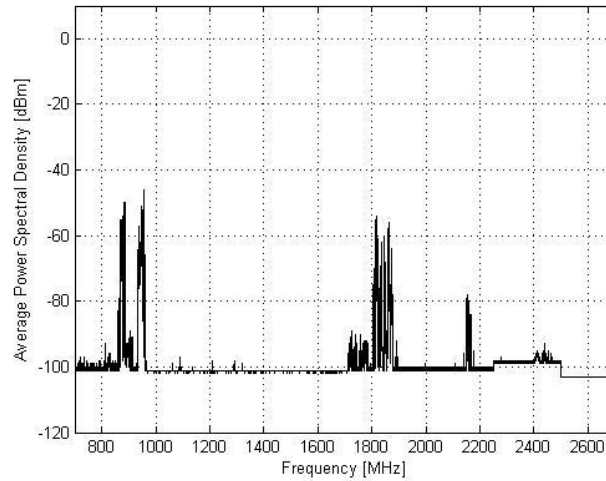


Figure 2.6: Average Received Power Versus Frequency

Spectrum Occupancy Analysis

This section presents the spectrum occupancy details from the spectrum measurement survey of the bands allocated to the different wireless services. The average received signal power variation above the threshold with respect to the frequency span of the measurement study is depicted into the plot, which is shown in figure 2.6. The plot shows the spectrum usage mostly, low with some patchy spots of spectrum use. The plot does not give the detailed picture of the spectrum usage in the various bands allocated to the different wireless services. We give the insight of the band wise occupancy statistics, which is summarized in table 2.2. The average spectrum usage found to be only 6.62%. From the table it is seen that the average duty cycle of different bands for day 1 and day 2 is almost same.

The first band 700 to 806 MHz is a part of the 470–960 MHz band, which is allocated for terrestrial TV broadcasting, fixed, and mobile services on a primary basis in India [53]. There are 14 TV channels available in the UHF Band-IV (470-582 MHz) and 28 channels in UHF Band-V (582-806 MHz) with each having a channel bandwidth of 8 MHz [54]. Doordarshan, the public television broadcaster of India, has not been assigned any channel in this sub-band for analogue TV transmission [54]. But Doordarshan operates short distance UHF links in the frequency bands 735–755 MHz, and 775–795 MHz. A few of the Government agencies are operating point

to point microwave links in 610–806 MHz. The spectrum occupancy of the band 700-806 MHz is 0.4 % only because of no analogue TV transmission in this sub-band by Doordarshan.

The next band is 806–890 MHz, which is allocated, for Public Mobile Radio Trunked Service (PMRTS), digital cellular services, and Radio Frequency Identification (RFID) according to the National Frequency Allocation Plan of India [53]. The average duty cycle of this band is 27.78%. The average spectrum occupancy on the two-way links of PMRTS is found to be 0.45%, and 19.58%. The Digital cellular communication system, which operates in, the 824-889 MHz band, and uses Code Division Multiple Access (CDMA) technology, has an asymmetric occupancy pattern between the uplink (0.4%), and down link (96.49%). The uplink spectrum occupancy is very low due to the fact that the CDMA signal, which is a wideband, and a low power signal might not be sensed by the monitoring station. The down link band is heavily occupied due to continuous transmission from the base station for updating procedures.

The 890-960 MHz band, and 1710-1880 MHz have been allocated for the GSM 900, and the GSM 1800 services respectively. These two bands have average spectrum occupancy of 37.2%, and 31.71% respectively, which is quite high. The occupancy of the uplink and downlink sides is not the same. The down-link occupancy is found to be 98.67% and 70.08 % in the GSM 900, and the GSM 1800 band respectively. The transmission power of control channels on the downlink from the GSM base stations is considerably, higher than that of cellular phones. Therefore, the presence of the GSM downlink signals can be more easily detected. Moreover, the antenna employed in our study was placed on a tower having a height of 25 meters from the ground providing a direct line-of-sight to several nearby base stations, which enabled us to an accurate measurement of the high spectral activity of the downlink. The high point measurement location could potentially, miss the signals from the micro base station, and hence the moderate spectrum occupancy for the GSM 1800 band. The uplink spectrum occupancy is found to be 4.41%, and 1.12% in the GSM 900, and the GSM 1800 band respectively. The low-occupancy on the uplink may be because of the low transmit power from the mobile terminals. Most of the mobile terminals operate at ground level, and the location of the antenna used in this work is at high altitude, and causes more signal attenuation. The system works on the energy detection principle, and cannot detect such weak signals. The choice of a decision threshold in the measurement method is highly influential in the evaluating spectrum occupancy since the signal from the licensed users below the threshold does not contribute to the spectrum occupancy rate.

The lacking occupancy could be due to the higher noise margin of 10 dB for selecting the decision threshold. Therefore, the occupancy estimate for these uplink bands does not represent a realistic estimate of occupancy. The third generation of mobile communication (3G) has recently started to in India and has shown 0.38%, and 22.83% spectrum occupancy for the uplink and the down-link respectively. The technology employed in 3G services is W-CDMA having spread spectrum nature of the uplink signal with low power.

The 2400-2700 MHz band exhibits very low spectrum usage with an occupancy rate of only 0.41%. This band includes popular unlicensed Industrial, Scientific, and Medical (ISM) band (2400-2483.5 MHz), Broadband Wireless Access (BWA), Indian National Satellite System (INSAT), and other services. The occupancy estimate from the measurement for the ISM band is not reflecting the actual occupancy since the wireless service in ISM band is employed in the indoor environment, and the short wave signals of this band do not penetrate through the walls. The occupancy in satellite services is very low due to the signal reached at the ground level may be very weak, and the measurement system might not able to detect it.

The measurement results of this study reveal that the spectrum utilization is not uniform over time, and frequency span of the measurement. Some part of the spectrum recording has heavy utilization over a longer period of time conversely, some portion of the spectrum comes out to be with rare or nil utilization. The substantial amount of spectrum utilization has been observed in the bands, which are allocated point to multipoint cellular communication services.

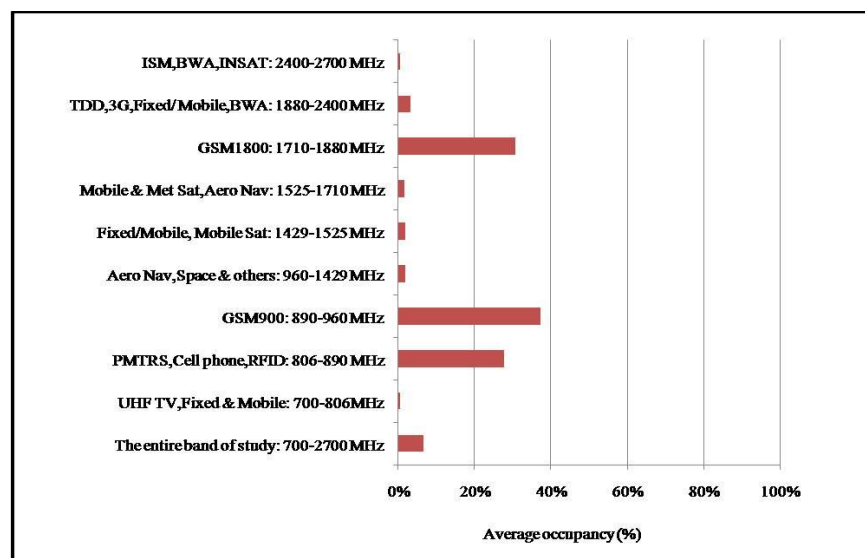


Figure 2.7: Band by Band Occupancy Statistics

Key Observations

This section summarizes the key observations from the spectrum occupancy measurement results, and graphically presents the band wise occupancy statistics in figure 2.7.

- The spectrum occupancy for the two day measurement period is very low 6.62 %, and that means 93.38% of the allocated spectrum is completely unutilized.
- The highest occupancy has been observed in the GSM 900 band.
- The bands allocated for the GSM 1800, cellular telecom services, and trunked radio services have moderate occupancy.
- Low occupancy has been recorded in the bands allocated for aeronautical radio navigation, radio navigation satellite, earth exploration satellite, radio location, space research, mobile satellite, meteorological satellite, and 3G.
- The band allocated for fixed and mobile services, broadband wireless access (BWA), and ISM records negligible utilization.

Discussions on CR Potential

It is clear from the result that the spectrum usage by the licensed users does not track specific pattern over the time. Some bands of spectrum are found to be heavily used (e.g. Down-link band of cellular communication), while some of the spectrum bands are rarely used by the licensed users. There are some short-comings of the measurement system, and methodological aspect is responsible for under estimation of the spectrum occupancy.

1. The energy detection method used in the system is less sensitive compared with other sensing techniques.
2. Very low power transmission from systems such as satellite system, CDMA systems can often not be detected from the measurement system.
3. Few wireless services use frequencies spatially, and sectorized antennas which are highly directional e.g cellular communication.
4. There are few spectrum bands such as Radio Astronomy band which are purposely left idle for passive services.

5. The noise margin of 10 dB is on higher side resulting in higher decision threshold for detection, which could have missed out the primary user activity.

Above mentioned points are to be taken in consideration before jumping on the final conclusions. However the basic results do not change. In this section we discuss the potential candidate bands for CR applications, which will require an extensive study to bring it into reality. All the bands except down-link cellular bands have shown the low occupancy, and could be considered for dynamic spectrum use. The 700-806 MHz band has excellent signal propagation characteristics, which is almost unoccupied most of the time, and has potential for the secondary use. The PMRTS band offer potential for CR application since the average spectrum occupancy is found to be only 0.45 %, and 19.58%.The bands which are allocated to aeronautical radio navigation, radio navigation, and radiolocation are also opportunistic bands. The accurate spectrum occupancy estimate should be done for ISM, BWA, and satellite bands before considering them for opportunistic use. This can be achieved with the use of some special equipments, methodology, and appropriate measurement location. The uplink channels of GSM (2G), and the recent entrants W-CDMA (3G) band appear as the other potential candidates for CR. The channel occupancy needs to be studied for long a term at appropriate locations since we conducted the measurement at a very high point location. Although, the downlink channels of 3G show a moderate level of spectral activity (22.83%), these channels also provide some opportunities for secondary access. Aeronautical band also one of the potential candidate for CR application since it has shown very low occupancy. This study is the ground-work for the next step, which needs a long term study of the identified bands for future deployment of the CR Network.

2.7 Conclusion

In this work, we have investigated the spectrum utilization in suburbs of Mumbai for the frequency span of 700-2700 MHz. Our 48 hours measurement results showed that the spectrum occupancy for an entire frequency band is quite low about 6.62%. The choice of high decision threshold in this campaign gave very low false alarm rate but it may have missed some primary user's activity. Very low spectrum utilization is found in the bands allocated for different wireless services in the frequency range under measurement except the bands allocated for cellular communication systems. Thus, a significant amount of spectrum is available for

opportunistic use. The potential candidate bands for CR applications are TV, PMRTS, UL cellular bands (2G), W-CDMA (3G), aeronautical radio navigation, radio navigation, and radiolocation ISM, satellite, and BWA. However, secondary use in an identified less utilized band cannot be solely considered on the basis of the spectrum measurement results. The feasibility of dynamic spectrum sharing in the less utilized bands require a long-term spectrum usage study of these bands to understand statistical characteristics of the spectrum occupancy. The low power transmission wireless services such as satellite system, radio astronomy, ISM and CDMA uplink systems need a high sensitivity measurement set up to detect the activity in such bands. Also we have to consider the sensitivity of the receivers which operates in these bands to finalize the decision threshold.

Stochastic Duty Cycle Model Based on Measurement for Cognitive Radio

This chapter reports the spectrum occupancy measurements conducted in the frequency band from 700 MHz to 2746.6 MHz at different locations in Pune, India. In this chapter, how spectrum use changes over space is presented. Stochastic duty cycle model based on the measurement is proposed to identify the potential for the CR in the measured band. This chapter also presents the spectrum opportunities in GSM bands for indoor and outdoor scenarios from the measurement results including statistical as well as spectral occupancy details. Also suitable wireless services in the identified bands for CR are discussed. Beta distribution for channel occupancy modeling is validated.

3.1 Introduction

In the previous chapter, we have shown the spectrum utilization vary with frequency, and time through the two day measurement campaign. We have also pointed out the underutilized bands showing the potential for Cognitive Radio application. To convert CR into reality, not only the temporal properties of spectrum occupancy are required but also the spatial properties should be considered. For this it is necessary to understand how spectrum use varies spatially. In this context, first we performed the measurement in Pune city at different locations to examine the spectrum usage variation over a spatial domain. The measurement was carried out for two days at each location. With the limited data collected in two days it is not possible to characterize the use of spectrum in the remaining days of the week, or weekday's corresponding to the days used. The comprehensive and long term spectrum occupancy measurement campaign is necessary to provide understanding and prediction of primary users' activity and valuable basis for spectrum modeling. The statistical information of current spectrum usage is necessary to find out the frequency bands for dynamic spectrum sharing through CR. So, a measurement campaign for a longer duration was conducted to determine the statistical characteristics of spectrum usage in different bands.

3.2 Related Work

Realistic spectrum occupancy modeling in the context of DSA has wide applications such as the design of CR networks, development of spectrum allocation algorithms, and spectrum sharing techniques. Duty cycle modeling is an important aspect in the development of a new mechanism, and protocol for a cognitive radio system. M.Wellens, and P.Mähönen [27] have pointed out, "Duty cycle model is beneficial for multiple applications in the evaluation of dynamic spectrum access systems." Also, it is shown that the modified beta distribution can reproduce the measured characteristics of the duty cycle. A theoretical model is proposed in [29] for predicting the spectrum occupancy level at any geographical location based on the knowledge of simple signal parameters. We have shown that the spectrum occupancy varies spatially, and temporally from the all the measurements conducted. We have used the stochastic duty cycle model (from M.Wellens, and P.Mähönen [27]) to estimate the Complementary Cumulative Distribution Function (CCDF) of the duty cycle from the real time data of measurement of seven days for finding the most probable bands for opportunistic use. Such information can improve the

spectrum sensing process particularly, in adaptive spectrum sensing. The adaptive spectrum sensing process reduces the amount of spectrum required to be sensed [55]. Also, the choices of the suitable services in the identified potential bands for the CR are discussed. The beta distribution has been considered in the modeling of the primary user channel occupancy in the existing literature. With reference to this we validate the beta distribution assumption by using real time measurements.

3.3 Pune Measurement Campaign

3.3.1 Measurement Set-up

The measurement set up employed in the measurement campaign in Pune is shown in figure 3.1 consists of a laptop, which is remotely control the Rhode and Schwarz portable spectrum analyzer R&S FSH 3 via an optical cable. The spectrum analyzer has a frequency range of 100 KHz to 3 GHz [56]. We used a smaller discone antenna AOR DA 5000 having a frequency range of 700-3000 MHz. It is vertically polarized, and has Omni-directional characteristics in the horizontal plane. The FSH Remote software [57] is used for automatically setting the equipment for measurement, and recording the captured data in a Laptop. The MATLAB software package is used to analyze the data.



Figure 3.1: Measurement Set-up Deployed at Location 3

Table 3.1: Spectrum Analyzer Configuration Parameters

Parameter	Value
Frequency Range	700 to 2746.6 MHz
Frequency Span	60 MHz (34 blocks x 60 MHz)
Frequency(measurement) points	301
Resolution bandwidth	100 KHz
Sweep time	Auto
Measurement duration	2 days and 7 days
Video bandwidth	100 KHz
Detection type	RMS detector
Reference level	-20 dBm
Built-in Preamplifier	Activated (10 MHz-2.5 GHz)
Instrument	R&S FSH 3

The spectrum analyzer configuration parameters settings are listed in table 3.1. The spectrum occupancy measurement campaign is conducted across the frequency range from 700 to 2746.6 MHz at four locations. The overall frequency range is divided into 34 bands; each is having a frequency span of 60 MHz. Each frequency span of 60 MHz has 301 frequency points. Thus, the total number of frequency points collected in the frequency range is $34 \times 301 = 10234$. The separation between two consecutive frequency points is 200 KHz. The details of the measurement campaign are previously, described in [58].

Table 3.2: Measurement Locations in Pune

Name	Brief Description of Location
SAE, Outdoor Location 1	Roof top of the Building of Sinhgad Academy of Engineering Latitude: 18° 26' 36.4" North, Longitude: 73° 53' 44.5" East.
SAE, Indoor Location 2	Room located on second floor of the Sinhgad Academy of Engineering Latitude: 18° 26' 36.7" North, Longitude: 73° 53' 45.6" East.
SBS, Outdoor Location 3	Roof top of the Building of Sinhgad Business School Latitude: 18° 30' 29.6" North, Longitude: 73° 50' 7.1" East
CB, Outdoor Location 4	Roof top of the Commercial Building on Law college road Latitude: 18° 50' 34.04" North, Longitude: 73° 49' 51" East



Figure 3.2: Measurement Location 1 and 2



Figure 3.3: Measurement Location 3

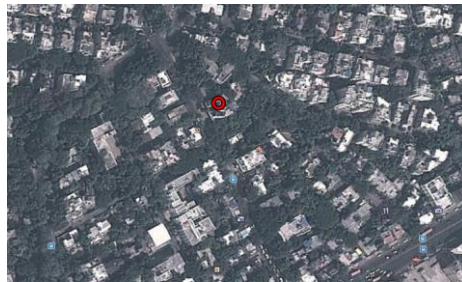


Figure 3.4: Measurement Location 4

3.3.2 Measurement Locations

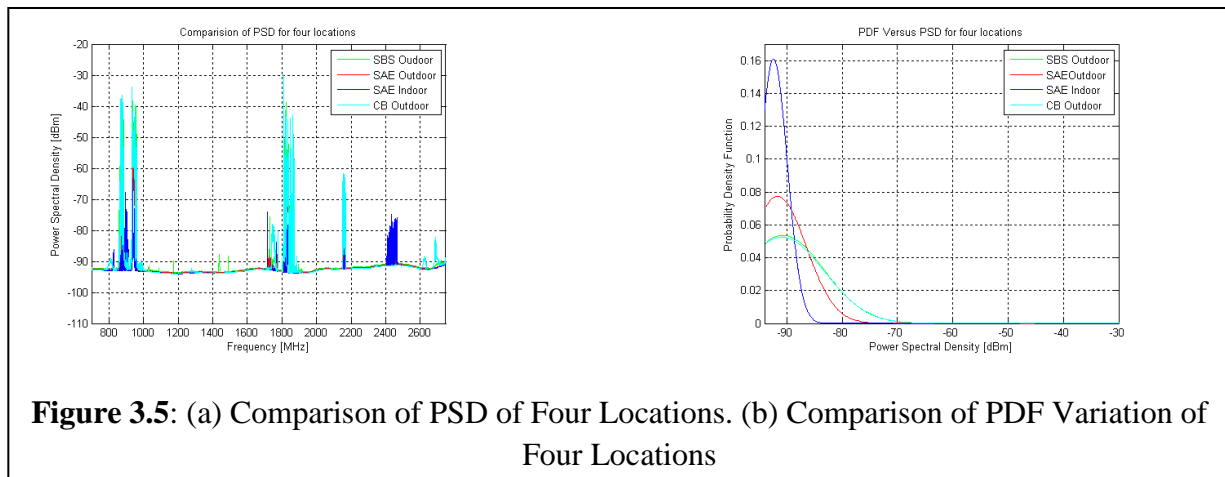
The spectrum occupancy measurement has been conducted at four locations in Pune city, which are shown in figure 3.2, 3.3, and 3.4, and listed in table 3.2, to see the effect of the location on the spectrum activity. We choose indoor and outdoor locations keeping in mind the real scenario of the CR user. The first measurement was conducted at roof top of the Sinhgad Academy of Engineering Institute, located at the outskirts of Pune city, and close to a rural area (Location 1). The second measurement was performed in the room located on second floor of the Sinhgad Academy of Engineering Institute, which gives the indoor scenario (Location 2). The third measurement was performed at the roof top of the Sinhgad Business School (Location 3). The measurement campaign was conducted at the above mentioned locations for two days. The fourth measurement was conducted for seven days at roof top of the commercial building (Location 4) on Law college road, Pune. The location 3 and 4 are located in crowded and commercial area of Pune city. There are many base stations in the vicinity of the location 3 and 4. The longer duration measurement has been opted for, to understand the statistical

characteristics of spectrum usage in the different bands which will be beneficial in future to consider the secondary use of a licensed band. To understand the spectrum utilization in a commercial area is important since the spectrum activities are expected to be higher. Thus, the demand for the frequencies for communication in such an area is higher. In the future, the opportunistic use of the licensed band is most likely to be considered for such an area where the demand is high.

3.3.3 Spectrum Occupancy Results

PSD and PDF plot

In this section, we compare the average power spectral density (PSD) measured over the spectrum measurement range at four locations as shown in figure 4.5 (a). A higher PSD is observed at exposed locations than the indoor. The measured power is higher at location 3, and 4 as compared to other locations since the measuring antenna is in the direct line of sight with the nearby base stations. Also, a significant amount of spectrum has shown low or zero activity, which shows the scope for the CR technology in the future. The down-link channels of cellular communication systems show consistently, higher power spectral density because of the continuous updating procedure through these channels. A significantly, higher spectral activity is observed in the ISM band for the indoor locations than the outdoor locations since this band is used by the short range indoor wireless services.



We compare the probability density function (PDF) of the average PSD of the samples over the entire frequency range. The PDF represents the probability density of the received signal strength, and also determines the range of the received signals. Figure 3.5(b) shows the

asymmetric nature of PDF for all locations. The probability density function is higher for noise than the real life signals. It may be due to the large number of received samples of the background noise as compared to the samples with higher power as they belong to real-life transmissions. The samples of the real-life signals are stronger at the more exposed location as it is also seen in figure 3.5 (a) because of the line of sight connections, and the lower path loss at the outdoor location. It is also seen from the graph that the background noise is stronger at the exposed location.

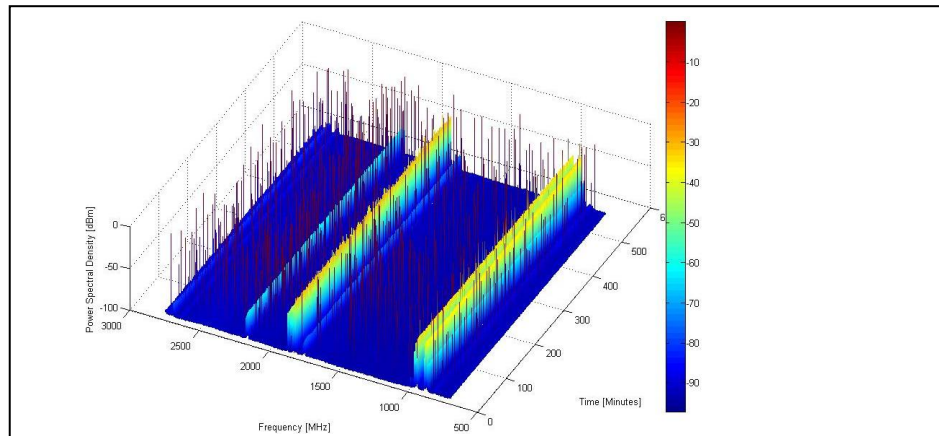


Figure 3.6: 3D Histogram for Location 4 (7 am to 7 pm)

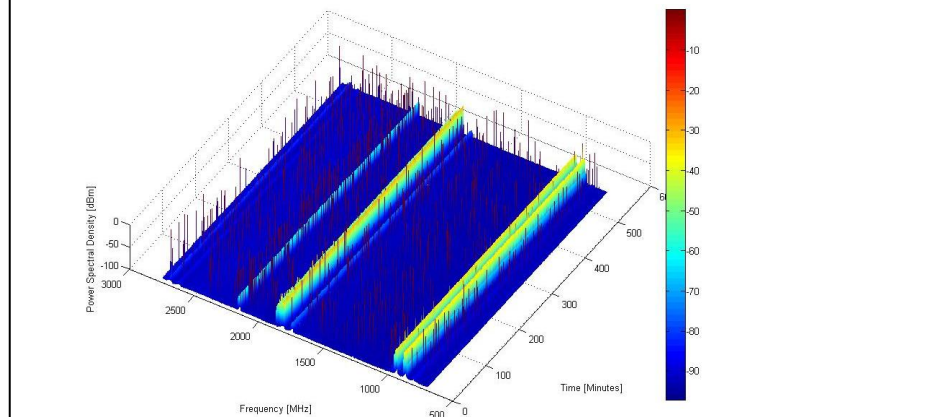


Figure 3.7: 3D Histogram for Location 4 (7 pm to 7 am)

3D Histogram

The primary users activity is shown by a three dimensional histogram with one axis being frequency span, one being time, and another being the amplitude. Figure 3.6 and 3.7 shows the

histogram of the outdoor measurement at location 4 covering the frequency range 700 to 2746.6 MHz for 7 AM to 7 PM and 7 PM to 7 AM respectively. Figure shows the more primary users' activity in day than the night time. The frequency usage varies with respective time is clearly visible from 3D histograms. There are many temporal white spaces seen in different bands except DL bands of GSM, digital cellular and 3G bands. These temporal white spaces also offer opportunity for secondary access to licensed spectrum.

Spectrum Occupancy

The spectrum occupancy is found by measuring the PSD using the spectrum analyzer working on the energy detection principle, and comparing it with a set decision threshold. If the PSD is above the set decision threshold in a certain frequency band, then the band is said to be occupied or otherwise vacant. The realistic decision threshold is set by adding some noise margin (NM) in the measured thermal noise of the spectrum analyzer. Thermal noise is measured by terminating the spectrum analyzer by a 50 ohm resistor. The decision threshold is a very important parameter in the evaluation of occupancy since it critically, hampers the spectrum occupancy. A high decision threshold leads to non-detection of a weak primary signal resulting in the underestimation of real spectrum occupancy. A low decision threshold results in the overestimation of spectrum occupancy by a false detection of noise as a primary signal. The decision threshold is set by adding 3 dB in the measured thermal noise. The noise varies with the frequency so the decision threshold is not taken as fixed for the entire band. The spectrum occupancy of the band is calculated as a product of the average duty cycle, and the bandwidth. The overall occupancy is obtained by dividing the sum of occupied spectrum with the total spectrum in consideration. The percentage average occupancy of the measured band for locations 1, 2, 3, and 4 is evaluated as 4.4, 2.03, 6.91, and 9.24 respectively. This shows that the spectrum occupancy varies spatially.

Table 3.3: Impact of NM on Spectrum Occupancy

Spectrum Occupancy (%)	Noise Margin			
	3 dB	5 dB	7 dB	10 dB
SAE, Indoor	2.03	1.46	1.07	0.76
SAE, Outdoor	4.40	3.89	3.63	3.38
SBS, Outdoor	6.91	4.99	4.58	4.39
CB, Outdoor	9.24	7.06	6.06	5.09

Table 3.4: Comparison of Measurement Results of All Measurement Campaigns

Band	Services	Average % occupancy (Mumbai Campaign)	*Average % occupancy (SAE, Indoor)	*Average % occupancy (SAE, Outdoor)	*Average % occupancy (SBS,Outdoor)	*Average % occupancy (CB,Outdoor)
700-806 MHz	UHF TV, Fixed, and Mobile services	0.40	0.023	0.10	0.23	2.63
806-890 MHz	PMTRS, Cell Phone, RFID	27.78	12.98	20.50	28.04	42.28
890-960 MHz	GSM 900,Cordless Phones	37.20	19.44	31.41	38.78	46.28
960-1429 MHz	Aeronautical Radio Navigation, Radio Navigation Satellite, Earth Exploration Satellite, Radio Location, Space Research	1.74	0.06	0.22	0.54	1.61
1429-1525 MHz	Fixed/Mobile, Mobile Satellite	1.80	0.02	0.03	0.64	0.02
1525-1710 MHz	Mobile Satellite, Meteorological Satellite Aeronautical Radio Navigation	1.50	0.02	0.09	0.13	0.02
1710-1880 MHz	GSM 1800	31.71	6.59	16.76	35.00	40.09
1880-2400 MHz	TDD,3G,Fixed/ Mobile,BWA	3.15	1.00	3.86	4.66	3.97
2400-2700 MHz	ISM,BWA,INSAT	0.41	0.07	0.25	0.97	6.34
	Total	6.62	2.03	4.40	6.91	9.24

*The measured frequency band is 700-2746.6 MHz. The noise margin is taken as 3dB as against 10 dB in Mumbai campaign. The measurement set up used for these locations is different than Mumbai campaign.

Impact of Noise Margin on Spectrum Occupancy

As we have discussed earlier the decision threshold is very important parameter in the evaluation of spectrum occupancy. It is depend on the choice of NM. We have shown here how the choice of NM greatly affects the spectrum occupancy. We have evaluated the spectrum occupancy for

different NM. It is quite evident from occupancy results summarized in the table 3.3 that as the noise margin increases the spectrum occupancy decreases. Our measurement results showed that the spectrum occupancy highly depends on the decision threshold.

Comparison of Measurement Results of all Measurement Campaigns

The results of Pune Measurement campaigns are compared with the Mumbai measurement campaign in table 3.4. The average occupancy varies from 2.03 % to 9.24 % for the measurement campaigns. Our measurement showed that the spectrum occupancy highly depends on the measurement location. The indoor measurement campaign shows the lowest average occupancy i.e. 2.03 % as compared to the outdoor campaigns in all bands. In case of indoor many spectrum bands are observed to be idle for longer period showing possibilities for secondary access. The highest average occupancy i.e. 9.24% is observed at location 4 which is in the busy part of city. The location 3 has average occupancy i.e. 6.91% which is less compared to location 4 since it located in less busy part of city. The outdoor location 1 is at outskirts of Pune city showing the occupancy 4.41% lower than location 3. The GSM 900 Cellular communication services show highest occupancy in all measurement campaigns. Also, the other cellular communication services (GSM 1800, CDMA) have shown significant spectrum activity in all campaigns except 3G services. As 3G and BWA services were just introduced in India at the time of measurement the occupancy in these bands found low. The average spectrum occupancy in the different band of wireless services shows the same inclination at all locations except in ISM, BWA and INSAT band for the CB outdoor location.

3.4 Stochastic Duty Cycle Model for CR Potential

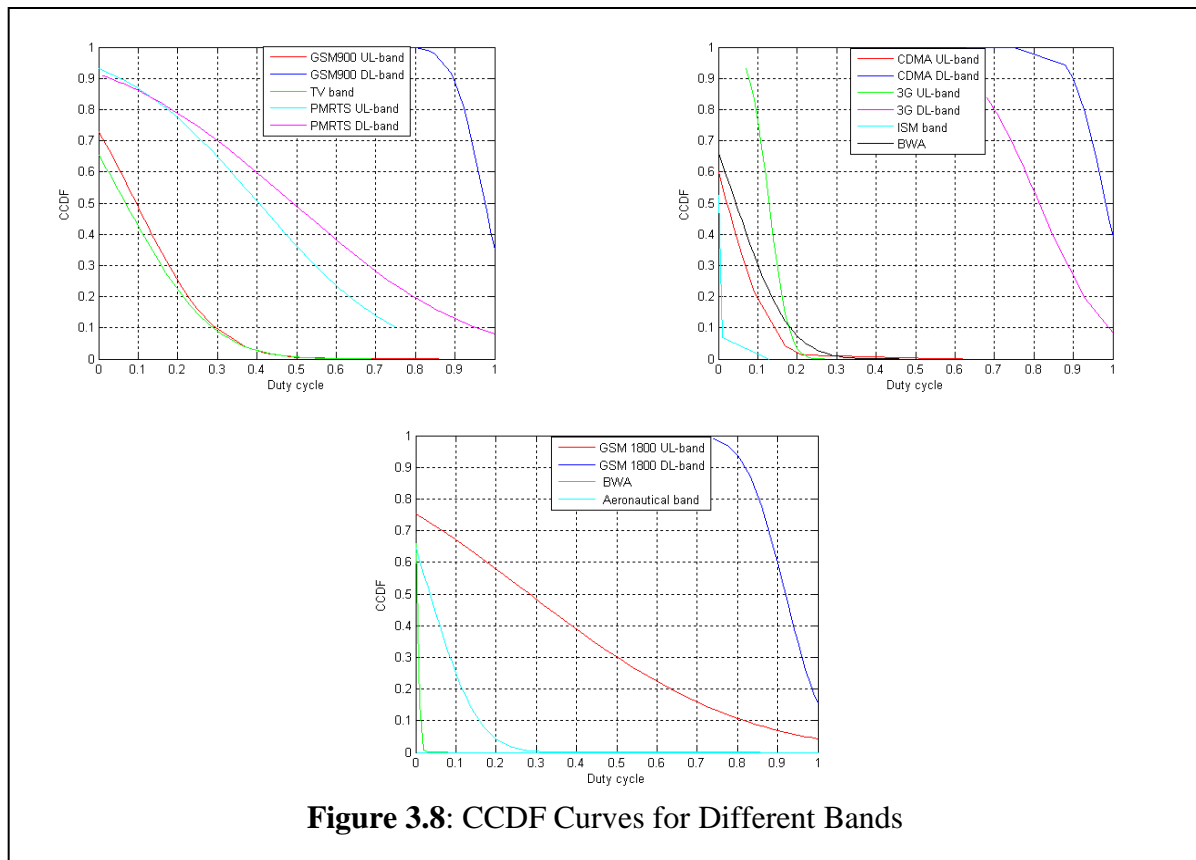
3.4.1 Stochastic Duty Cycle Model

In this section we present the duty cycle model for the distribution of the duty cycle of the different wireless services. The duty cycle quantifies the fraction of time a given frequency is used. The duty cycle model is based on the 200 KHz channelization that we used in the entire measurement campaign. The decision threshold values used in data processing are $\lambda = [-90.2, -90.92, -90.13, -90.56, -89.87, -89]/200$ KHz. The spectrum occupancy $O_{t,i}$ of the channel i at any time t is the binary spectrogram defined as

$$O_{t,i} = \begin{cases} 0 & \text{if } P_{t,i} < \lambda \\ 1 & \text{if } P_{t,i} \geq \lambda \end{cases} \quad (3.1)$$

Where $P_{t,i}$ is the received power spectral density in the channel i at time t . When, the received signal power is greater than or equal to the threshold then the channel is said to be occupied and if it is less than the decision threshold then the channel is said to be free or unoccupied. If the number of measured samples of the channel i are N_i in the measurement period then the duty cycle for the channel i is calculated by (from M.Wellens, and P.Mähönen [27])

$$\delta_i = \frac{1}{N_i} \sum_{t=1}^{N_i} O_{t,i} \quad (3.2)$$



3.4.2 CCDF of Duty Cycle Distribution

The duty cycle distribution over all the channels of the allocated band of a particular wireless service is a matter of interest in the context of CR potentials. The probability of finding the low duty cycle distribution in a band could open up opportunities for the secondary use of the band. The CCDF of the duty cycle distribution denotes the probability that the duty cycle of a

particular wireless service exceeds a given threshold duty cycle. Thus, a CCDF curve shows how much time the duty cycle distribution spends above a specific duty cycle level. The development of the CCDF curve mathematically is as follows. We obtain the probability density function $f_X(x)$ from the data set collected through the measurement. To obtain the cumulative distribution function (CDF) $F_X(x)$, compute the integral of the PDF. Finally, invert the CDF to get CCDF.

$$\text{CCDF} = 1 - F_X(x). \quad (3.3)$$

We have estimated the CCDF of the duty cycle using MATLAB. We have plotted the CCDF of the duty cycle distribution over all the channels in a band, which is allocated for the specific wireless services such as the PLMR band. For this, we took the dataset of location 4 where high spectral activity is observed. The CCDF curves for the different wireless services are shown in figure 3.8.

The CCDF curve for the vestige of the TV band (700-806 MHz) shows high slope at low duty cycle since there is no TV transmission in this region. The analogue TV transmission in this area is in the band III CH-5 (174-181 MHz). However, Doordarshan, the public TV broadcaster of India, is operating short distance UHF links in the band 735-755 MHz and 775-795 MHz. Also, some of the Government agencies are operating point to point microwave links in 610-806 MHz. This band exhibits sufficient scope for CR operation. The Public Mobile Radio Trunked Systems (PMRTS) uplink (UL) band and downlink (DL) band CCDF curves are similar in nature with moderate slope leaving some scope for secondary use. The GSM 900 UL band CCDF curve shows that the probability of getting the vacant channel for CR is high due to large slope at low duty cycle, which indicates that most of the time the duty cycle distribution is low. For GSM 1800, the UL band curve has moderate slope with some scope for opportunistic use. The CCDF curves for DL band of GSM 900 and 1800 shows high slope at higher duty cycle due to the continuous updating procedure on these channels leaving no scope for spectrum sharing. The aeronautical band, and the ISM band CCDF curves also show a large spectral opportunistic for dynamic spectrum access since these bands have large slope at low duty cycle. The recently introduced 3G, and Broadband Wireless Access (BWA) services band also shows large slope at low duty cycle in the CCDF curve indicating low penetration of these services in the region. The usage of these bands may increase in the future depending on the cost of these services. The satellite service signals could not be detected in the measurement system since it has very low

signal level. So this band is not discussed for the CR system. The CCDF curve of the UL band of CDMA service shows significant slope at low duty cycle but this cannot provide for CR operation since the CDMA signal is a wideband with low power level which might not be sensed by the measurement system. The DL band CCDF curve shows consistent occupation of this band due to the continuous transmission from the base station for updating procedures leaving no room for secondary use.

3.4.3 Distribution of the Duty Cycle

In this section we show that the modified beta distribution is a good model of fit for duty cycle distribution. We shall now consider the distribution of duty cycle δ_i over all channels i that belong to certain band which allocated to a specific group of wireless services such as the GSM band. We shall estimate the Cumulative Distribution Function of Duty cycle of different bands. After application of the energy detection we estimate the cumulative distribution function (CDF) of the duty cycle δ_i and compute the PDF by simple differencing. Figure 3.9 shows CDF graph for GSM 900 uplink and downlink band. The slope of CDF graphs is the highest for very low and very high duty cycles indicating that these cases are most probable. This result is not only valid for the shown frequency bands but for nearly all technologies and frequency bands that we investigated.

Duty cycle $\delta_i=0$, when not a single sample passes the detection threshold. In contrast, a strong continuous signal as transmitted by e.g., broadcasting stations, results in $\delta_i \equiv 1$. The Digital cellular system is based on Code Division Multiple Access (CDMA) having more probabilities of two extremes. The base stations transmit continuous signals in the downlink direction. If the received PSD is above the detection threshold then duty cycle δ_i become 1. The other case of duty cycle equal to zero is due to unused CDMA channels.

Distributions with high probabilities for the two extremes, $\delta_i \approx 0$ and $\delta_i \approx 1$, can usually be modeled well with the beta distribution, given by

$$f(x, \alpha, \beta) = \frac{1}{B(\alpha, \beta)} x^{\alpha-1} (1-x)^{\beta-1}, 0 < x < 1 \quad (3.4)$$

Where $B(\alpha, \beta)$ is the Beta function defined as

$$B(\alpha, \beta) = \int_0^1 t^{\alpha-1} (1-t)^{\beta-1} dt \quad (3.5)$$

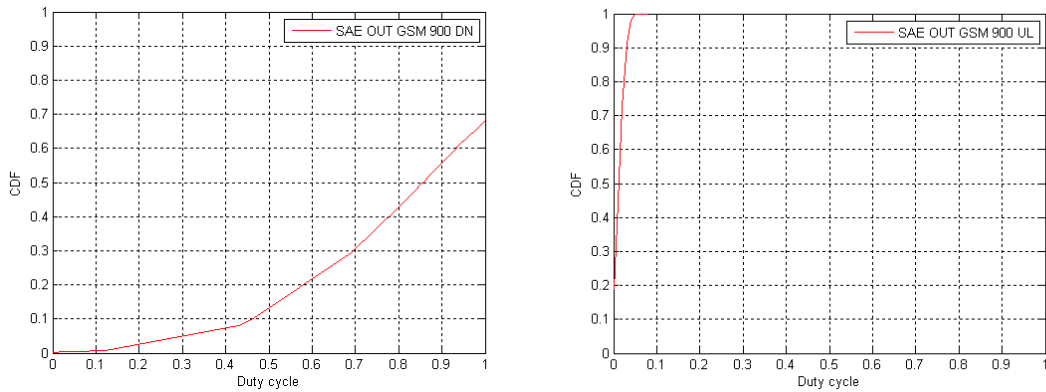


Fig. 3.9: Comparison of different duty cycle distribution based on measurement SAE outdoor using appropriate threshold

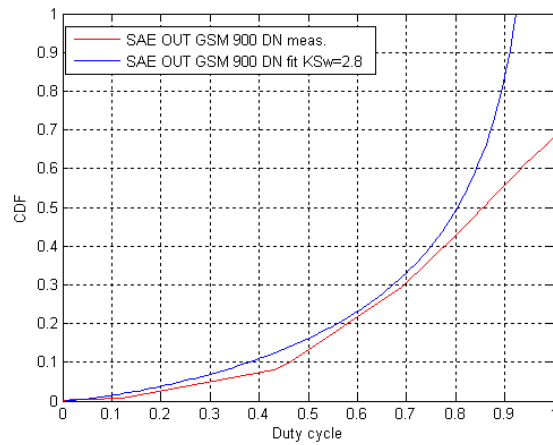


Fig. 3.10: GSM 900 DL Band duty cycle distribution and corresponding modified beta distribution fit.

α and β are two free parameters to control the behavior of the distribution and $B(\alpha, \beta)$ is the beta function. As discussed above, we found a significant number of channels with $\delta_i \equiv 0$ or $\delta_i \equiv 1$ in several of our measured traces. Since the beta distribution does never approach 0 or 1 we use a modified beta distribution for duty cycle modeling. Let $P_{DC} = 0$ denote the probability of a completely idle channel and $P_{DC} = 1$ denotes the probability of completely occupied channel, respectively.

We define the modified beta distribution $f_{mb}(x; \alpha, \beta)$ as [27]

$$f_{mb}(x; \alpha, \beta) = p_{DC=0} \cdot \delta(x) + (1 - p_{DC=0} - p_{DC=1}) \cdot f_b(x; \alpha, \beta) + p_{DC=1} \cdot \delta(x-1), x \in [0,1] \quad (3.6)$$

where $\delta(x)$ is the Dirac delta-function.

We will now use our measurement results and the estimated distribution functions to show that the modified beta distribution is a good model for the duty cycle distribution. We will apply *goodness-of-fit* metric to evaluate the accuracy of the distribution fits [132]. We use a reweighted version of the Kolmogorov-Smirnov (KS_w) metric as applied, e.g., in [133]:

$$KS_w(k) = \max_{k \in [1, j]} \frac{|F(k) - G(k)|}{\sqrt{G(k)(1-G(k))}} \quad (3.7)$$

where F is the measured CDF, G is the CDF of the fitted model, and J denotes the number of bins used during the estimation of the CDF. We use the KS_w -metric because it is reweighted to consider also the differences at the extreme ranges of k appropriately.

Figure 3.10 shows CDF graph for GSM 900 downlink band and also shows the corresponding modified beta distribution fits. Additionally, the results for the KS_w are given. All fits are sufficiently close to the measured distribution and prove that the modified beta distribution can reproduce the measured characteristics of the duty cycle.

Table 3.5: Parameters of the Modified Beta Distribution for Duty Cycle Modeling

Data set	Location	Band	Threshold	P_{DC0}	P_{DC100}	α	β	KS_w
GSM900 DN	SAE,IN	935-960 MHz	-90dBm	0.1129	0.2591	1.99	0.73	1.16
GSM900 DN	SAE OUT	935-960 MHz	-90dBm	0.0565	0.5565	2.3	0.45	2.86
GSM900 DN	SBS OUT	935-960 MHz	-90dBm	0	0.6694	2.1	0.74	2.2
GSM900 DN	CB OUT	935-960 MHz	-90dBm	0	0.7823	1.8	0.88	1.95

Table 3.5 lists all required parameters for the modified beta distribution for GSM band. We also include the *goodness-of-fit* results in order to show how well each case could be modeled by the modified beta distribution. We list parameters for both calm radio environments at SAE, IN and the busier environment at SAE OUT, SBS OUT and CB OUT in order to enable scenario generation for different types of radio environments. Additionally, for the busier radio environments the better fits of the SAE OUT, SBS OUT and CB OUT can be selected. The given parameters enable straightforward generation of realistic duty cycle data sets for DSA and cognitive radio research.

3.5 Evaluation of Spectrum Usage for GSM Band

The general characterization of the traffic density at the GSM frequency bands as well as detailed analysis of the temporal frequency occupation described in this section.

CCDF Plot

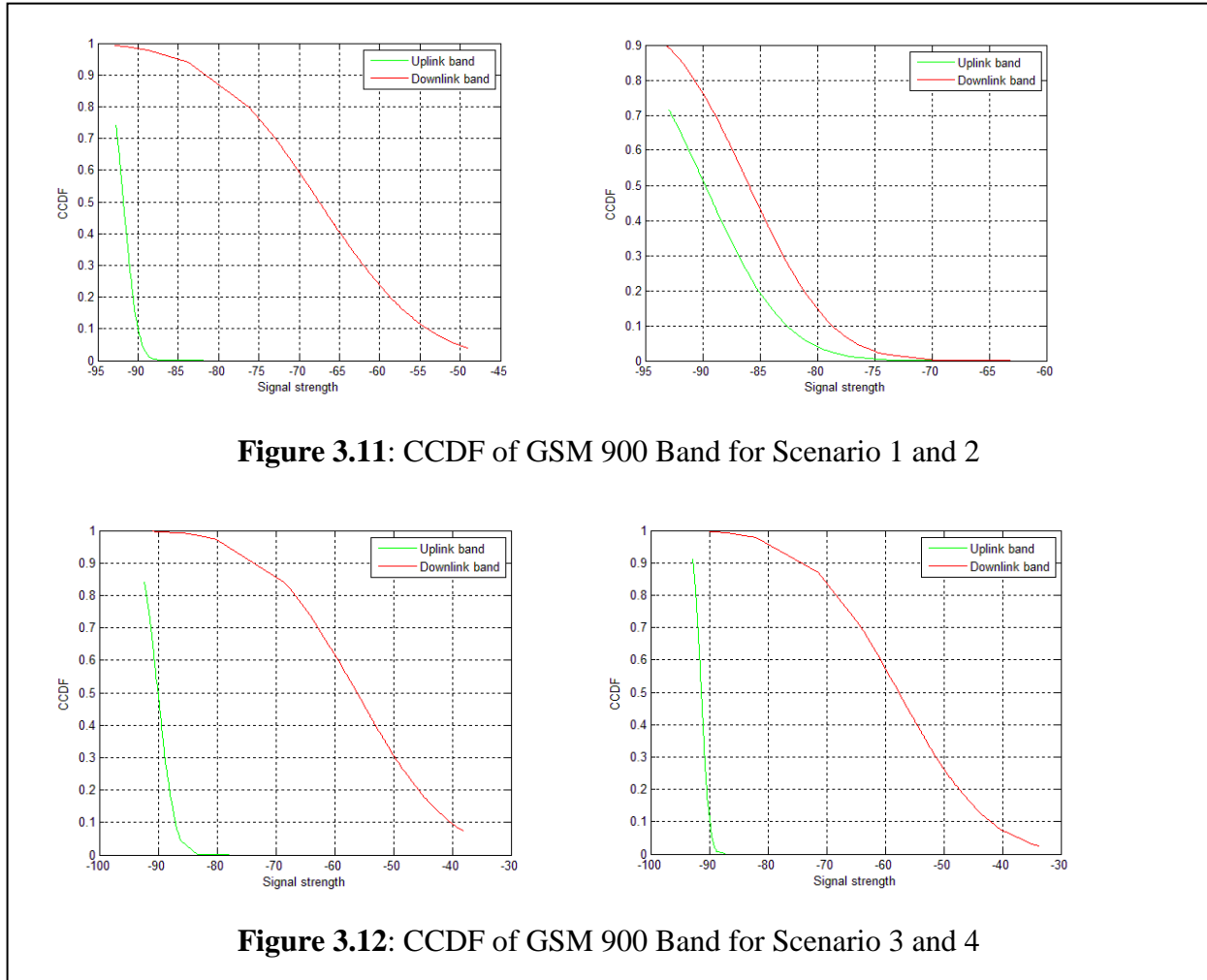
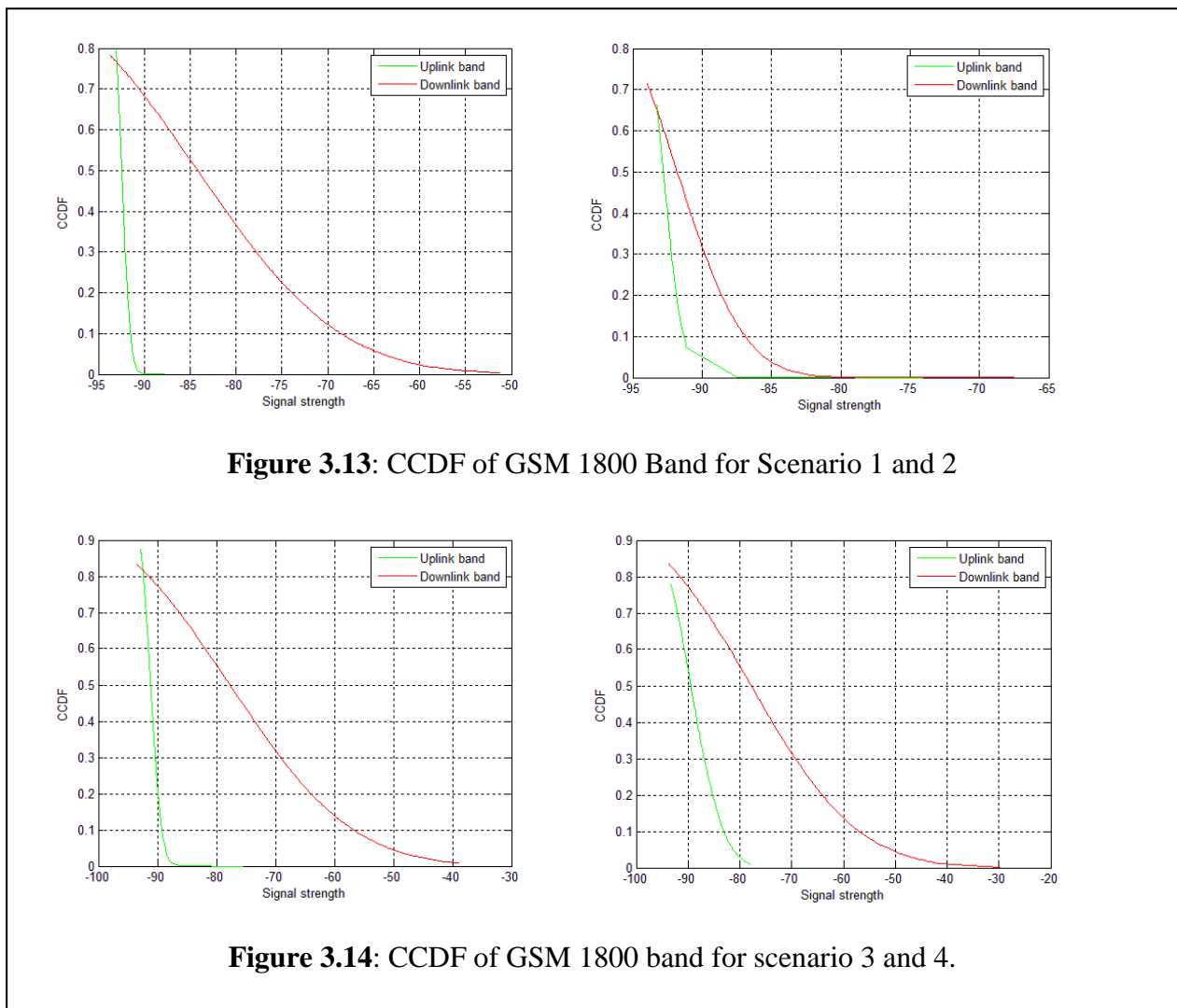


Figure 3.11: CCDF of GSM 900 Band for Scenario 1 and 2

Figure 3.12: CCDF of GSM 900 Band for Scenario 3 and 4

Figure 3.11-3.14 shows CCDF curves for the GSM 900 and GSM 1800 bands for four scenarios. Figure shows CCDF curves for two bands: downlink (DL) and uplink band (UL). The DL band (red line) operates at high power level than UL band (green line). The DL curves has moderate slope while UL band curve has large slope for both GSM bands. The uplink band signal strength varies around noise level for outdoor for both GSM bands showing potential for cognitive radio operation at outdoor location for GSM 900 and 1800 bands. The primary signal activity for scenario 2 seems to be more than scenario 1 for both GSM 900 band as well as GSM 1800 band.

The fall in the downlink CCDF curve for GSM 900 and 1800 bands is sharper for indoor scenario due to no direct line of sight for signal and attenuation from walls. CCDF curves for outdoor scenarios are similar for both GSM bands. The downlink of GSM 1800 shows low power level compared to GSM 900 band. DL curves consistently shows high power level as continuous transmission of control channels from base stations with high power. Downlink channels of GSM 1800 band have highest signal strength in scenario 4 as compared to the other three scenarios and this may be due to the measurement location being close to base stations.



Power Spectral Density (PSD) Plot

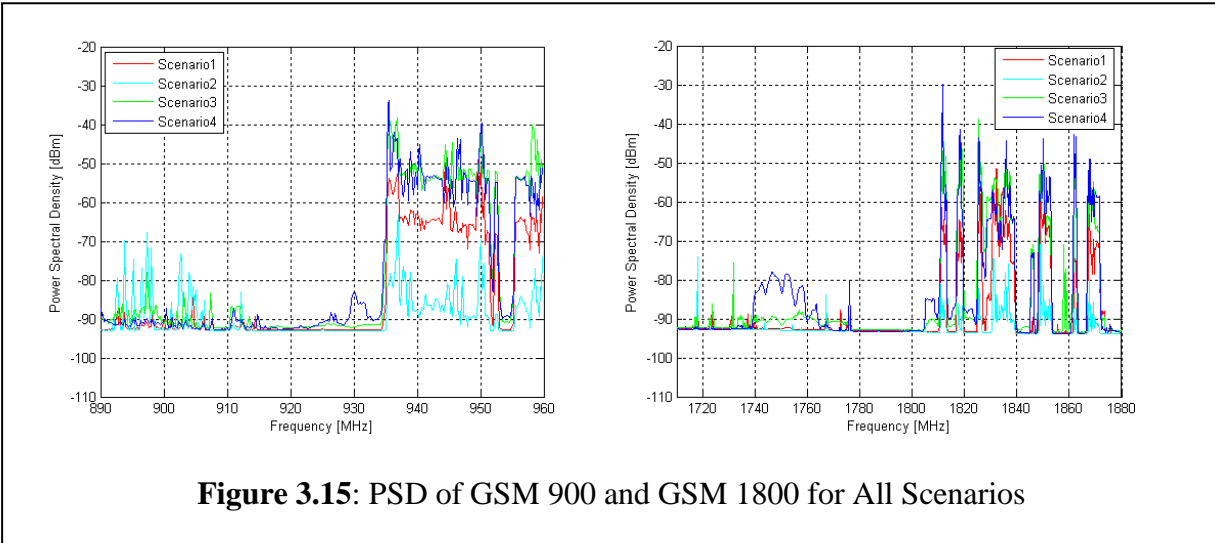
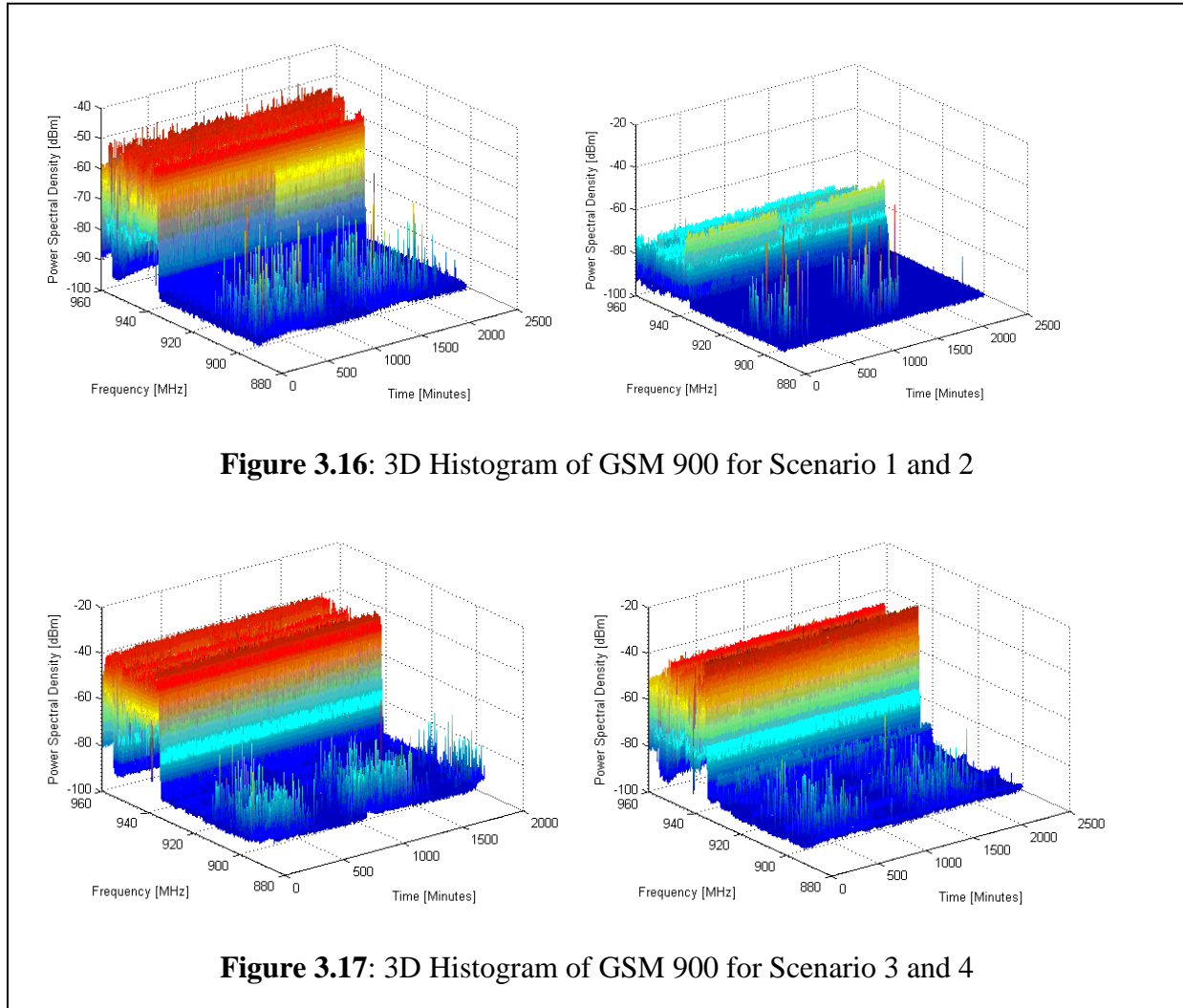


Figure 3.15 shows average PSD variation for GSM 900 and GSM 1800 bands for four scenarios. For outdoor measurement the power level in down-link is observed higher (since it is in direct line of site with base stations) than indoor location as the signals are severely attenuated by walls in indoor. The DL channels of GSM band is fully occupied as there is continuous transmission with relatively high power for updating the procedures from base stations. The usage of uplink channels varies according to the active users on network. We have also observed that the received power from GSM 900 mobile units is more than the GSM 1800 mobile units. We have also noted that the uplink channel power level more in indoor than outdoor in GSM 900 and 1800. This may be due to the calls generated from nearby area of indoor measurement location.

3-D Histogram

A 3-D histogram is a three dimensional plot that displays the power of the signal versus time and frequency. The vertical axis represents time, the horizontal axis represents frequency and the third axis represents power level. The band gap between the uplink and downlink is observed prominently from figures 3.16-3.19. The signal strength after the time zone 1000 minute and before 1400 (i.e. during night) is almost zero for both the outdoor and indoor.

These temporal white spaces can be used for cognitive radio. The primary signals activity in indoor is only observed during college working hours. There is a higher probability of the channel to be vacant in GSM 1800 uplink band than GSM 900 for secondary use. Figure 3.16-3.19 shows



the probability of finding a band vacant is higher in indoor scenarios than outdoor scenarios. Thus, the probability of finding the channel vacant depends on location i.e. indoor or outdoor. Figure 3.16 and 3.18 shows that the indoor scenario has very low occupancy during the day time and trifling during the night which indicates potential for cognitive radio.

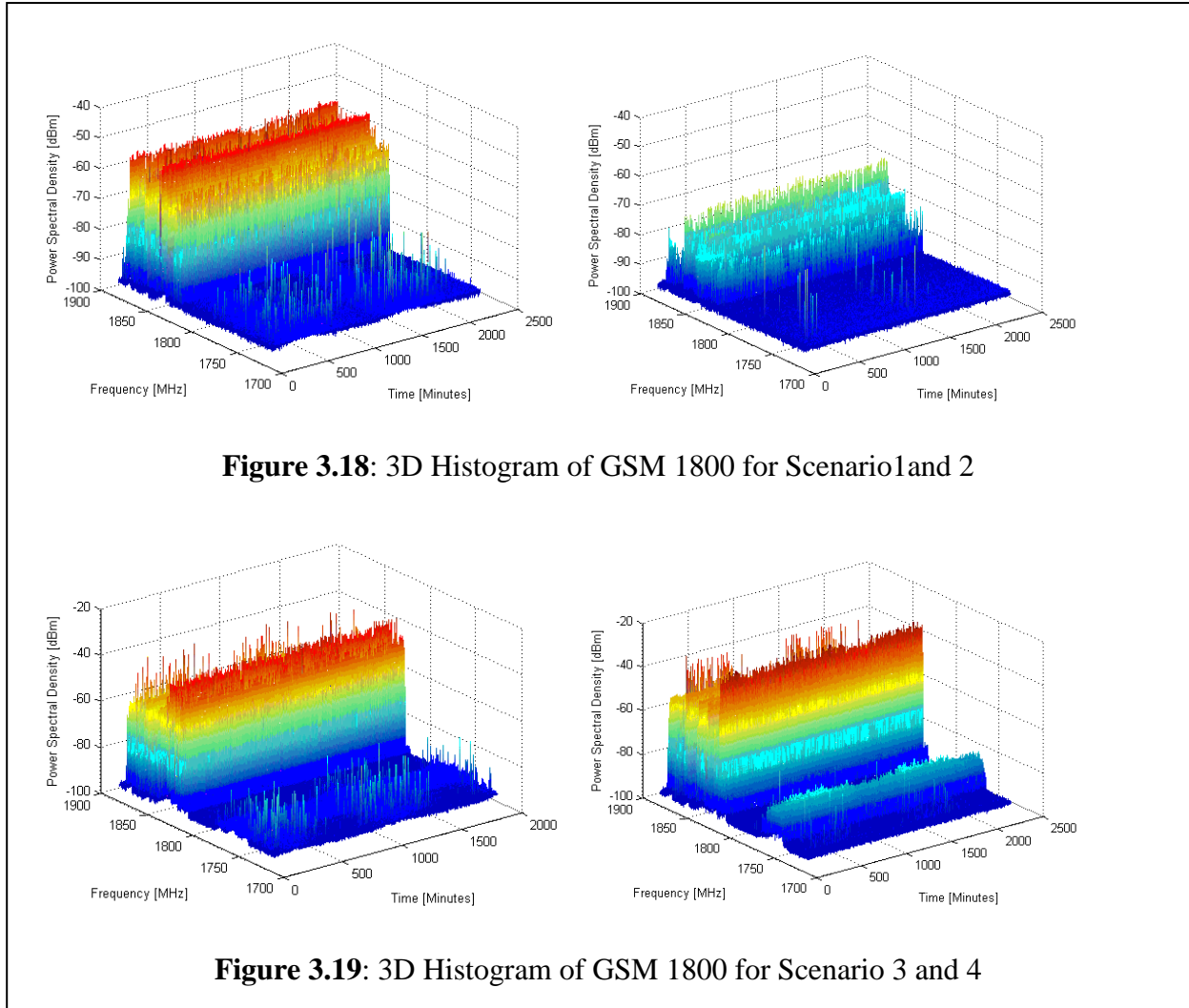


Figure 3.18: 3D Histogram of GSM 1800 for Scenario 1 and 2

Figure 3.19: 3D Histogram of GSM 1800 for Scenario 3 and 4

In figure 3.19 for scenario 4, the frequency range 1740-1765 MHz shows occupancy during the complete measurement period of 48 hours which clearly indicate that this particular band is not suitable for cognitive radio application. The down link occupancy is observed higher in case of GSM 900 band than GSM 1800 band.

GSM Band Occupancy

The table 3.6 shows that the uplink and down link occupancy is not identical for GSM bands at indoor and outdoor location. The downlink band occupancy is higher than uplink as expected due to continuous transmission of signal on control channels. The spectrum occupancy for outdoor is observed high as compared to indoor. The uplink occupancy at both the scenarios is less indicating high scope for dynamic spectrum access.

Table 3.6: Spectrum Occupancy for Scenario 1, 2, 3 and 4

Frequency Band	Occupancy (%) for Scenario 1	Occupancy (%) for Scenario 2	Occupancy (%) for Scenario 3	Occupancy (%) for Scenario 4
GSM 900 UL	1.32	0.19	9.44	9.18
GSM 900 DL	86.05	54.62	93.23	96.51
GSM 900 Band	31.41	19.44	38.79	46.28
GSM 1800 UL	0.86	0.086	24.3	30.96
GSM 1800 DL	37.03	14.82	54.82	59.46
GSM 1800 Band	16.76	6.59	35	40.09

3.6 Consideration in Choice of Suitable Wireless Services

In this section we discuss, the wireless services that can be considered in the bands, which are probable for dynamic spectrum sharing. CR is a developing technology, which bridges the traditional wireless services with the frequency agile networking of the future. The measurement reports have shown opportunities for CR, but the development of a new wireless network introduces many technical challenges such as spectrum sensing of an incumbent user, new wireless PHY, and MAC layer design, frequency agile operation, Geolocation, stringent spectral mask requirement, and reliable service [59].

The IEEE 802.22 standard is being developed for Wireless Regional Area Networks (WRANs) using TVWS. It is the first standard that focuses licensed-exempt broadband wireless access to rural areas on non interference basis in TVWS, thus, helping to bridge the digital divide. The IEEE 802.22 standard takes the benefit of the excellent propagation characteristics of the VHF, and UHF TV bands to provide broadband wireless access up to maximum 100 KM from the transmitter [60]. The IEEE 802.22 Working Group has defined an air interface (PHY and MAC) standard based on CR techniques. The first sign of it is the decision of FCC to allow the TV White space (TVWS) for CR [61].

In the FP7 project Quasar the need to use different business, and services scenarios for evaluation of use of the secondary spectrum has been identified. A number of service scenarios have been identified, and described [62].

- Cellular use of TV white spaces.
- Wi-Fi like use of white spaces.
- Secondary wireless backhaul.
- Secondary spectrum commons in radar band.
- Indoor broadband in an aeronautical spectrum.
- Cognitive Machine-to-Machine.

The spectral opportunities for secondary use in different bands have been shown in the previous section. The frequency band 700-806 MHz is a part of the digital dividend spectrum, which has great demand from the different stakeholders due to its favorable characteristics. It is best suited for the mobile communication since it offers better propagation characteristics, lower cost of semiconductor devices, and the less effect of the Doppler shift at this frequency. The secondary use of this band cannot be considered since band 698-806 MHz is identified for IMT and BWA [53]. The CR activity could be considered in TV white spaces only after the complete transition from analogue to digital TV transmission.

The Public Land Mobile Radio (PLMR) bands are the potential regions where dynamic spectrum access technology can be developed. The use of this band in emergencies for public safety through opportunistic spectrum access is proposed in [63]. The PLMR band could be considered for the modern public safety, non-military, and business/industrial applications through policy based cognitive radio. A CR network is proposed for aeronautical air to ground communication in [64] to solve the existing system problem like limited availability of the spectrum and its inefficient usage. The requirements, challenges, and implementation issues of aeronautical band spectrum sharing with indoor femtocell are discussed in [65]. An indoor broadband can be considered as a possible service in this band. The feasibility of the CR system in the ISM band has been shown in [66] since the channel utilization is not uniform in ISM bands. The smart sensing, and channel selection based on the occupancy of the channel has shown the immense potential for the ad-hoc network. Wireless mobile Ad-hoc network (MANET) is particularly, useful for military mission operations or vehicular communication within motorcade.

3.7 Validation of Beta Distribution for Modeling Channel Occupancy

The primary users' arrival, and departure in the licensed band is random in nature, and this poses a problem in modeling the spectrum occupancy or availability of the channel. The existing research literature has shown the Beta distribution in the modeling the spectrum occupancy of the primary user in a licensed band. Beta distribution for channel occupancy modeling is assumed by P.F.Marshall in [67]. This assumption is validated in [68] using real time measurement performed in Aachen, Germany on the 1500 MHz spectrum centered at 770 MHz.

Beta distribution is a good fit to the channel occupancy due to following facts:

1. Continuous broadcast channels e.g. The downlink channels in GSM or CDMA services are always available on the air have a high probability of occupancy.
2. Moderately, used channels e.g. PMRTS, FM, and ISM channels have moderate probability of occupancy.
3. Rarely, used channels e.g. space navigation, radio astronomy, and military channels have a low probability of occupancy.

In this section, we validated the beta distribution assumption of channel occupancy using our real time measurement performed in Pune, India.

3.6.1 Beta Distribution

The probability density function of a Beta distribution function has two parameters $\alpha > 0$ and $\beta > 0$, and is given by equation 3.4. The beta distribution takes on many different shapes, and is described by two positive shape parameters, α and β . The entity $B(\alpha, \beta)$ is normalization constant to ensure that function in Equation (3.4) integrates to unity. The choice of Beta distribution for generating a set of channel free probabilities randomly because any continuous probability distribution on $(0, 1)$ can reasonably be approximated by a Beta distribution [69].

3.7.2 Kolmogorov-Smirnov (K-S) test

The validation of assumption of beta distribution is done with the Kolmogorov-Smirnov (K-S) test. This approach, assesses the underlying distribution of the data set. This test is Goodness of Fit test (GoF) based on statistical theory. The data set obtained over a long term measurement is used for validation. The data set has to be divided into the three or four intervals of interest. The random sample of channels is taken with occupancy probabilities between 0, and 1 for each time

interval under consideration. The different mean (μ_{occ}), and variance (σ_{occ}) of the channel occupancy over the different data sets is to be evaluated. To implement the K-S test, we have to follow a well-defined series of steps. First, we assume a pre-specified distribution. (e.g. Beta). Then we estimate the distribution parameters (e.g. α and β) from the data set. The α , and β parameters can be computed from the obtained data using the following expression [70]:

$$\hat{\alpha} = \mu_{occ} \left(\mu_{occ} \frac{(1-\mu_{occ})}{\sigma_{occ}} - 1 \right) \quad (3.8)$$

$$\hat{\beta} = (1 - \mu_{occ}) \left(\mu_{occ} \frac{(1-\mu_{occ})}{\sigma_{occ}} - 1 \right) \quad (3.9)$$

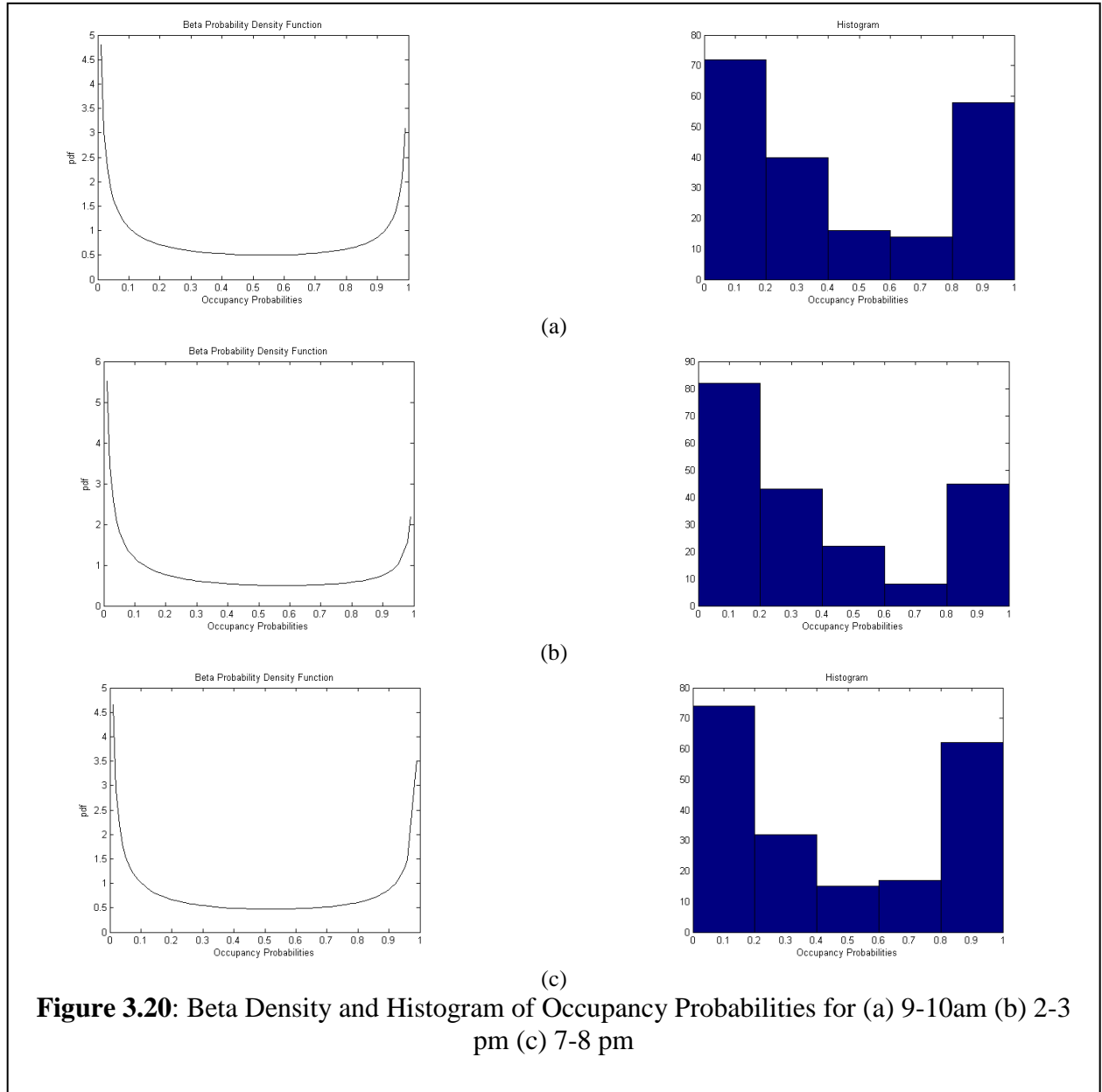
Such a process yields a distribution hypothesis, also called null hypothesis H_0 with several parts must be jointly true. The negation of the assumed distribution (or its parameters) is the alternative hypothesis (also called H_1). We test the assumed distribution using the data set. Finally, H_0 is rejected whenever any one of the several elements composing of the null hypothesis H_0 is not supported by the data. The stepwise KS GoF test procedure is in table 3.7.

Table 3.7: Step-By-Step Summary of the K-S GoF Test for Beta Distribution.

Step No	Step description
1	Establish the(H_0) assumed distribution: Beta
2	Estimate the Beta parameters: α , β
3	Sort the data in ascending order
4	Obtain the theoretical distribution (F_0)
5	Obtain the empirical distribution (F_n)
6	Obtain $D_+ = F_n - F_0$ and $D_- = F_0 - F_{n-1}$ for every data point
7	Obtain the KS statistics $D = \max(D_+, D_-)$
8	Obtain the KS table critical value CV
9	Since $KS < CV$ assume the data from a Beta
10	We can also use MATLAB software and p-value for K-S test

In this distance test, when the assumed distribution is correct, the theoretical (assumed) CDF closely, follows the empirical, step function CDF there. The data is given as an ordered sample, and the assumed (H_0) theoretical distribution has a CDF, $F_0(x)$. Then, we obtain the corresponding GoF test statistical values. Finally, we compare the theoretical and empirical

results. If they agree (probabilistically), then the data supports the assumed distribution. If they do not, the distribution assumption is rejected.



3.7.3 Validation of Beta distribution using K-S Test

The beta distribution assumption is validated for primary user channel occupancy using real time measurements on a band from 700 to 2746.6 MHz in Pune. The measurement was conducted at location 4 for 7 days. The detail of the measurement is already described in the section 3.1. We

have divided the data of the seven days period into three intervals of interest, which is given below.

1. Morning 9.00-10.00 am
2. Afternoon 2.00-3.00 pm
3. Evening 7.00-8.00 pm

Table 3.8: Estimated Parameters from the K-S Test

Time Interval	Sample size	μ_{occ}	σ_{occ}	α	β	h	p	k
9.00-10.00 am	48	0.4358	0.1418	0.32	0.4144	0	0.2078	0.1050
2.00-3.00 pm	48	0.3758	0.1298	0.3033	0.5037	0	0.1324	0.1150
7.00-8.00 pm	48	0.4543	0.1483	0.3053	0.3668	0	0.2562	0.10

We have considered 200 random channels from the measured band. A random sample of channels with occupancy probability is collected over the each time interval. The mean (μ_{occ}), and variance (σ_{occ}), alpha and beta parameters are estimated from the data set over the specified duration of an hour, and given in the table. The validation of beta distribution is done using the Kolmogorov-Smirnov (K-S) test in MATLAB. The null hypothesis is tested using the K-S test. The Kolmogorov-Smirnov test compares the distributions of the values in the two data vectors. The null hypothesis is that the two data sets are from the same continuous distribution. The alternative hypothesis is that they are from different continuous distributions. The result h is 1 if the test rejects the null hypothesis at the 5% significance level; 0 otherwise. The parameters from the K-S test are given in the table 3.8. It is evident from the h value = 0 the null hypothesis of Beta distribution assumption for spectrum occupancy is accepted based from the K-S test. The observed frequencies and the beta distribution with the estimated parameters are shown in the figure 3.20 for different time intervals.

3.8 Conclusion

The spectrum utilization found through the measurement is quite low showing ample opportunities for CR. We have presented the comparison of the measurement results for the four locations. We have observed high occupancy at busiest part of city. The results show that spectrum occupancy varies spatially, and temporally. The spectrum occupancy rates are highly, influenced by the choice of a decision threshold in the measurement method, and the measurement location. This suggests that CR operation requires location based spectrum usage map. The future CR systems should be ideally location aware radios for efficient operation. The power spectral density of the samples from real time transmission and background noise is observed more for outdoor location than indoor location. The stochastic duty cycle model based on the measurement has been presented for exploring the opportunistic bands for dynamic spectrum access. The most probable bands for CR have been identified. These bands are TV, PMRTS, UL cellular bands (2G), W-CDMA (3G), aeronautical radio navigation, radio navigation, and radiolocation ISM, satellite, and BWA. The stochastic duty cycle model is useful for the assessment of the DSA systems. The statistical characteristics of spectrum usage are beneficial not only for spectrum sensing, but also in the dynamic allocation of frequencies to the secondary users. The information of location in future CR system will be essential for efficient operation.

Based on our extensive measurement results we have shown that the cases of completely busy or vacant channels are very possible. The modified beta distribution is a good model to reproduce these characteristics. We have demonstrated that the model fits well and have listed model parameters for GSM wireless systems. The presented duty cycle model is useful for multiple applications in the assessment of dynamic spectrum access systems.

The occupancy results of GSM 900 and 1800 band leads to the conclusion that the bands are underutilized. The GSM uplink bands have considerable scope for cognitive radio operation. The 3D histogram shows that the uplink band usage of GSM 900 and 1800 band at night is almost zero. Thus, the bands can be used for cognitive radio during night time without causing any interference to the primary users. This result provides the opportunity for regulators and operators to know the extent to which the spectrum is utilized and its variation over different locations. Some potential wireless services in opportunistic bands have been discussed as well.

The random arrival and departure of the primary users in licensed bands poses challenges in modeling the channel occupancy. We have validated the assumption of the beta distribution in modeling the channel occupancy of primary users in licensed spectrum through the Kolmogorov-Smirnov test.

4

Cognitive Access to TVWS in India: TV Spectrum Occupancy and Wireless Broadband Network

In this chapter, TV white space concept is introduced. TV band spectrum measurement and analysis in support of cognitive radio operation is presented. The generic technical and regulatory requirements for Cognitive access of TVWSs in India are proposed. The major ongoing CR/TVWS standardization activities are also discussed. Wireless broadband connectivity for rural areas using CR/TVWSs in India is proposed in this chapter. Finally, implications of Cognitive Radio on spectrum regulation in India are discussed.

4.1 Introduction

The TV broadcast spectrum is a low frequency spectrum in the VHF and UHF portion of the radio spectrum, which traditionally has been used exclusively by television broadcasters for analogue transmission. The spectrum section offers attractive features like high building penetration, wide coverage, and moreover, small antenna size acceptable for portable and handheld devices. However, regulatory rules don't allow the use of unlicensed devices in the TV bands, with the exception of remote control, medical telemetry devices and wireless microphones. Currently, there is a global move to convert TV stations from analogue to digital transmission. This is termed the digital switch-over (DSO) referring to the time when digital transmission effectively starts or in some cases the analogue switch-off (ASO) referring to the time when analogue transmission effectively stops operation. Although the DSO process is underway worldwide, the ASO process will differ from country to country depending on the market configuration. The switchover from analog to spectrum efficient digital TV transmission will free a significant amount of spectrum. Thus, the switchover from analog to digital television is resulting in a once-in-this-lifetime opportunity for reallocation of this immensely valuable spectrum. In addition to cleared spectrum, there will be typically a number of TV channels in a given geographic area not being used by DTV stations after the DTV transition.

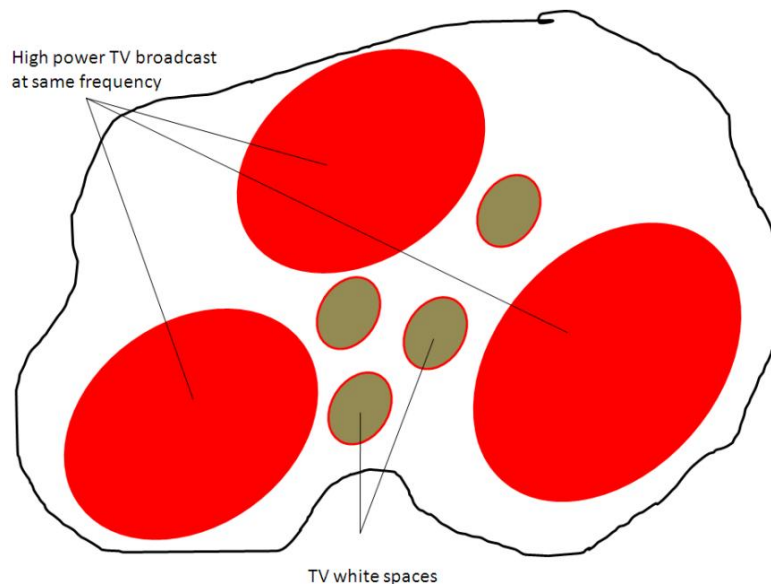


Figure 4.1: TV White Spaces

This is because the operation of such stations on these channels would cause interference to co-channel or adjacent channel stations. The interference will be lower in digital than analog transmission since DTV transmission is power efficient than analog. However, a low power transmission on such a locally vacant TV channel at a much lower power level would not need a great (physical) separation from co-channel and adjacent channel TV stations to avoid causing interference. Low power devices can therefore; operate on vacant channels in locations that could not be used by TV stations due to interference planning. The unused geographical interleaved spectrum band is called as TV white space. Figure 4.1 shows TV white spaces. The unused geographical interleaved spectrum bands provide an opportunity for deploying new wireless services. The Cognitive Radio (CR) technology can exploit the TV white spaces without harmful interference to the incumbent services. Currently, Cognitive radio is being intensively researched for cognitive access to the TV White Spaces (TVWS). There are many projects like COGEU and QUASAR [62, 71] have focus on the utilization of geographic interleaved spectrum based on cognitive radio technology.

In UK, the interleaved spectrum of 256 MHz is available after DSO which can be used on a geographical basis for license- exempt access by using cognitive radio technology. It shows that there is significant capacity available for cognitive access in the UHF bands. However, due to its secondary nature the availability and frequency decomposition of the UHF spectrum for cognitive access is not the same at all locations and depends also on the power levels used by cognitive devices [72]. This is an important feature of license-exempt cognitive access to TV bands which differentiate it from, e.g. Wi-Fi access to the ISM bands. In USA, FCC has adopted rules to allow unlicensed radio transmitters to operate in the broadcast television spectrum at locations where that spectrum is not being used by licensed services which are described in [61] [73]. Ofcom, the UK regulator is also in process to allow cognitive radio operation in interleaved spectrum of TV band [74]. In the next step, Ofcom has called consultation on white space device requirements on 22 November 2012 [75].

The TV white spaces have significant importance especially, in a developing country like India. The new telecom policy of India suggests the promotion of use of white spaces with low power devices, without causing harmful interference to the licensed applications in specific frequency bands by deployment of Software Defined Radios (SDRs), Cognitive Radios (CRs). The secondary use of TV white spaces can provide a platform to bring innovation in wireless

services. It can develop new methods to provide future broadband wireless services and applications at low cost and will bring broadband revolution especially, in rural India. With reference to the unlicensed operation in TV band what opportunities available in India are need to be assessed? In addition to this what are the potential applications in TV whitespaces suitable for Indian scenario needs to be explored. Some of the potential applications in TV white spaces in India context have been discussed in [76]. To define the technical and operational requirements for the possible CR operation in white spaces require compatibility studies of protection of incumbent radio services authorized for operation on a given band with a regulatory priority.

4.2 TV band Occupancy in India

4.2.1 VHF and UHF Assignment in India for TV

The terrestrial TV broadcasting in India is operates in VHF and UHF band. The frequency allocation of terrestrial broadcasting is in the line with the other parts of the world. The spectrum available for Terrestrial TV broadcasting along with TV channel distribution in India is given in table 4.1. The total spectrum presently available in India from VHF and UHF TV band is 413MHz. Doordarshan, the public TV broadcaster of India, has assigned only one channel (channel number 4) in the VHF band I for the terrestrial TV broadcast. Doordarshan has assigned all the 8 channels of the VHF III band for analogue TV transmission.

Table 4.1: TV Channel Allocation in VHF and UHF Band in India [54]

Band	No of TV channels available	TV channel number	Amount (MHz)
VHF band I (47-68 MHz)	3	2-4	21
VHF band III (174-230 MHz)	8	5-12	56
UHF band IV (470-582 MHz)	14	21-34	115
UHF band V (582-806 MHz)	28	35-62	221

There are 14 TV channels available in the UHF band-IV (470-582 MHz) with each having a channel bandwidth of 8 MHz. Doordarshan has assigned, and is operating about 330 transmitters in this band. Doordarshan's three digital TV transmitters at Kolkata, Chennai, and

Mumbai are also operating on an experimental basis in this band. There are 28 channels available with a 8 MHz bandwidth in UHF band-V from 582-806 MHz. Doordarshan has not been assigned any channel in this sub-band for analogue TV transmission. However, frequency band of 735-755 MHz and 775-795 MHz has been assigned to Doordarshan to operate short distance UHF links. Some of the Government agencies are operating point to point microwave links in 610-806 MHz. In India, Doordarshan is the only national carrier for TV broadcasting, which covers almost the entire country. The Doordarshan runs very few channels such as DD1, DD metro, DD news, and regional channels. In contrast to this, Europe, and US runs many channels and uses all available TV channels. Traditionally, broadcast TV transmission takes place in VHF and UHF range in a 6-8 MHz band per channel. But, these band of frequencies which occupy different slots in the frequency range from 470-698 MHz, remain highly underutilized. Their usage pattern changes with geo-location, and in rural, and semi-urban areas, they are mostly unutilized owing to fewer broadcasters.

4.2.2 Measurement Set-up and Methodology



Figure 4.2: Measurement Set-up Deployed at Measurement Location

The equipments used for the spectrum survey consist of a broadband discone antenna AOR DA 753G having frequency range 75MHz - 3GHz, which was connected with 10-meter a low loss co-axial cable RG58A/U to a high performance portable spectrum analyzer R&S FSH having frequency range of 100KHz to 3GHz. Antenna is vertically polarized, and having an Omni-

directional radiation pattern in horizontal plane. Spectrum analyzer was controlled by laptop connected via RS 232 optical interface cable. The optical connection prevents spurious measurements being caused by interference from these devices.

Table 4.2: Spectrum Analyzer Configuration Parameters

Parameter	Value
Frequency Range	174 to 806 MHz
Frequency Span	60 MHz (11 blocks x 60 MHz)
Frequency(measurement) points	301
Resolution bandwidth	100 KHz
Sweep time	Auto
Measurement duration	24 hour
Video bandwidth	100 KHz
Detection type	RMS detector
Reference level	-50 dBm
Built-in Preamplifier	Activated (10 MHz-2.5 GHz)
Instrument	R&S FSH 3

Table 4.3: Measurement Locations

Name	Brief Description of Outdoor Location
Location 1	Roof top of the Building of Sinhgad Academy of Engineering, Kondhwa, Pune Latitude: 18° 26' 36.4" North, Longitude: 73° 53' 44.5" East.
Location 2	Roof top of the Residential Building, Kothrud, Pune Latitude: 18° 29' 58.52" North, Longitude: 73° 48' 47" East.
Location 3	Roof top of the Residential Building, Parvati, Pune Latitude: 18° 29' 10.7" North, Longitude: 73° 50' 37.31" East
Location 4	Roof top of the Residential Building, Katraj, Pune Latitude: 18° 27' 26.43" North, Longitude: 73° 51' 51.37" East
Location 5	Roof top of the IMEET college building, Kumbhivali village, Khalapur. Latitude: 18° 49' 12.76" North, Longitude: 73° 16' 14.52" East

The measurement set-up is shown in figure 4.2. The FSH Remote software is used for automatically setting the equipment for measurement and recording the captured data in Laptop. The MATLAB software package is used to analyze the data. The spectrum analyzer

configuration parameters setting for evaluation of occupancy are listed in Table II. The spectrum occupancy measurement campaign was conducted across the frequency range of 174 to 806 MHz. The overall frequency range is divided into 11 bands; each is having a frequency span of 60 MHz. Each frequency span of 60 MHz has 301 frequency points. Thus the total number of frequency points collected in the frequency range is $11 \times 301 = 3311$. The separation between two consecutive frequency points is 200 KHz. The details of the measurement campaign are previously, described in [77, 78].

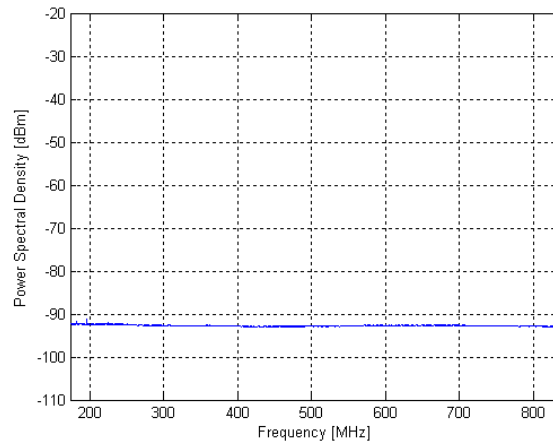
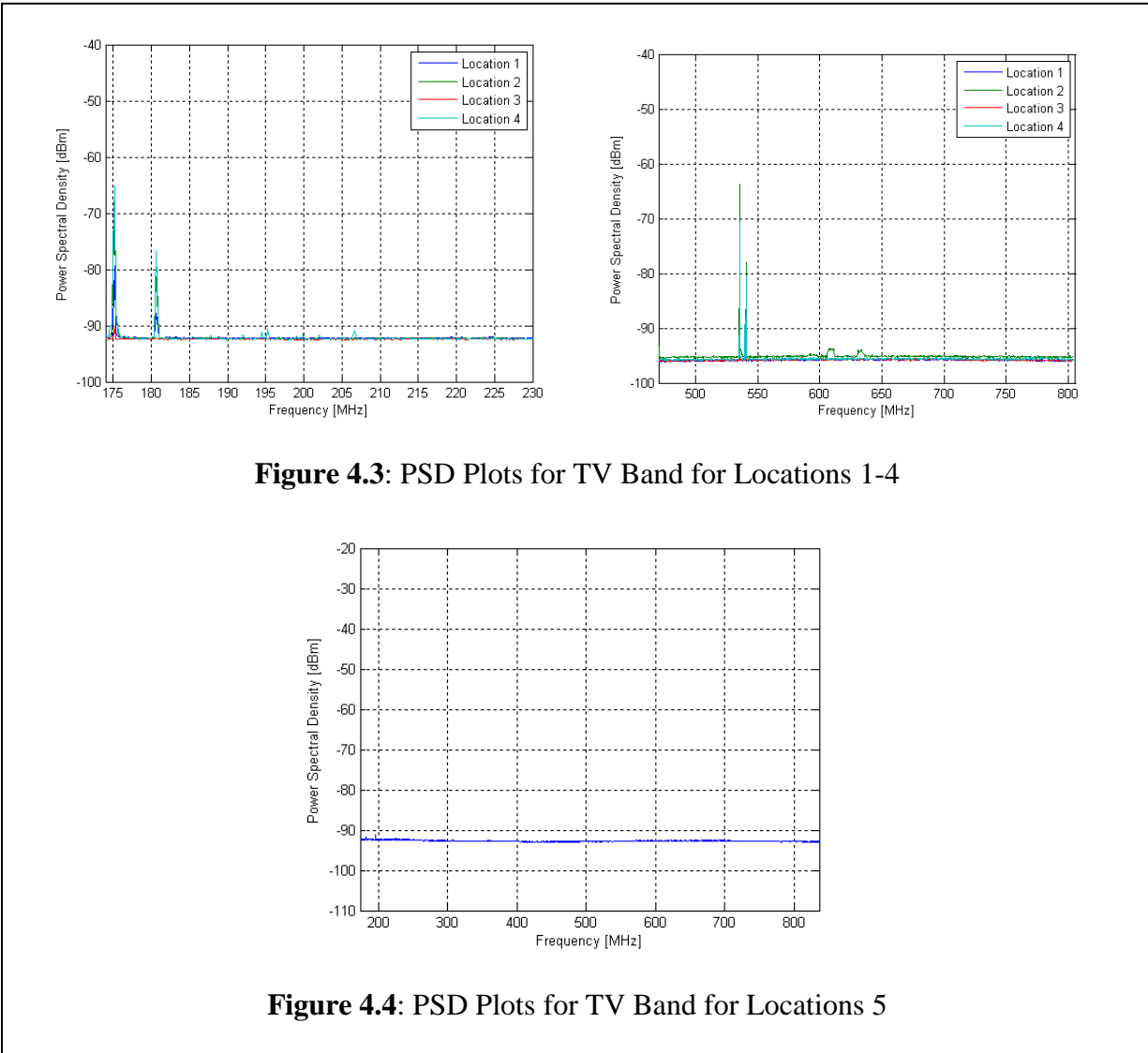
4.2.3 Measurement Locations

The measurements have been taken at five different locations listed in table 4.3 since the availability of the bands need to be evaluated spatially. First four locations are in Pune city and the fifth location is near Navi Mumbai at Kumbhivali village which is 90 KM away from Pune city. The measurement location is 15 KM away from Khopoli town in which a Low Power TV Transmitter is operating. The measurement performed at the roof top of Sinhgad Academy of Engineering, Kondhwa (location 1) for 24 hours to estimate spectrum occupancy. The terrestrial mode TV transmission by Doordarshan in India is from 5.30 AM to midnight which shows activity in TV band is more static. As the activity in TV band is more static i.e. there is no transmission in periods during the night so we have conducted measurements for few hours' at other locations.

4.2.4 Spectrum Occupancy Results

Spectrum occupancy, also referred to as duty cycle, shows at what degree the frequency band is occupied over the observation period. The average spectrum occupancy evaluated for VHF band (174-230 MHz) is 3.55%, and 7.22% for UHF band (470-806 MHz) for location 1. The measurement results for location 5 depicted in figure 4.4 shows absence of TV signal at measurement location. So the TV band occupancy found in village location is 0 %. The result shows the TV band is underutilized and usage pattern is different for suburban and village areas. Thus significant amounts of spectrum are potentially available for CR. The average PSD plots for the TV bands for first four locations are shown in figure 4.3. The PSD plots show the TV channel CH-5 (174-181 MHz), and CH 29 (534-542 MHz) are operating at measurement locations 1-4. The other TV channels are geographically unused in coverage range of Pune city TV transmitter. For efficient use of TV broadcast spectrum certain regulatory reforms are

essential. The required regulatory measures can include spectrum rearming of TV broadcast spectrum; to adapt spectrum efficient technology and allow the licensed TV band for secondary use.



4.3 Cognitive Access to TVWS in India

Few TV channels cannot be used by TV stations in given geographical region after digital switchover since it can cause interference to adjacent or co-channel TV stations. These vacant channels can be used by low power unlicensed devices without causing interference to adjacent or channel stations. The unused TV frequencies are known as TV white spaces (TVWS). The TV broadcast spectrum is licensed spectrum, which is traditionally been used exclusively by licensed

television broadcasters. However, regulatory rules don't allow the use of unlicensed devices in the TV bands, with the exception of remote control, medical telemetry devices and wireless microphones. The TVWS can be allowed for cognitive operation without causing harmful interference to the licensed users in TV band including wireless microphones. The introduction of CR in the telecommunication market may require new regulations or changes to the way of spectrum that is to be licensed and the conditions under which it can be used. According to one study, the economic potential for the TVWSs was estimated at \$100 billion [79].

Table 4.4: Incumbent and Adjacent Wireless Services of 470 -698 MHz Band [53]

Frequency band	Allocation to services/India Remarks
450.5-457.5 MHz paired with 460.5-467.5 MHz	The requirement of IMT applications in the frequency band may be considered for coordination on a case-by-case basis subject to its availability.
440-470 MHz	Public protection and disaster relief (PPDR)
470-585 MHz	Broadcasting
470-520 MHz and 520-585 MHz	The requirements of fixed and mobile services will be considered in the frequency band on case-by-case basis.
549.75-550.25 MHz	The frequency band is also allocated to the space operation service (space-to-Earth) on a secondary basis.
585-698 MHz	The requirement of Digital Broadcasting Services including Mobile TV may be considered in the frequency band subject to coordination on case-by-case basis.
608-614 MHz	The band is allocated to the radio astronomy service on a primary basis.
698-806 MHz	The requirement for IMT and Broadband Wireless Access may be considered in the frequency band subject to coordination on a case-by-case basis.

In India, TV bands are currently licensed band, hence regulatory norms doesn't allow any unlicensed user to access those. The use of TV white spaces may be allowed in future for CR operation in India. A proposal has been submitted to Wireless Planning and Coordination (WPC) Wing about TV white spaces for the revision of the national frequency allocation plan. The proposal recommends that the frequency band 470 – 685 MHz may be considered for lightly licensed operations [80]. This move will make most efficient use of TV white space spectrum in India in addition, offering tremendous benefits to the Indian industry and end users alike.

The technical and regulatory requirements can be derived for CR operation in white spaces of TV band for India based on existing requirements of other regions. For this, we need to consider the analog and digital terrestrial TV broadcasting with many channels in operation. The frequency band 470-698 MHz can be considered for the unlicensed operation provided that no harmful interference to incumbent and adjacent services from the unlicensed devices. The table 4.4 shows the incumbent and adjacent services for the TV white space band 470-698 MHz according to national frequency allocation plan-2011. To define the technical and operational requirements for the possible CR operation in white spaces require compatibility studies of protection of incumbent radio services authorized for operation on a given band with a regulatory priority. There is no as such compatibility study conducted in India. The primary users operating in this band in India and other geographies such as US and Europe are similar. So we recommend the harmonization of spectrum rules with these regions. The rules for protecting the TV broadcasting services in Europe can be used as guideline since India using same DVB-T standard as used in Europe. Since simulcast of analogue and digital transmission will continue till analog switch off we have to consider protection for DAB-T TV and PAL TV systems. Also a quantitative analysis of TVWSs availability for CR access in India is required. Rural Broadband is one of the scenarios for opportunistic access enabled by cognitive radio which is the most suitable option for rural India.

4.4 Existing requirements for cognitive access to TVWSs in Europe and USA

The unlicensed access of TVWS has been allowed in USA by FCC. Ofcom is also considering the same in UK. The European Conference of Postal and Telecommunications Administrations (CEPT) have come out with the detailed report on technical and operational requirements for

cognitive radio operation in White spaces for Europe region [89]. We introduce these requirements in the next section.

4.4.1 Requirements for the Europe region

The CEPT is a coordinating body for European state Telecommunications and postal organizations. CEPT's activities included co-operation on commercial, operational, regulatory and technical standardization issues. Electronic Communications Committee (ECC) is one of the sections of CEPT. The ECC considers and develops policies on electronic communications activities in European context, taking account of European and international legislations and regulations. The ECC report 24 provides technical and operational requirements for Cognitive Radio Systems in the white spaces of the frequency band of 470-790 MHz in order to ensure protection of the incumbent radio services. The definition of cognitive radio, white space and white space device considered for the study are given below.

Cognitive Radio System

The definition from ITU-R Report SM.2152 [18]:

Cognitive radio system (CRS): A radio system employing technology that allows the system to obtain knowledge of its operational and geographical environment, established policies and its internal state; to dynamically and autonomously adjust its operational parameters and protocols according to its obtained knowledge in order to achieve predefined objectives; and to learn from the results obtained.

White Space

According to CEPT report for definition of white space [134]:

‘White Space’ is a label indicating a part of the spectrum, which is available for a Radio communication application (service, system) at a given time in a given geographical area on a non-interfering / non-protected basis with regard to other services with a higher priority on a national basis.

White space device

White space devices (WSDs) are devices that can use white space spectrum without causing harmful interference to protected services by employing required cognitive capabilities.

Incumbent wireless services

The incumbent wireless services vary according to national administration of the country. The Band 470 – 790 MHz where potential TVWS may exist is currently used by several applications in Europe. The main usage is Digital terrestrial television based on DVB-T standard. The incumbent radio services/systems authorized for operation on a given frequency band with a regulatory priority include:

1. Terrestrial Broadcasting Service (BS) including DVB-T in particular.
2. Program Making and Special Event (PMSE) systems including radio microphones in particular.
3. Radio Astronomy Service (RAS) in the 608-614 MHz band.
4. Aeronautical Radio Navigation Service (ARNS) in the 645–790 MHz band.
5. Mobile Service (MS) below 470 MHz and above 790 MHz.

The three broad categories of WSDs are presumed: Personal/portable, home/office devices and private and public access points. The radiation power level would depend on the applications. Short range wireless service application by WSDs is likely to use power levels 10 mW to around 50 mW. The longer range communications are likely to use powers levels 1 to 10 W. The technology to be used by the WSD is considered to be from OFDM family because of it offer most efficient and reliable transmission. The in band power limit and out of block limit are the two important parameters of WSD which require careful estimation since it decides interference to protected services.

In-block power limit: When a WSD is operating within a vacant channel; the in-block power limit determines how much power can be emitted within the bandwidth of this particular channel. When a channel adjacent to the vacant channel is occupied by a protected service, then the in-band power limit may be linked to the level of the signal(s) in the adjacent channels.

Out of block limit: This determines how much power can be tolerated in channels adjacent to the vacant channel. This limit also may be linked to whether, and where there are protected services in adjacent channels, what their signal levels are.

Bandwidth: The WSD-bandwidth within which transmission occurs determines the power density, which in turn influences the potential impact on the protected services.

Potential cognitive techniques considered for white space devices

There are three methods for ensuring that cognitive devices do not cause harmful interference to incumbent: spectrum sensing, geo-location combined with access to a database, and beacons. Currently, the database approach seems to offer the best short-term solution for incumbent detection and interference avoidance. Both in the US and UK regulatory and industry efforts are, therefore, underway to further develop the concepts, algorithms and regulatory framework necessary for this approach. In spectrum sensing, WSDs autonomously detect the presence of the protected incumbent services in each of the potentially available channels. In Geo-location technique, WSDs would determine their location and access a geo-location database to determine the TV channels that are vacant at that location. Beacons are control signals which can be used to indicate that particular channels are either in use by protected services or vacant. The use of beacons as a cognitive technique for the operation of WSDs in the 470-790 MHz is not considered in CEPT report. The three techniques are described in detail in [89].

Operational and technical requirements for white space devices in the band 470-790 MHz

Emission limits

The two main approaches with WSD emission limits are considered:

Location specific output power: The allowed output power can be determined for each location, frequency and device type/class within the database. Such an approach requires the use of geo-location. An upper limit of the output power for each device type/class could be defined, with the understanding that devices could operate at any power between zero and their associated upper limits;

Fixed output power: There may be a few device types (such as portable and fixed) for which the key main characteristics are predefined, and certain fixed output power limits are allowed for them to be used outside the protected areas. The limits may be different for use of adjacent channels and for other channels. This approach has currently been chosen by the FCC. In this case the specific device types and associated e.i.r.p. should be defined.

The complexity of a WSD and the system may increase in the location specific output power approach due to the considerable amount of calculations to be performed by the database and somewhat increased amount of information to be passed between the WSD and a geo-

location database. The location specific output power approach may allow higher WSD output power than in the fixed output power approach in places where it is possible from the protection point of view. Thus location specific output power approach may be useful for deployments in the rural areas. In the restricted transmission area of fixed output power approach, WSD's with location specific output power approach may be allowed for lower power. Thus the use of location specific output power approach offers more efficient use of the spectrum.

The positive aspect of fixed output power approach is simpler from the device and database point of view. The negative aspect is that it is more restrictive for the devices due to rigid power limits for some location. Due to this it may restrict innovation in the new device. Thus the location specific output power seems to be better from spectrum utilization view though it is complex.

Sensing Challenges

The designing of sensing detectors into WSD has some practical challenges. The required tuning range would have to be very wide if the WSD is designed to operate over the full UHF-band. The attached antenna would have to support the same frequency range. This will result in low antenna efficiency, possibly in the order of -10 dBi. Such an antenna practically would have certain directivity, rather than being ideally Omni directional.

The personal/portable WSD will probably include several radio Rx/Tx systems as well as high processing power, memories and displays etc. components. The wide band noise generated due to the high speed clocks and buses in the device electronics will interfere the operation typically at the frequencies of interest for WSD. The sensing receiver with high sensitivity will pick up the noise from the built in antenna. The shielding will minimize the problem but effective shielding for the whole TV white space frequency band will be very challenging. State-of-the-art implementation of devices can decrease the noise level. Other factors which will be responsible for decreasing the sensing sensitivity of such device are self generated noise and manmade noise. Man made noise affects all types of WSD. Another challenge is that the detector may have to operate in the presence of very strong broadcasting signals from the near-by transmitters, while still trying to detect a more distant transmitter at very low level. This sets high linearity requirements to the RF-part of the sensing receiver.

Different algorithms are needed for sensing a PMSE signal since it is very different from sensing of DTT signals.

The practical sensing device implementations in personal/portable WSD may have a reduced sensitivity in the order of tens of dB.

It has shown that sensing only will not provide adequate protection to the broadcasting service, taking into account current technologies. This means that there is a need to employ geo-location with access to database. If the geo-location in connection with access to database approach can provide sufficient protection to the broadcast service then the sensing should not be a requirement. Further consideration is required for assessing the potential benefit of using sensing in addition to the geo-location database. In case of implementation of sensing, testing procedures would need to be developed by standardization bodies to assess the reliability and the efficiency of the sensing device. Continuous updating in sensing algorithm will be required to protect emerging DTT and PMSE systems. This may raise some legacy issues.

Requirements for the geo-location database approach

In this approach, cognitive devices determine their location and get information from database about the frequencies which they can use at their location. They are not allowed for transmission till they have successfully determined from the database in which frequencies with which power levels, they are allowed to transmit in the indicated location. The approach is based on a certain accuracy of the position determination by the WSD and the guarantee that this accuracy will be maintained while the WSD is in operation. When a WSD operates in indoor then the reliable position determination is required because any malfunctions of this position determination may have a severe impact on those services which have to be protected by the WSD Master/slave architecture is proposed for WSD deployment. It identifies the information which needs to be communicated by the WSD to the geo-location database and vice-versa. In response to the information received WSD, the database will provide the list of allowed frequencies and their associated maximum transmit powers to the WSD. A general methodology is to be followed by national administration for the input/output translation process. The example algorithms are such that administrations can adapt the framework to their national circumstances (e.g. national DTV planning model, specific national quality requirements, etc.). The algorithms and underlying modeling assumptions should be chosen very carefully since it affects the protection to the

incumbent services. Several options for the management of a geo-location database including the decision for a database at a national or European level, one or various databases, public or closed database, are presented in [89].

4.4.2 FCC requirements for unlicensed operation in TV band

The unlicensed access to vacant Television (TV) white spaces has been considered first in the USA. Earlier Spectrum Policy Task Force (SPTF) has recommended increasing the amount of unlicensed spectrum to promote spectrum access by [5]. The first measurements showed that the TV bands are underutilized in space and time and significant amount of capacity is unused. FCC published a notice of proposed rulemaking and requested comments on the unlicensed operation of White Space Devices (WSDs) in TV bands in 2004 [81]. In subsequent studies have acknowledged that considerable amount of TV white spaces exists [82, 83]. Broadband Internet access has been identified as one of the potential application due to excellent propagation characteristics of frequencies in the TV bands. In addition to this application, home networking and multimedia streaming applications have been discussed. The efforts for commercial exploitation of TV white spaces have started by different industry consortium, such as the White Spaces Coalition or the Wireless Innovation Alliance [84]. The incumbent services in TV bands in the USA are TV broadcastings, wireless microphones and few services such as offshore radio telephony services. The types of transmitter operating are: Advanced Television Systems Committee (ATSC) standard, the American equivalent to Digital Video Broadcasting - Terrestrial (DVB-T), and National Television System Committee (NTSC) standard. Wireless microphones are allowed to use vacant TV channels [85].

Three different techniques have been proposed in the initial notice of proposed rulemaking. First, WSDs may know about their Geolocation by means of positioning techniques, such as Global Positioning System (GPS), and retrieve the list of available TV channels from a centrally hosted database. Second, WSD's may perform spectrum sensing in order to identify any active PU in the surroundings. Third, PU may transmit the information on available TV channels. The first two options have been investigated in greater detail. The third option has not been explored in greater detail. According to the coordinates communicated by the WSD to the database, the database determines the available channels and maximum Effective Isotropic Radiated Power (EIRP) for the requested location. FCC has developed many test systems for

testing the WSDs and research purpose. To assess WSDs performance in terms of the probability of PU detection failures and subsequent harmful interference to the primary service, FCC has conducted two extensive test series in order. All sensing based WSDs failed to pass all defined tests in the first test round [86]. Also, WSDs based on spectrum sensing couldn't go through the test in the second round. Though some of the finest spectrum sensing devices have passed nearly all tests but remains vulnerable in few specific scenarios [87]. The prototype WSD based on the database have passed all FCC tests successfully. FCC has adopted rules to allow unlicensed radio transmitters to operate in the broadcast television spectrum at locations where that spectrum is not being used by licensed services which are described in [61]. These rules require WSDs to rely on a geolocation database. However, the FCC has not said full stop for the spectrum sensing option. It has been kept wide open for further testing and extension of the rules. Interested parties may submit further prototypes for evaluation and certification. Further FCC has modified the rules in certain respects which are described in [73]. The modified rules are (1) increasing the maximum height above average terrain (HAAT) for sites where fixed devices may operate; (2) modifying the adjacent channel emission limits to specify fixed rather than relative levels; and (3) slightly increasing the maximum permissible power spectral density (PSD) for each category of TV bands device. Spectrum Bridge's TV White Spaces Database System is the first FCC approved TV white space database system. Recently, FCC announced opening of Public Testing for Google Inc.'s TV Band Database System and Key Bridge Global LLC's TV Band Database System [88].

Summary of the existing requirements

We here briefs the major requirements for the operation unlicensed devices in TV white spaces. The unlicensed devices permitted to operate in the broadcast television frequency bands at 54-60 MHz, 76 - 88 MHz, 174 - 216 MHz, 470 - 608 MHz and 614 - 698 MHz bands. The two device categories to operate in the TV white spaces on an unlicensed basis are fixed and personal/portable devices. The channels in which these two types of unlicensed devices can operate are also specified. The devices will be required to identify unused channels as follows:

- a) A fixed device must employ both geo-location/database access and spectrum sensing capabilities that enable the device to listen for and identify the presence of signals from other transmitters;

- b) A personal/portable device must either (1) be under the control of a fixed device or a personal/portable device that employs Geolocation /database access and spectrum sensing or (2) employ geo-location/database access and spectrum sensing itself.

Personal/portable devices will be allowed to communicate with fixed devices and with other personal/portable devices. These devices will be allowed to operate in two different modes: (1) Mode I - client, whereby a personal/portable device is controlled by a fixed or a personal/portable device operating in Mode II that has determined the available channels in the area and/or (2) Mode II - independent, whereby a personal/portable device determines the available channels using its own internal geo-location/database access capabilities.

All devices, except personal/portable devices operating in client mode, must include a geolocation capability and provisions to access over the Internet a database of protected radio services and the locations and channels that may be used by the unlicensed devices at each location. Fixed and personal/portable devices must also have a capability to sense TV broadcasting and wireless microphone signals as a further means to minimize potential interference. However for TV broadcasting the database will be the controlling mechanism.

Requirements for unlicensed operation in TV white spaces

The technical requirements are divided in two general categories. The first consists of transmission system characteristics, including the transmitter power, antenna characteristics and out-of-band emission limits. The second category consists of specific standards and requirements for the procedures to be used to enable unlicensed TV band devices to use the TV white space without causing interference to TV and other authorized services.

The transmit power limit for TVBDs

1. Fixed devices permitted to operate on any channel between 2 and 51, except channels 3, 4 and 37. For fixed TVBDs, the maximum transmit power limit over the TV channel of operation is one watt. Transmitter power will be measured at the antenna input to account for any cable losses between the transmitter and the antenna. If transmitting antennas of directional gain greater than 6 dBi are used, the maximum conducted output power shall be reduced by the amount in dB that the directional gain of the antenna exceeds 6 dBi.

2. Personal portable devices may operate on any unoccupied channel between 21 and 51, except channel 37. Personal portable devices may operate at up to 100 milliwatts of power, except that operation on adjacent channels will be limited to 40 milliwatts.
3. The transmit power control is required to use optimum power for successful communication. TVBDs shall incorporate transmit power control to limit their operating power to the minimum necessary for successful communication.
4. Maximum conducted output power is the total transmit power in the entire emission bandwidth delivered to all antennas and antenna elements averaged across all symbols in the signaling alphabet when the transmitter is operating at its maximum power control level.
5. The power spectral density from the TVBD shall not be greater than the following values when measured in any 100 kHz band during any time interval of continuous transmission.
 - Fixed devices: 12.6 dBm conducted power. If transmitting antennas of directional gain greater than 6 dBi are used, this conducted power level shall be reduced by the amount in dB that the directional gain of the antenna exceeds 6 dBi.
 - Personal/portable device operating adjacent to occupied TV channels: -1.4 dBm EIRP.
 - Sensing-only devices: -0.4 dBm EIRP.
 - All other personal/portable devices: 2.6 dBm EIRP.

Antenna requirements

1. For personal/portable TVBDs, the antenna shall be permanently attached.
2. The transmit antenna used with fixed devices may not be more than 30 meters above the ground. In addition, fixed devices may not be located at sites where the antenna height above average terrain is more than 250 meters.

Out of band emission limits

- (1) In the television channels immediately adjacent to the channel in which the TVBD is operating, emissions from the TVBD shall not exceed the following levels.
- Fixed devices: -42.8 dBm conducted power.
 - Personal/portable device operating adjacent to occupied TV channels: -56.8 dBm EIRP.
 - Sensing-only devices: -55.8 dBm EIRP.
 - All other personal/portable devices: -52.8 dBm EIRP.

(2) Emission measurements in the adjacent channels shall be performed using a minimum resolution bandwidth of 100 kHz with an average detector. A narrower resolution bandwidth may be employed near the band edge, when necessary, provided the measured energy is integrated to show the total power over 100 kHz.

Television channel availability for a TVBD is determined based on either the geo-location and database access mechanism or spectrum sensing.

- a) A TVBD should provide protection for the following authorized services: digital television stations, and digital and analog Class A, low power, translator and booster stations; translator receive; fixed broadcast auxiliary service links; private land mobile service/commercial radio service (PLMRS/CMRS) operations; offshore radiotelephone service; and cable system head-ends. In addition, protection shall be provided in border areas near Canada and Mexico.
- b) Geolocation and database access
 - Fixed and Mode II personal/portable device shall incorporate a geo-location capability to determine its geographic coordinates to an accuracy of +/- 50 meters.
 - Fixed and Mode II personal/portable devices must access a TV bands database over the Internet to determine the TV channels that are available at their geographic coordinates prior to their initial service transmission at a given location.
- c) Spectrum sensing Detection threshold
 - All fixed and personal/portable TVBDs must be capable of detecting ATSC digital TV, NTSC analog TV and wireless microphone signals using analog or digital modulation methods. The required detection thresholds are.
 - ATSC signals: -114 dBm, averaged over a 6 MHz bandwidth;
 - NTSC signals: -114 dBm, averaged over a 100 kHz bandwidth;
 - Wireless microphone signals: -114 dBm, averaged over a 200 kHz bandwidth
 - The detection thresholds are referenced to an Omni-directional receive antenna with a gain of 0 dBi. If a receive antenna with a minimum directional gain of less than 0 dBi is used, the detection threshold shall be reduced by the amount in dB that the minimum directional gain of the antenna is less than 0 dBi.

- Low power auxiliary device may start operating on a TV channel if no wireless microphone or other low power auxiliary device signals above the detection threshold are detected within a minimum time interval of 30 seconds.
 - A TVBD is required to check for TV signals for a minimum time interval of 30 seconds.
 - A TVBD must perform in-service monitoring of an operating channel a minimum of once every 60 seconds.
 - After a wireless microphone or other low power auxiliary device signal is detected on a TVBD operating channel, all transmissions by the TVBD must cease within two seconds.
- d) A TVBD must incorporate the capability to display a list of identified available channels and its operating channels.
- e) Fixed TVBDs shall transmit identifying information. The identification signal must conform to a standard established by a recognized industry standards setting organization. The identification signal shall carry sufficient information to identify the device and its geographic coordinates.

4.5 Proposal on Requirements for CR Operation in TV White Spaces in India

The successful CR operation in white spaces greatly depends on the reliable information of unoccupied channels and the no harmful interference to the protected services from unlicensed devices. To derive the requirements for CR operation in specific band needs to consider mainly following:

- Cognitive device categories such as personal/portable, home/office, private and public access points
- Deployment scenarios
- Radiation characteristics of Cognitive device
- Potential cognitive techniques for Cognitive device
- Protection to incumbent radio services

The technical and regulatory requirements based on study of literature regarding the unlicensed operation in TV band are discussed in the next section. The requirements in Europe region is taken as guideline since India using same DVB-T standards as used in Europe.

A. Technical Requirements

The technical requirements are divided in two general categories. The first consists of transmission system characteristics, including the transmitter power, antenna characteristics and out-of-band emission limits. The second category consists of specific standards and requirements for the procedures to be used to enable unlicensed TV band devices to use the TV white space without causing interference to TV and other authorized services.

Emission Characteristics The interference to the protected services is possible from the emission from the white space devices, so the selections of emission parameters are crucial for the success of Cognitive radio in White spaces. The emitted power should not provide harmful interference to protected services, co-channel and any adjacent channel. The emission parameters are directly linked with the technology to be used by services. We expect WSDs to use variants of OFDM technology since it currently represent the most efficient and reliable transmission. The radiated power levels are depending on the use case. From the literature it is found that the short distance communications by WSDs are probably to use power levels between 10 mW to around 50 mW and the long distance communication are probable to use power levels between 1W to 10 W. The transmit power limit will also depend on the device category fixed or portable. The in band and out band emission limits and protection distance be specified as per the device category because outdoor devices will have greater interference potential than WSDs that are intended to be operated indoors. We recommend transmit power control in technical requirements to avoid using power more than necessary for a given communication. It is the best spectrum management practice which encourages efficient use of resource. The white space devices should limit the transmit power to bare minimum necessary for successful communication. The emission of the WSD will also interfere in the channels adjacent in which the WSD is operating. It is necessary to limit the out of band emission from WSDs.

Antenna Characteristics If the WSD is designed to operate over the full UHF-band, then the WSD antenna would have to support the same frequency range. This will result in low antenna efficiency, possibly in the order of -10 dBi. Furthermore, it can be expected that such an antenna would have certain directivity, instead of being ideally Omni-directional. Antenna gain and polarization are crucial in defining the detection threshold. Generally the detection thresholds are referenced to an Omni-directional receive antenna with a gain of 0 dBi. If a receive antenna with

a minimum directional gain of less than 0 dBi is used, then detection threshold has to be reduced by the amount in dB that the minimum directional gain of the antenna is less than 0 dBi. Antenna height is another important parameter since it affects WSD's signal coverage and the distance at which it could cause interference to other RF operations in the TV bands services. According to literature, we found for the fixed devices the recommended height of antenna at least 10 m with maximum height of 30 m.

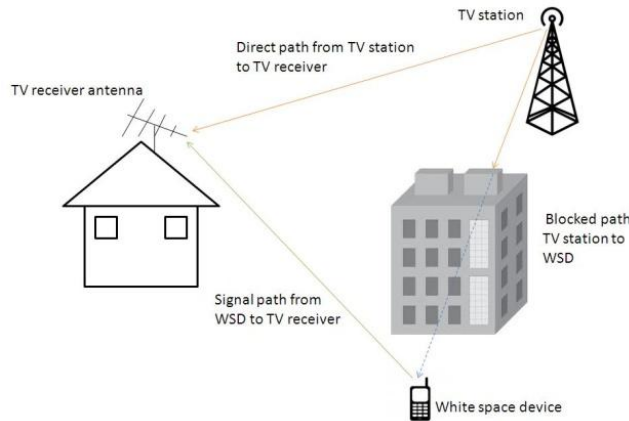


Figure 4.5: Hidden Node Problem

There are three cognitive techniques currently proposed to help the WSDs in finding the vacant channels: spectrum sensing; Geolocation database and beacons.

Spectrum Sensing

In spectrum sensing, WSDs autonomously detect the presence of the protected incumbent services in each of the potentially available channels. When a channel is determined to be vacant, sensing might also be applied to adjacent channels to determine what constraints there might be on transmission power, if any. Some channels, which are used for Radio Astronomy, should be precluded from WSD sensing since the services cannot be protected by sensing. If the characteristics of the signal protected services are known, then the sensitivity can be enhanced. Autonomous spectrum sensing does not require any existing local infrastructure, such as connection to a database. The sensing techniques are useful where internet access is more limited. It is also useful when WSDs are used to provide only local connectivity between multiple devices, without requiring access to the Internet. The sensing threshold is crucial to determine the potential end users.

The low threshold to protect the existing services may reduce the number of detected channels. Sensing can be subject to the hidden node problem, which is depicted in figure 4.5. This problem can arise when there is a blockage between the WSD and a TV station, but no blockage between the TV station and a TV receiver antenna and no blockage between the WSD and the same TV receiver antenna. In such a case, a WSD may not detect the presence of the TV signal and could start using an occupied channel, causing harmful interference to the TV receiver. The cooperative sensing can solve the hidden node problem by sharing measurement information of WSDs to determine the presence of protected services.

Key parameters for spectrum sensing include:

- Sensing threshold
- Periodicity of re-sensing on channels that have been detected as vacant
- Sampling duration

Feature detection method for sensing offer less possibility of false alarms than energy detection method. But it has the drawback of dependency on the specific feature which limits its utility for the new radio system in TV band.

Geo-location

In this technique, WSDs would determine their location and accesses a geo-location database to determine the TV channels that are vacant at that location. The essential parameters of this technique are location accuracy, frequency of database enquiry and quality of the database. WSDs are not allowed to transmit until they have successfully determined from the database which channels, if any, are available in their location. The initial access to the database is not done on white space frequencies but by some other means. In some cases, for example if a WSD is connected to an access point, one WSD may act as a proxy for the database queries for another WSD or a set of other WSDs. The querying WSD would be called the master WSD and the WSD(s) it does the query for would be called slave WSD(s). In this case the master WSD would have to ensure in an appropriate way that the slave WSDs operate according to the constraints returned by the database. Depending on the particular implementation this may require that the master WSD has some form of control over the operation of the slave WSDs. In the case where there are several access points available that are connected to each other by some means (e.g. a core network or a distribution system), triangulation or some other network based positioning

method can be used to measure the WSD location. This measured position may be used by the WSD, or by an access point (e.g. a master WSD), to query the database for the available radio channels, bandwidths and corresponding maximum transmit powers. Using the geo-location approach would require that the WSD has valid information about the available channels, either by including the time validity of the received information or by requiring sufficiently frequent re-consultation with the database.

Beacons

Beacons are control 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 lower threshold values. The interference protection provided to licensed users comes at a cost in spectrum capacity as well as the cost of purchasing and operating the beacons.

According to literature survey, the sensing only will not provide adequate protection to the broadcasting service, taking into account current technologies. The Geolocation database approach is the most viable option to protect the incumbent services. The combined sensing and geo-location approach, where applicable, may have the advantage of reducing the risk of interference compared to sensing or geo-location, only. However, there is a need of detail study of the combined approach. The combined approach may provide a better protection of incumbent use systems from WSD emissions. We suggest the Geolocation white space database (GWSDB) approach for protection of incumbent services. A master slave architecture discussed earlier can be considered for the deployment of WSDs.

B. Regulatory Requirements

The following terminology may be used in the unlicensed operation in TV white spaces with geolocation database.

Terminology

White space frequency band: 470-698 MHz

TV white space device (WSD): A radio instrument that operate in the white spaces frequency band of the 470-698 MHz.

White space: A part of the spectrum, which is available for a Radio communication application (service, system) at a given time in a given geographical area on a non-interfering / non-protected basis with regard to other services with a higher priority on a national basis.

Geolocation White space database (GWSDB): A Database systems that provide information to WSDs on the available frequencies and allowed transmit power levels at specific geographic locations. This data base based on white space data provided regulatory body.

Geo-location capability: Capability of a WSD to determine its geographic latitude and longitude coordinates.

Master WSD: A WSD which directly communicates with a GWSDB to obtain operating parameters specific to its geographic location.

Slave WSD: A WSD which does not directly communicate with a GWSDB, and which obtains operating parameters specific to its geographic location from its serving master WSD.

Fixed WSD: A WSD whose antennas are permanently mounted on a non-moving platform (e.g., fixed base station, fixed consumer premises equipment, home router. A fixed WSD can be a master or a slave device.

Portable/mobile WSD – A WSD whose antennas are mounted on a portable/mobile platform. A portable/mobile WSD can be a master or a slave device.

Indoor WSD: A WSD whose antennas are located within a building.

Outdoor WSD: A WSD whose antennas are not located within a building.

In-band emissions: Emissions corresponding to those segments of a radiated signal's frequency spectrum which carry information intended for a receiver. The width of the in-block segment of the frequency spectrum is the nominal bandwidth of the signal. Emissions are specified here as equivalent isotropic radiated power (EIRP).

Out-of-band emissions: Emissions corresponding to those segments of a radiated signal's frequency spectrum (outside the in-block segment) which correspond to unintended radiations. Emissions are to be specified as equivalent isotropic radiated power (EIRP).

4.6 CR/TVWS Standardization Activities

The research and development on CR has been so far mainly focused in the USA and Europe. There are a lot of ongoing standardization activities related to cognitive access to TVWS. The major CR/TVWS standardization activities are discussed below.

IEEE 802.11af White Fi:

IEEE 802.11af [90] is the one of the standardization activities for cognitive access in TVWS. IEEE 802.11af task group was formed in 2009 under IEEE 802.11 working group. The objective is to define modifications to both the 802.11 physical layers (PHY) and Medium Access Control Layer (MAC) to meet the legal requirements for channel access and coexistence in the TVWS. Also use of OFDM PHYs with 5, 10, and 20 MHz channel widths to specify the basis for a system that the regulators can approve for operation in TVWS band. The 802.11af has been closely following various regulations in order to prompt the Wi-Fi technologies in TVWS worldwide. It is widely considered as one of the most promising technologies for the TVWS. In September 2012, the 802.11af released its first stable draft standard (Draft 2.0). IEEE SA sponsor ballots is planned to start from July 2013. The review committee and standards board final or continuous process approval is planned for June 2014.

IEEE 802.22 WRAN:

The IEEE 802.22 standard is developed for Wireless Regional Area Networks (WRANs) using TVWS and published as an Official IEEE Standard on July 2011. It is the first standard that focuses on licensed-exempt broadband wireless access to rural areas on non interference basis in TVWS, thus helping to bridge the digital divide. The IEEE 802.22 standard takes the benefit of the excellent propagation characteristics of the VHF and UHF TV bands to provide broadband wireless access up to maximum 100 KM from transmitter [91]. Each WRAN will deliver up to 22 Mbps per channel without interfering with reception of existing TV broadcast stations, using the so-called white spaces between the occupied TV channels. This technology is especially useful for serving less densely populated areas, such as rural areas, and developing countries where most vacant TV channels can be found. The IEEE 802.22 Working Group has defined an air interface (PHY and MAC) standard based on CR techniques. IEEE 802.22 incorporates advanced CR capabilities including dynamic spectrum access, incumbent database access,

accurate geolocation techniques, spectrum sensing, regulatory domain dependent policies, spectrum etiquette, and coexistence for optimal use of the available spectrum.

IEEE 802.19:

IEEE 802.19 develops standards for coexistence between wireless standards of unlicensed devices. The purpose of the standard is to enable the family of IEEE 802 Wireless Standards to most effectively use TV White Space by providing standard coexistence methods among dissimilar or independently operated TV band device (TVBD) networks and dissimilar TVBDs [92]. This standard addresses coexistence for IEEE 802 networks and devices and will also be useful for non IEEE 802 networks and TVBDs. The draft is expected to be submitted to sponsor ballot in September 2013 and final approval is due in October 2014.

4.7 Wireless Broadband Connectivity for Rural India in TVWS

According to latest census of year 2011 nearly 70% of the India's population lives in the rural areas, and the agriculture is the main source of income for majority of the rural population. The overall urban teledensity in India is 148.46%, and rural teledensity 40.07% which is quite low. There is a strong need of broadband services in rural part of India which can improve people lives by an affordable access to information, and knowledge. Recognizing the significance of broadband connectivity as a tool for empowering India's rural masses, the government of India had launched the National Optical Fiber Network (NOFN) project to provide broadband to all Gram Panchayats (GP) [93]. In India, GP (i.e. villages above population 10000) is village council, a basic administrative unit in villages [94]. The project aims to extend the existing optical fiber network (OFN), which is available up to district, and block levels, to the gram panchayat level, by utilizing \$ 4 billion, which will help in offering governance, banking, and health services online. The guaranteed bandwidth through this project is 100 Mbps at GP. This unique project (NOFN) will usher a new era in telecommunications by establishing information highways across the whole length and breadth of India, particularly in the rural areas. Table 5.5 gives the organization of villages into GPs in India.

The wireless broadband connectivity to the rural population living small villages (with no GP) where no point of presence (PoP) of OFN is remains unsolved. We propose wireless broadband network using cognitive access to TVWSs for the smaller villages around the GP.

Figure 4.6 shows the reach of OFN from Block level to GP. The TVWS link provides the last mile connectivity to small villages.

Table 4.5: Organization of Villages into GPs

Number of villages	6,38,619
Number of Gram Panchayats	2,50,000
Number of Blocks	6,382
Number of Districts	640
Average Number of GPs per District	390
Average Number of GPs per Block	40
Average Number of villages per GP	3

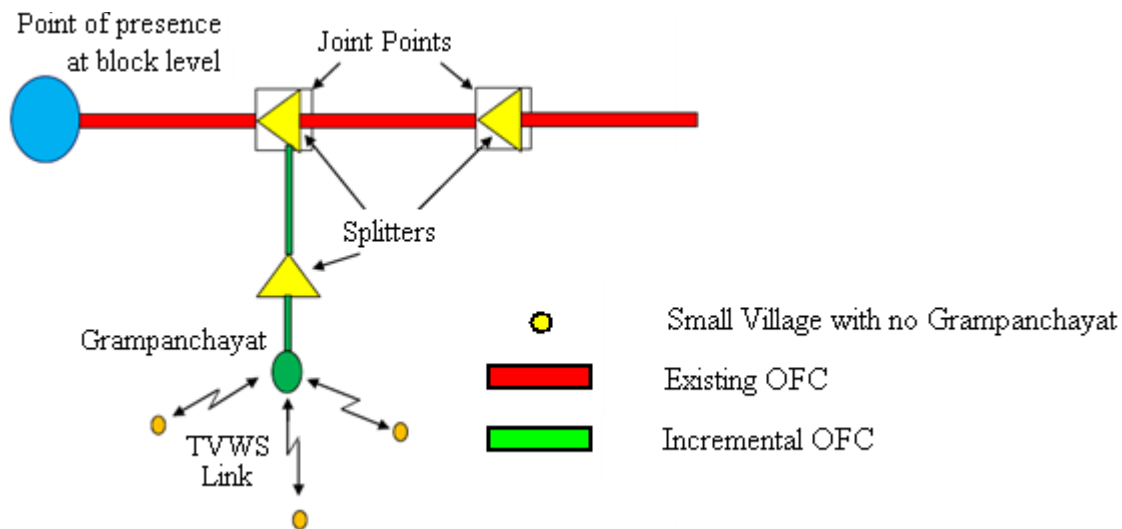


Figure 4.6: Wireless Broadband Connectivity to Small Villages

4.8 Implications of Cognitive Radio on Spectrum Regulation in India

Spectrum management is an area in which economic and policy considerations play an important role for both the allocation and the assignment of radio spectrum. Allocation is the distribution of radio spectrum to particular radio services, and assignment is the distribution of radio spectrum to specific radio stations. The implications of technology trends must be seen in the context of the ongoing liberalization and market orientation of frequency management [95].

Cognitive Radio makes spectrum use more flexible. The radio's spectrum usage, as well as the type of service that the radio is supposed to deliver, are not fixed during manufacturing at

the factory, but can be dynamically altered, with a varying degree of user intervention. This flexibility enables a much more efficient use of the available radio spectrum. Current spectrum regulations must find a way to deal with this flexibility appropriately, making room for innovation while protecting users from harmful interference. Most current spectrum allocations are specific for one type of service (e.g., mobile wireless voice communications, or television broadcasts), one type of technology (GSM, or analogue TV), and one licensed spectrum user. The new radio technologies CR and SDR ask for a more flexible approach, one that is technology and service neutral, and allows for spectrum sharing by multiple users. The paradigm of cognitive radio and DSA will enable simpler, dynamic and efficient spectrum management of spectrum resources. With rapid development reconfigurability and cognitive capability we can see the spectrum management model based on rigidly defined frequency bands disappear together. Instead, the spectrum will be managed as a continuum-type resource whose spectrum access barrier and sharing largely self regulated by devices which are engaged, on behalf of their users, in continuous process of communication, negotiation, trading and cooperation [96]. It will be easier to introduce new applications, because there will be far less occasion to issue separate licenses.

The flexibility in spectrum utilization by Cognitive Radio technology poses a challenge to the spectrum regulator: a significant amount of control over the spectrum use is lost. The amount of parties to divide the spectrum over increases drastically: whereas first there were only network managers to divide spectrum among, now in principle each individual radio-terminal forms a party of its own as it is free to determine its own spectrum use. Also, the flexibility of hardware renders certification of device difficult.

Spectrum reallocation or refarming will become a more prominent element of spectrum management in the future. The development of new wireless service applications may create a need for freeing spectrum resources in a particular band in order to be compliant with international market standards and enable the use of mass produced wireless equipment. Regulators may need therefore to refarm current use of spectrum resources. Regulators must examine the possibilities for incorporating beneficial spectrum trading into their schemes. CR can be used to make the market for spectrum more fluid by the creation of a spot market and by creating an incentive to sell unused spectrum [97].

4.9 Conclusion

TV bands are harmonized worldwide in VHF and UHF band. The transition from analog to digital TV transmission not only frees significant amount of spectrum but also creates TV White spaces i.e. geographically the unused portions of spectrum in the TV bands. Currently TV white spaces are actively considered for the unlicensed operation. USA and UK have opened up TVWSs for unlicensed operation. In context to cognitive access to TVWSs, TV spectrum occupancy measurement campaign conducted in India. The TV spectrum occupancy measurement campaign has shown only two active analog TV channel operation in Pune city. The evaluated occupancy for VHF band (174-230 MHz) is 3.55% and 7.22% for UHF band (470-806 MHz) in Pune city. The measurement in rural area has shown zero activity in TV band. Thus significant amount of spectrum is lying vacant in TV band showing opportunity for spectrum refarming and CR operation in TVWSs. To achieve this regulatory reforms are proposed to exploit the TV band which has excellent propagation characteristic to its fullest. Due to the good propagation characteristics of TVWSs, wireless broadband Internet access has been identified as one of the possible applications. FCC has adopted rules to allow unlicensed radio transmitters to operate in the broadcast television spectrum at locations where that spectrum is not being used by licensed services. We have studied the existing technical and regulatory requirements for the cognitive radio operation in TV white spaces in other regions.

In India, the TVWSs will be available in the frequency band 470-698 MHz. The new telecom policy of India suggests the promotion of use of white spaces with low power devices, without causing harmful interference to the licensed applications in specific frequency bands by deployment of Software Defined Radios (SDRs), Cognitive Radios (CRs). As the same band is considered for CR operation in US and Europe, we recommend the harmonization of spectrum rules with these regions. We propose the rules for protecting the TV broadcasting services should be in line with Europe since India using same DVB-T standard as used in Europe. So we have proposed generic requirements for the operation of unlicensed devices in TV band. We also propose the need of compatibility studies of protection of incumbent radio services authorized for operation on a given band with a regulatory priority. Many scenarios are envisaged for opportunistic access based on cognitive radio in the TV whitespaces. Wireless broadband access using TVWSs is the most suitable scenario for empowering the rural India. All the gram

panchayats of India will get the broadband connectivity under National Optical Fiber Network (NOFN) project. We have proposed cost effective last mile connectivity to the small village population through wireless broadband network using TVWSs.

There are pros and cons of CR while considering implications on spectrum management. CR/DSA paradigm provides benefits like simpler, dynamic and efficient spectrum management, scope for innovations, easier to introduce new applications and flexible spectrum access. However, problems like interference control, hardware device certification, and hidden node problem may prevail under CR/DSA paradigm.

5

Frequency Usage and Digital Dividend in India

This chapter has addressed the problem of spectrum requirement for mobile telecommunication service in India. The measurement results for GSM bands have been presented showing heavy spectrum usage and demand for mobile services in India. Digital switchover plan and digital dividend in India is discussed. Digital dividend spectrum is proposed for the IMT advanced mobile services in the line of ITU efforts for harmonization in 698-806 MHz band. Different stakeholder's view about 700 MHz band plan of India, and the two harmonized frequency arrangement for International Mobile Telecommunications (IMT) systems agreed by Asia Pacific Telecommunity (APT) for 700 MHz band i.e. 698-806 MHz along with discussion on 700 MHz plan is presented in this chapter.

5.1 Introduction

Worldwide the terrestrial television broadcast operating in the VHF and UHF band which is precious because its ability to carry signal long distances, penetrate buildings and carry large amounts of data. Terrestrial TV broadcasters around the world are moving to digital-only platforms for bandwidth saving and improved quality. The spectrum freed up as a result of the switchover from analog to digital television transmission is referred as the digital dividend. Digital dividend is the outcome of higher spectral efficiency from DSO. The amount of spectrum to be released in the switchover depends primarily on national peculiarities such as the geography and topography of a country, the degree of penetration of cable and/or satellite television services, requirements for regional or minority television services, and spectrum usage in neighboring countries. There is debate going over the allocation of the digital dividend among different stakeholders. The national regulators can decide how and for what to use this spectrum to achieve maximum value of the digital dividend spectrum. A fragmented digital dividend spectrum is not desirable to provide a range of communications services. It is advantageous have defragmented digital dividend spectrum in higher UHF band to maximize its value to users. However, harmonizing of dividend spectrum globally is an important consideration in enhancing the potential for communications and equipment manufacturers to realize economies of scale and set lower prices for network and handset equipment, and to facilitate global roaming for users.

The focus of this chapter is digital dividend and its potential use based on the real time measurement results. In this chapter spectrum refarming of TV band in India is proposed on the basis of the frequency usage results obtained from the spectrum measurement campaigns described in previous chapters. We focus on frequency usage results in cellular band of the spectrum occupancy measurement campaign conducted at Pune, India. We have observed highest occupancy rate in 2G cellular telecom services band. This show the demand for mobile telecom services is high in India and so for the spectrum. International Telecommunication Union (ITU) has shown huge demand for the spectrum for mobile services in its future projection. There is urgent need of spectrum allocation for the cellular telecom services in India. The digital dividend spectrum allocation for mobile services is proposed in the line with ITU efforts for global frequency harmonization in the IMT-Advanced services.

5.2 Spectrum Occupancy Results of Cellular Band

This section particularly, focuses on the results of the spectrum occupancy of the GSM 900 and the GSM 1800 band of the spectrum occupancy measurement campaign. The details of the measurement campaign are described in [58]. Figure 5.1 shows the average PSD variation for the measured range revealing the higher spectral activity in the cellular communication services. The 890-960 MHz band (GSM900) and 1710-1880 MHz (GSM 1800) has been allocated for the cellular telecom services [53].

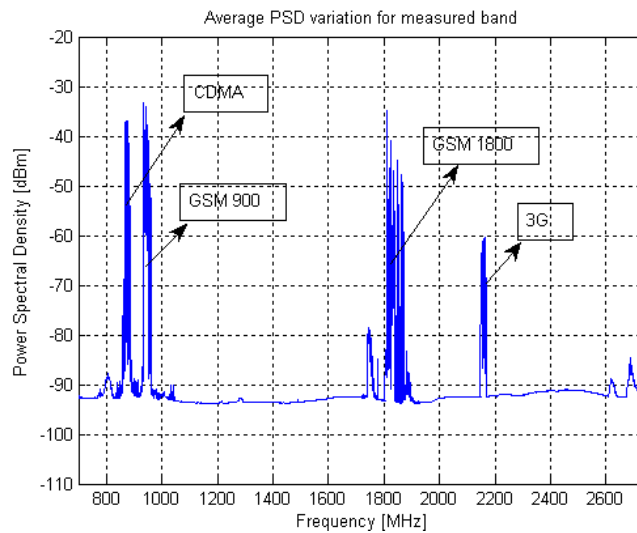


Figure 5.1: Average PSD Variation over Frequency Range 700-2746.6 MHz [98]

Figure 5.2 shows highest occupancy in all 2G cellular bands than any other services. The two GSM bands have an average occupancy of 46.29, and 40.09% respectively which is quite high. The occupancy of the uplink, and the downlink sides is not the same. The uplink occupancy is found to be 11.16%, and 28.36% in the GSM 900 and the GSM 1800 band respectively. The downlink occupancy is found to be 97.78% and 61.44% in the GSM 900 and the GSM 1800 band respectively. The spectrum occupancy in cellular band is found to be quite high. The spectrum occupancy is highly dependent on the location and the choice of decision threshold. The location is in a crowded and commercial area of Pune city. The decision threshold selected in this campaign is 3 dB above the measured thermal noise. Thermal noise is measured by terminating the spectrum analyzer by a 50 ohm resistor. The active primary user signals, which are below the decision threshold level may not detect, and will not contribute to evaluated

spectrum occupancy. Thus the actual spectrum occupancy may be higher than the evaluated one. This shows that the occupancy in the busy part of the Pune is high indicating the demand for the mobile services and the potential need for additional spectrum.

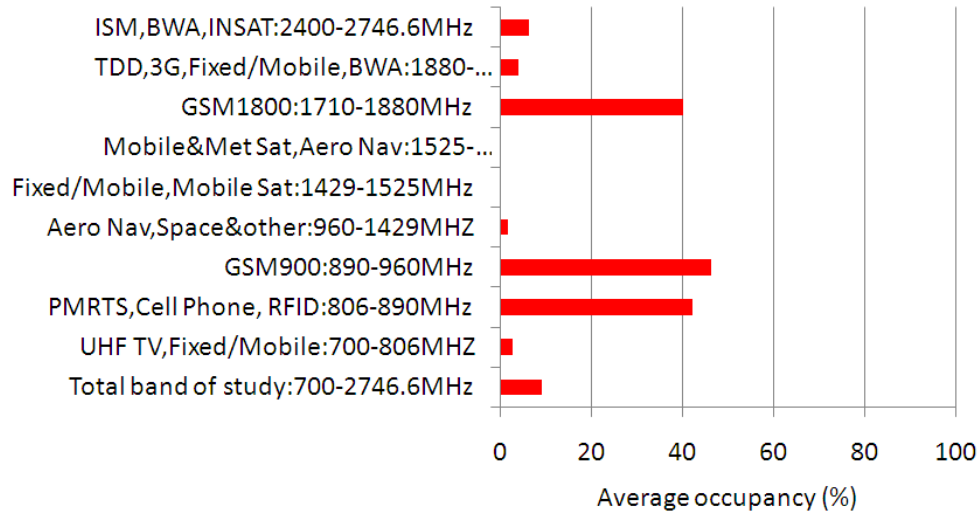


Figure 5.2: Band by Band Occupancy Statistics

5.3 Future Requirement of the Spectrum for Mobile Services

For past several years, the Indian telecom industry has seen an exponential growth due to the cellular communication services. Every month more than 18 million mobile subscribers are being added [99]. The tremendous growth has put the pressure on the available spectrum, which is limited. The current spectrum management policy in India for mobile communication is thoroughly analyzed in [100]. The observations are:

- The spectrum allocated for the 2G cellular communication in India is less as compared to the other countries. It is in between 2×40 MHz, and 2×70 MHz in most cities. Most countries have allocated it between 2×90 MHz and 2×110 MHz.
- The total amount of spectrum allocated to the 2G cellular services is around 20% less in India than the average of the benchmark countries.
- When measured in terms of busy hour traffic per square kilometer per MHz in the dense urban areas, mobile operators in India generate typically eight times more capacity in their use of spectrum than operators elsewhere in the world.

So there is an urgent need to identify, and open up the new frequency bands for the cellular services, which can be used for future growth in India. The ITU conducted a highly, detailed analysis of the spectrum needs as a basis for work on the IMT-Advanced project. The ITU report, projects a total spectrum requirement of as much as 840 MHz by 2010, 1300 MHz by 2015, and 1720 MHz by the year 2020. Even at a lower market development rate, the projections are 760 MHz by 2010, 1300 MHz by 2015, and 1280 MHz by 2020 [101].

5.4 Digital Dividend: Solution to the spectrum requirement of mobile services

5.4.1 DTTV Transition Plan in India

Spectrum refarming in the traditional sense means the recovery of spectrum from its existing users for the purpose of re-assignment, either for new uses, or for the introduction of new spectrally efficient technologies. As such refarming is a spectrum management tool that can be used to satisfy new market demands and increase spectrum efficiency [102]. The digital switchover of TV transmission is going on around the world for better quality and bandwidth saving. USA switched to digital TV broadcasting from analogue TV transmission for full power stations from June 12, 2009. The United Kingdom has a phased switchover based upon region, with the last analogue signals to be shut down by the end of 2012. The Geneva 2006 agreement sets 17 June 2015 as the date after, which countries will no longer be required to protect the analogue services of the neighboring countries against interference, and will be able to freely use frequencies assigned for digital services. This date is generally, viewed as an internationally mandated analogue switch-off date; at least along the national borders [98]. The European Union (EU) has mandated the end of 2012 as the final date for the analogue switch off (ASO). There is a proposal of a phase wise digitization of TV transmission in India by March 31, 2015. In this proposal, the four metros of Delhi, Mumbai, Kolkata, and Chennai will be the first to switch from the analogue to digital, phase-II that includes 35 cities with a population of more than one million will have to make the transition by March 31, 2013. All the urban areas are expected to digitize by November 30, 2014, and the remaining areas by March 31, 2015. The key factors, which are affecting switchover strategies include the size of the terrestrial platform, the availability of spectrum, digital terrestrial television (DTT) penetration, and coverage as well as compliance with the international obligations [102]. During the transition period, the double transmission i.e. analogue, and digital terrestrial transmission will increase the spectrum

requirements. In addition to this, the double transmission period needs to be shortened to release the spectrum. As projected by Doordarshan, and the Telecom Regulatory Authority of India (TRAI), the additional spectrum requirement to be accommodated in the 585-698 MHz band. The complete analogue switch off is expected by March 31, 2015. The analogue transmission may continue side by side few more years. The actual cutoff is depending on the auction of the 700 MHz spectrum, and its availability.

5.4.2 Digital Dividend

The digital dividend refers to the spectrum, which is released in the process of digital TV transition. The EU defines the digital dividend as the spectrum over and above the frequencies required to support the existing broadcasting services in a fully digital environment, including current public service obligations [103].

Table 5.1: The India VHF and UHF TV Band Plan

CH 5	CH 6	CH 7	CH 8	CH 9	CH 10	CH 11	CH 12				
174-181 MHz	181-188 MHz	188-195 MHz	195-202 MHz	202-209 MHz	209-216 MHz	216-223 MHz	223-230 MHz				
				CH 21	CH 22	CH 23	CH 24	CH 25	CH 26	CH 27	CH 28
				470-478 MHz	478-486 MHz	486-494 MHz	494-502 MHz	502-510 MHz	510-518 MHz	518-526 MHz	526-534 MHz
CH 29	CH 30	CH 31	CH 32	CH 33	CH 34	CH 35	CH 36	CH 37	CH 38	CH 39	CH 40
534-542 MHz	542-550 MHz	550-558 MHz	558-566 MHz	566-574 MHz	574-582 MHz	582-590 MHz	590-598 MHz	598-606 MHz	606-614 MHz	614-622 MHz	622-630 MHz
CH 41	CH 42	CH 43	CH 44	CH 45	CH 46	CH 47	CH 48	CH 49	CH 50	CH 51	CH 52
630-638 MHz	638-646 MHz	646-654 MHz	654-662 MHz	662-670 MHz	670-678 MHz	678-686 MHz	686-694 MHz	694-702 MHz	702-710 MHz	710-718 MHz	718-726 MHz
CH 53	CH 54	CH 55	CH 56	CH 57	CH 58	CH 59	CH 60	CH 61	CH 62		
726-734 MHz	734-742 MHz	742-750 MHz	750-758 MHz	758-766 MHz	766-774 MHz	774-782 MHz	782-790 MHz	790-798 MHz	798-806 MHz		

VHF TV band

UHF TV band

585-698 MHz Digital TV broadcasting services proposed

Proposed spectrum for mobile broadband (4G) 698-806 MHz

When TV broadcasters switch from analogue platforms to digital only platforms, part of the electromagnetic spectrum that has been used for broadcasting will be freed up because the digital TV needs fewer spectrums than analogue TV. The reason is that new digital compression technology can transmit 6 to 8 digital TV channels by using the same amount of spectrum used to transmit one analogue TV channel. Thus, depending on the different technological parameters a spectrum efficiency of 6 to 8 times can be achieved when we go from analogue to digital [104]. The size of the dividend will also depend on the technology being used [105]. The size of the dividend will vary from one country to another, owing to the national circumstances, such as the geographical position, size, and topography, penetration of satellite/cable services, the requirements for regional or minority services, and spectrum usage in adjacent countries. The digital transition radically changes the spectrum situation. Digital dividend has a broader meaning in ICT for the development relating to developing economies like India. The effective management of the digital dividend spectrum shall boost the innovation in ICT, and can provide cost effective services to the people.

Refarming of analogue TV broadcast frequencies in the UHF band - to free about 125 MHz of spectrum - has been completed in many countries, like in Australia and the UK. The Europe has the digital dividend spectrum in the 800 MHz band and in the VHF band. According to the European commission decision the 800 MHz band will be used for mobile broadband on a technology neutral basis. The spectrum will be harmonized at a European level and because of its good propagation characteristics will be suited for covering rural areas with mobile broadband. Denmark is also following the European decision regarding the digital dividend spectrum.

The digital dividend band has become available in India also, following the conversion of analogue TV transmission to digital. The India VHF and UHF TV band plan shown in table 5.1. In India, the digital dividend will be available in the VHF-I band and the UHF-band V. The mobile industry is not showing interest in VHF-I band due to the technical characteristics of VHF devices, telescopic antenna, and the characteristic of spectrum. The UHF-band V 582-806 MHz is already shared by Doordarshan for short distance UHF link and military services. So there is no as such digital dividend in the UHF band since there is no analogue TV transmission in this band. But the band 698-806 MHz i.e. the 700 MHz band will be refarmed by vacating the spectrum by existing user and reallocating for the IMT services. This 700 MHz band is widely

termed as digital dividend spectrum in India. This band is identified for the IMT services according to NFAP-11 [53].

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“The requirement for IMT and Broadband Wireless Access may be considered in the frequency band 698-806 MHz subject to coordination on a case-by-case basis.”

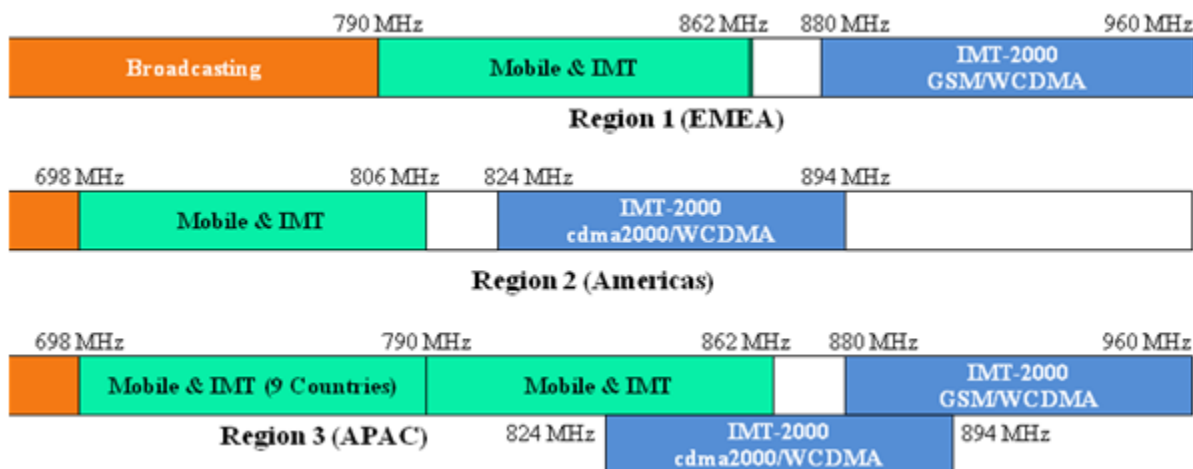


Figure 5.3: The Band 698 -960 in ITU [106]

Table 5.2: New Spectrum Identified for IMT in WRC 07 [108]

Spectrum amount	Frequency band	Region
20 MHz	450-470 MHz	Globally
72 MHz	790-862 MHz	Region 1 (Europe) and Parts of Region 3 (Asia)
108 MHz	698-806 MHz	Region 2 (Americas) and some countries of Region 3 (Asia)
100 MHz	2.3-2.4 GHz	Globally
200 M	3.4-3.6 GHz	No global allocations, but identified in 82 countries

5.5 The Band 698-960 MHz in ITU

The recommendation ITU-R M.1645 concluded that internationally agreed frequency bands will encourage in particular the adoption of IMT-Advanced systems [107]. A common global spectrum should be the preferred objective to ensure global roaming, generic terminal to avail IMT-Advanced services, and equipment cost reduction through the economies of scale. Global harmonization of the spectrum produces substantial benefits for businesses, consumers,

governments, and the mobile industry. Fragmentation of the spectrum creates unnecessary costs. The World Radio communication Conference 2007 (WRC-07) has identified the globally harmonized spectrum for the use by IMT-2000 and IMT-Advanced is summarized in Table 5.2. WRC-07 identified the parts of the UHF band for IMT attracting significant interest from both the Member States and the mobile industry understanding the potential benefit that this frequency band would give to customers and the society as a whole when being used by mobile communications. Presently, the 698-806 MHz band has been arranged in the USA, while in the European Conference of Postal and Telecommunications Administrations (CEPT) countries the band 790-862 MHz is being considered for a 2×30 MHz arrangement. Several key region 3 countries - Bangladesh, China, Korea (Republic of), India, Japan, New Zealand, Papua New Guinea, Philippines and Singapore identified the 698-790 MHz band for IMT-Advanced. The band 698-960 MHz in ITU is shown in figure 5.3.

5.6 The 700MHz Band Plan

5.6.1 700 MHz Band Plan for India from the Perspective of Stakeholders

Wireless planning and coordination (WPC) wing of the department of telecom is an authority for coordinating, and assigning radio spectrum in India for the various wireless users. The proposal has been invited by the WPC wing for the 700 MHz band plan from the different stake holders. Most of the stakeholders including the GSM Association (GSMA), Telecom Equipment Manufacturers Association (TEMA), Association of Unified Telecom Service Providers of India (AUSPI), Ericsson, Nokia-Siemens network / Nokia and Cellular Operator Association of India (COAI) except the WiMAX forum and Doordarshan proposed mobile broadband with 2×50 MHz FDD arrangement shown in the figure 5.4 for the 700 MHz band [109]-[114]. This arrangement has benefits like

- Most spectrum efficient design.
- Can implement dual duplexer and reverse duplex arrangement for better co-existence with the adjacent radio communication services.
- Avoid potential fragmentation of the frequency band for mobile broadband usages, thereby reducing the complexity of the terminals, and possible in-band interference issues.

The GSM Association (GSMA) proposes that all countries should consider the use of the UHF band for mobile services, in order to benefit from the significant propagation advantages this

band provides in providing ubiquitous, affordable, mobile broadband services. Also, put forth the regional harmonization in the UHF band that is required to realize the potential economies of scale, driving down handset and network equipment costs [109]. The proposal from the WiMAX Forum (WF) for the 700 MHz band included the following [115]:



Figure 5.4: 2×50 MHz FDD Arrangement for the 700 MHz Band Plan

- The basic raster should be on a 5 MHz grid to allow 5 MHz and 10 MHz and 20 MHz channels.
- Technology neutrality - The frequency arrangements in the band should not be specific to any one technology.
- Duplex - Both TDD and FDD should be possible.
- Service Neutrality - The market should decide what services are provided by operators (data, voice, video, etc.).
- Usage neutrality - Fixed, nomadic (Portable) and mobile should be permitted by regulation.
- TV set protection – The FDD will probably need a reverse duplex i.e. a downlink in the lower sub-band. The TDD will need a guard band to be determined (could be 5-10 MHz).

The Doordarshan proposal suggests the allocation of 698-806 MHz band for many important broadcasting applications given in [116].

5.6.2 700MHz Band Plan in APT

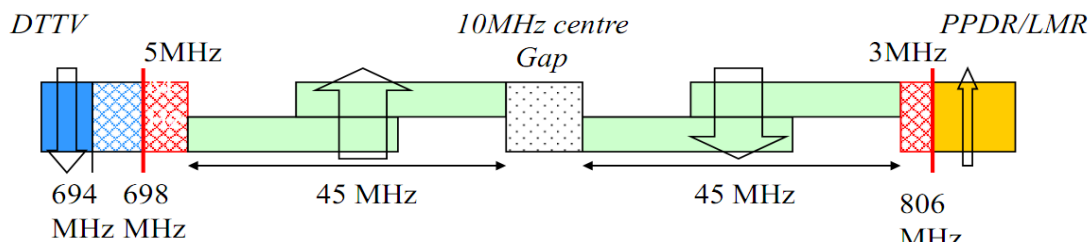


Figure 5.5: The FDD Frequency Arrangement for the 700 MHz Band Plan [117]

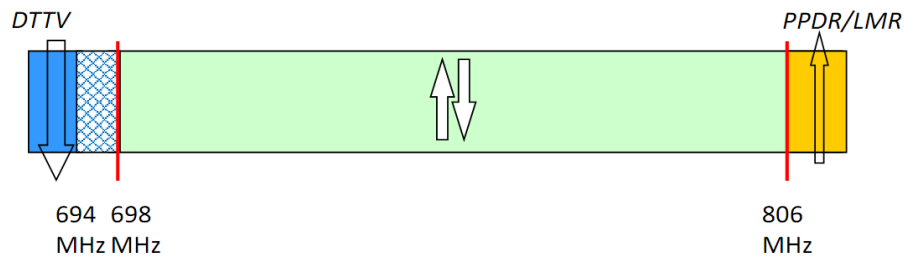


Figure 5.6: The TDD Frequency Arrangement for 700MHz Band Plan [117]

The harmonization of the 700 MHz band for region 3 is the agenda for the ITU WP 5D meeting. The two harmonized frequency arrangements agreed by APT members for the band 698-806 MHz for the IMT services is shown in figure 5.5, and 5.6, and it is in line of the Indian proposal for the 700 MHz plan. One is based on the FDD and another on the TDD. The 2×45 MHz FDD frequency arrangement with a 10 MHz central gap is proposed. This plan has a conventional duplex arrangement with an uplink frequency band allocated to the lower spectrum block of the FDD pair. The internal guard band of 5 MHz is kept at 698 MHz, and 3 MHz at 806 MHz. In addition to this a 4 MHz external guard band below the 698 MHz is available after deploying an 8 MHz TV channel raster in India. Thus, the total guard band at 698 MHz frequency border will be 9 MHz, which is higher than the minimum requirement of an 8 MHz guard band between the DTTV broadcast, and mobile services as suggested in [118]. Another 700 MHz band plan based on the TDD include internal guard band of 5 MHz at 806 MHz. An additional 4 MHz external guard band below 698 MHz is also available because of the 8MHz TV channel raster in India. The band plan shown in figure 5.6 may be considered more suitable for India's particular domestic situation as mentioned earlier because it maximizes the use of the limited spectrum available in India, delivers large contiguous blocks of spectrum for mobile broadband, avoids the potential fragmentation of the band and possible in band interference issues, and it is technically the most efficient design of the band.

5.7 Discussions on 700 MHz Spectrum for Mobile Services

Spectrum utilization found in the 2G cellular bands in India from the measurement campaigns is quite high indicating the demand for the mobile services. The high utilization of the 2G spectrum is possible because of a large number of mobile subscribers, and this number is growing in every month by more than 18 million subscribers. Also, the spectrum available for these services is less

as compared to other countries. There is big demand of spectrum for mobile services according to TRAI and ITU in future.

With around 833 million people living in the rural areas of India having only 32% rural teledensity, there is a big market for introduction of the latest technologies. The introduction of new wireless technologies can bridge the digital divide in developing countries such as India [119]. The wireless broadband can play a vital role in achieving penetration of broadband in the rural region. Thus, promoting the wireless broadband in the rural areas is the key to ensuring that the whole population is able to benefit from the wireless broadband services. If just 25%, or around 100 MHz, of the spectrum currently, used by analogue TV (470-862 MHz) is re-allocated to mobile communications, the mobile industry could dramatically speed up the rollout of broadband communications, and increase coverage. The enormous benefits would ensure around the world, in terms of both social impact and increased productivity [120]. The widespread use of mobile broadband technology will not only support a growing industry, but it will also increase the overall broadband penetration, which shows a strong positive correlation with the country's economic welfare. For example, one study that is done across multiple countries shows a correlation in which a 1% increase in broadband penetration corresponds to \$2000 per capita higher Gross Domestic product (GDP) [121]-[122].

Telecom Regulatory Authority of India (TRAI) issued a pre-consultation paper on 10th February 2010 requesting the stakeholders to suggest likely issues involved in the deployment of IMT- Advanced technologies in the country. Based on the comments received from the stakeholders and in-house study, TRAI issued a Consultation paper on 'IMT - Advanced Mobile Wireless Broadband Services' on 19th August 2011. Recently TRAI has issued recommendation on IMT – Advanced Mobile Wireless Broadband Services' on 19 March 2013. Both the IMT-Advanced technologies, 3GPP LTE-Advanced and IEEE 802.16m are the potential candidates of 4G technology. The APT700 plan has been adopted as a standard by the international 3rd Generation Partnership Project (3GPP) as a band for Long Term Evolution (LTE) technology and provides the most efficient use of the spectrum possible. TRAI has recommended the APT700 band plan should be adopted for the 700 MHz spectrum band (698-806 MHz) with FDD based 2x45 MHz frequency arrangement.

Currently several studies had been conducted to assess the interference between potential services in digital dividend spectrum. The two potential services widely considered in digital

dividend spectrum are Digital Video Broadcasting –Terrestrial (DVB-T) and Long Term Evolution (LTE). This will cause potentially harmful mutual interference between TV and mobile radio services that needs to be carefully analyzed. The work related to the co-existence between mobile and digital broadcast television, generally focus on one system that has to be protected, thus providing the operational constraints for the other system, which is considered as interferer. In paper [135] a study of the co-channel interference problem is presented, proposing a methodology to take into account the mutual interference between a LTE mobile network and a DVB-T system. In [135] and [136], the authors have tested the interference influences on the DVB-T signals, transmitted over the simulated AWGN (Additive White Gaussian Noise) channel. On the other hand, in [137] signal distortions caused by the UMTS (Universal Mobile Telecommunications System) and LTE (Long Term Evolution) on the DVB-T system are explored. Interference analysis study between DVB-T and E-UTRA is presented in [138]. The paper concludes that the required minimum protection distance between DVB-T transmitter and E-UTRA base station receiver is 310 km for co-channel interference and 9.5 km for adjacent-channel interference. At least 4 MHz guard band is required in case of adjacent-channel between interferer DVB-T transmitter and E-UTRA downlink. The interference study is required in India to determine the technical operation limitation, such as the minimum guard band and minimum distance, between mobile broadband and digital terrestrial television broadcasting also mutual interference between these two services.

The key problem in developing the wireless broadband networks is the access to spectrum. In India, the 3G licenses were auctioned in May 2010. However, the auction of the digital dividend and refarming of spectrum in the 900 MHz and the 1800 MHz bands has long been delayed, despite the TRAI recommendation. In our view, the Government authority should take its final decisions on the spectrum in these bands soon, which will enable the wireless broadband to cover the rural and remote areas more effectively, and thus, assist in reducing the digital divide. Because of excellent signal propagation characteristics of digital dividend spectrum, fewer infrastructures will be required to provide wider mobile coverage, meaning that communications services can be provided in rural areas at a lower cost.

5.8 Conclusion

The spectrum occupancy measurement campaign provides valuable information about the dynamic spectrum utilization of the wireless services. Thus, the results of the campaign provides the necessary inputs to the regulatory body to take accordingly certain decisions such as spectrum refarming and spectrum sharing in certain bands for efficient spectrum utilization. Our measurement campaign reports that the highest spectrum utilization found in the 2G wireless cellular band. The high utilization of the spectrum in cellular band, growing number of mobile subscribers and the benefits of the mobile services experienced show the need of an additional spectrum for mobile services for the future development. The digital dividend is the excellent opportunity for penetrating the wireless broadband in the rural area. The digital dividend is the spectrum freed after switchover from the analogue TV transmissions to spectrum efficient digital TV transmission. During the switch over, the double transmission i.e. the analogue and digital TV transmission period need to be shortened to get the immediate benefits of the digital dividend and minimize the period with additional spectrum required during the switchover for double transmission. There are different interests in the use of the digital dividend; however, most of the stakeholders agree that the digital dividend can be the efficient solution for the spectrum requirement of the IMT-Advanced mobile services. There is a strong need of global frequency harmonization in the IMT-Advanced services via generic terminal layout, which will provide substantial socio-economic benefits for society at large. To achieve this in the India, access to the spectrum should be given by auctioning the digital dividend spectrum after refarming as soon as possible. The 700 MHz band plan agreed consensually, by the APT members includes the FDD based frequency arrangement, and the TDD based frequency arrangement in the ITU WP 5D meeting.

6

CTMC Based Spectrum Sharing Scheme for Cognitive Radio Networks

In this chapter, a coexistence form of spectrum sharing scheme for cognitive radio network is proposed. A continuous-time Markov chains (CTMC) model is presented for the interactions between the licensed users (primary users) and the unlicensed users (secondary users) by which we can capture the performance of DSA system, especially the effect of the primary user's activities on the unlicensed users. Numeric experiments are given to investigate impacts of various parameters on the derived statistics of the proposed scheme.

6.1 Introduction

In the chapter second and third, we have identified potential bands from real time measurement for dynamic spectrum sharing to increase the efficiency of spectrum usage using CR technology. The dynamic spectrum sharing exploit the underutilized spectrum by allowing access to the unlicensed user i.e. secondary user when the license user i.e. primary user not using it. The primary user always has priority over the secondary user. Also the secondary user should not provide interference to the primary user. This spectrum sharing also termed as primary secondary sharing. This type of spectrum sharing has two forms: cooperation and co-existence [123]. The cooperation form of spectrum sharing means communication and coordination between PU and SU. The coexistence form of spectrum sharing means the PU is unaware of the SU, and there is no coordination or communication between PU and SU. The secondary system become more complex since it has inbuilt cognitive functionality.

The challenges associated with spectrum sharing in CRN are:

- Enhance the spectrum efficiency
- Spectrum allocation to unlicensed users in consideration with primary user activity
- Reoptimise the spectrum allocation for all secondary users according to dynamic radio environment
- In above process reduce the computational complexity
- Maximize spectrum utilization along with fairness among the different SUs
- Performance evaluation of DSA system
- Coordinate the SU access to alleviate the interference within SUs
- Avoid conflict with primary users

6.2 Related Work

Dynamic spectrum sharing is extensively investigated by the research community. A primary system prioritized Markov approach for dynamic spectrum access is examined through modeling the interactions between the primary users and the secondary users as continuous time Markov chains in paper [124]. It achieves a good statistical tradeoff between spectrum efficiency and fairness. A Markov chain analysis for spectrum access in licensed bands for cognitive radios is presented in [125] and forced termination probability, blocking probability and traffic throughput

are derived. In [126], quality-of-service (QoS) performance in a Cognitive radio system involving primary and secondary users was analyzed by using a Markov chain. In [127] a continuous-time Markov model is investigated for dynamic spectrum access in open spectrum wireless networks. A spectrum sharing scheme using one PU and multiple SUs is presented in [128] for which performance metrics are derived.

A general scenario of CRNs with multiple primary users and multiple secondary users is shown in figure 6.1. So a coexistence form of spectrum sharing scheme having two primary users and multiple secondary users in cognitive radio network is proposed. There are two frequency bands of primary users divided into multiple radio bands and each secondary user can access any radio band if the licensed band is not used primary users. We propose to model the interactions between the licensed users (primary users) and the unlicensed users (secondary users) as continuous-time Markov chains (CTMC), by which we can capture the performance of DSA system, especially the effect of the primary user's activities on the unlicensed users. We have investigated this fundamental spectrum sharing scheme with the help of the CTMC analysis model. Also we got some important statistics such as mean number of radio bands used by the secondary users, deprivation rate and blocking rate of the secondary users, and the utilization ratio of the spectrum.

6.3 CTMC Model and Assumptions

Dynamic spectrum Access proposes the use of idle licensed spectrum by unlicensed users to improve spectrum utilization. In this paradigm PUs and SUs coexist and share the licensed spectrum with PUs having priority over SUs. Listen before talk strategy is adapted by SUs for avoiding the interference to PUs.

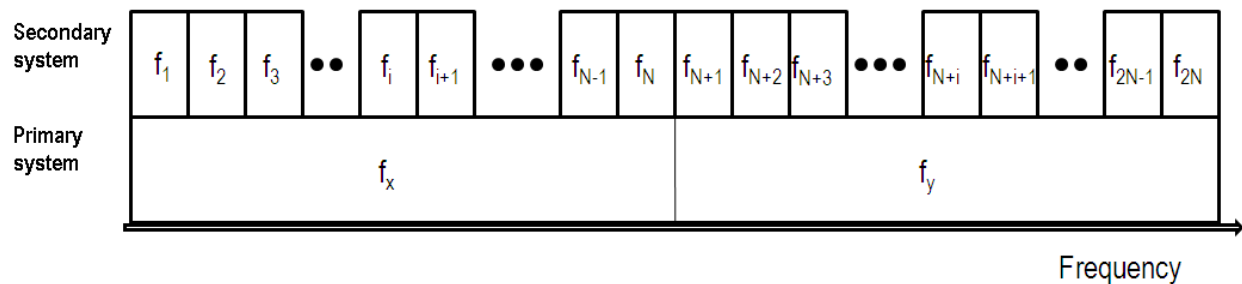


Figure 6.1: Spectrum Sharing Scheme

In the proposed spectrum sharing scheme there are two licensed frequency bands namely f_x and f_y . The legitimate users for f_x and f_y are PU1 and PU2 respectively. Each band is divided into N sub bands as shown in figure 6.1. Orthogonal Frequency division Multiplexing (OFDM) is considered for the SU transmission modulation scheme because of its flexibility and computational efficiency [16]. The proposed scheme which has two PUs is considered in view to extend the model for multiple PUs and SUs. So the $2N$ SUs are allowed to use the sub-bands in parallel when the spectrum is not used by the PUs. If a primary user appears in the spectrum band, the SUs existing in that spectrum band need to vacate the bands. The following assumptions are for deriving the statistics:

- (i) The arrival of the PU is modeled as Poisson process with rate $\lambda_p \text{ ms}^{-1}$. So the inter accessing time is negative-exponentially distributed with mean time $1/\lambda_p$ (ms);
- (ii) The spectrum access duration of PU is negative-exponentially distributed with mean time $1/\mu_p$ (ms);
- (iii) The inter-arrival time of SUs accessing the spectrum is negative-exponentially distributed with mean time $1/\lambda_s$ (ms); and
- (iv) The spectrum access duration of each SU is negative-exponentially distributed with mean $1/\mu_s$ (ms).

The exponential distribution and CTMC are both memory less. The negative-exponential distribution of the random variables representing inter-arrival times and services times are considered so as to be suitable for CTMC. We assume that each SU is equipped with CR able to access all the N bands but only uses one of the bands at a time. We neglect the time for a SU to vacate a band. The spectrum access duration of SUs' remains negative-exponentially distributed no matter whether the SUs are forced to stop their communication by the PU arrival or not. This is because negative-exponential distribution possesses memory less property as mentioned earlier.

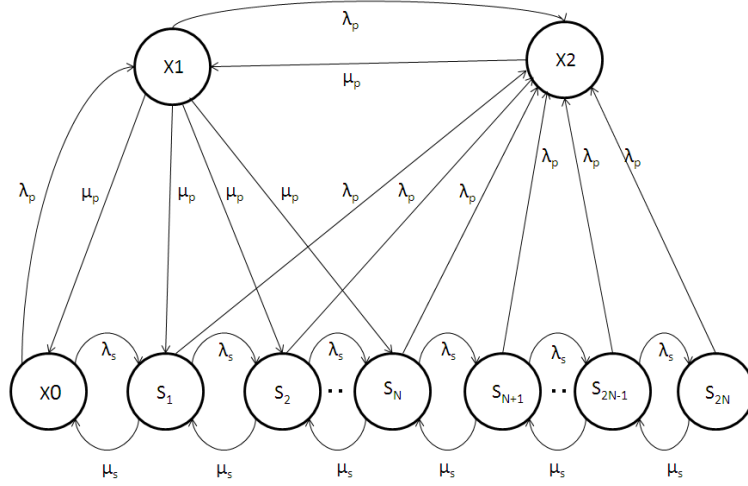


Figure 6.2: The CTMC Model for Two PU and 2N SUs

Let X0 stand for the state that neither primary nor secondary user uses the spectrum. X1 and X2 are the states when one PU is exclusively using one of two spectral bands and when both of the bands are used by two PUs respectively. S_j represent the state that there are j SUs using bands ($j = 1, 2, \dots, 2N$). In addition, we use C to denote the set of states, i.e., $C = \{X0, X1, X2, S1, \dots, S2N\}$. Thus, the state transitions are depicted in figure 7.2. It is intuitive that no SUs more than $2N$ can occupy the spectrum since the available sub-bands can only be $2N$. From the basic queuing theory applied to CTMC, the following balance equations for the model can be derived. Π_j are steady state probabilities of states S_j and Π_{X0} , Π_{X1} and Π_{X2} are steady state probabilities of states X0, X1, and X2 respectively.

$$\left\{ \begin{array}{l} \Pi_{X2}\mu_P = \Pi_{X1}\lambda_P + \sum_{n=1}^{2N} \Pi_n \lambda_P \\ \Pi_{X1}(\lambda_P + (N + 1)\mu_P) = \Pi_{X0}\lambda_P + \Pi_{X2}\mu_P \\ \Pi_{X0}(\lambda_P + \lambda_S) = \Pi_1\mu_S + \Pi_{X1}\mu_P \\ \Pi_j(\lambda_S + \mu_S) = \Pi_{j-1}\lambda_S + \Pi_{j+1}\mu_S + \Pi_{X1}\mu_P \quad \text{--- for } 1 \leq j \leq N \\ \Pi_j(\lambda_P + \lambda_S + \mu_S) = \Pi_{j-1}\lambda_S + \Pi_{j+1}\mu_S \quad \text{--- for } N+1 \leq j \leq 2N-1 \end{array} \right. \quad (6.1)$$

$$\sum_{j=1}^{2N} \Pi_{X0} + \Pi_j + \Pi_{X1} + \Pi_{X2} = 1 \quad (6.2)$$

Combining equation 6.1 and 6.2 we obtain $A \Pi = B$ where

$$\Pi = (\Pi_{x0}, \Pi_1 \dots \dots, \Pi_{2N}, \Pi_{x1} \Pi_{x2})^T, \quad B = (1, 0, 0, \dots)^T$$

and

$$A = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 0 & \lambda p & \lambda p & \lambda p & \lambda p & \lambda p & \lambda p & \lambda p & \lambda - \mu p \\ \lambda p & 0 & 0 & 0 & 0 & 0 & 0 & -(\lambda p + (N+1)\mu p) & \mu p \\ -(\lambda p + \lambda s) & \mu s & 0 & 0 & 0 & 0 & 0 & \mu p & 0 \\ \lambda s & -(\lambda s + \mu s) & \mu s & 0 & 0 & 0 & 0 & \mu p & 0 \\ 0 & \lambda s & -(\lambda s + \mu s) & \mu s & 0 & 0 & 0 & \mu p & 0 \\ 0 & 0 & \lambda s & -(\lambda s + \mu s) & \mu s & 0 & 0 & \mu p & 0 \\ 0 & 0 & 0 & \lambda s & -(\lambda s + \mu s) & \mu s & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \lambda s & -(\lambda s + \mu s) & \mu s & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & \lambda s & \lambda p + \mu s - \lambda s & \mu s & 0 \end{bmatrix}$$

Thus we have

$$\Pi = A^{-1}B \quad (6.3)$$

The following performance metrics are considered and defined as follows.

The mean number of Radio bands used by the secondary users is

$$\text{Mean Number of SUs} = \sum_{j=1}^{2N} j * \Pi_j \quad (6.4)$$

The deprivation rate of SU is the rate that the SU is forced to vacate the band due to arrival of the PU.

$$\text{Total Deprivation Rate} = \lambda_p \sum_{j=1}^{2N} \Pi_j \quad (6.5)$$

A secondary user gets blocked if there are 2N SUs using the spectrum.

$$\text{Blocking Rate} = \lambda_s * \Pi_{2N} \quad (6.6)$$

The utilization ratio is the ratio of the number of radio bands used by the PUs and the SUs to the total number of bands available.

$$\text{Utilization Ratio} = \frac{1}{2N} (2 * \Pi_p * N + \sum_{j=1}^{2N} j * \Pi_j) \quad (6.7)$$

6.4 Numeric Experiments and its Results

In the numeric experiments for testing the feasibility of the model, we consider $N=3$ that is total 6 number of SUs and two number of PUs are considered.

Let λ_p vary, $\mu_p=0.4$, $\lambda_s=0.6$ and $\mu_s=0.2, 0.4, 0.6$ and 0.8 . The graph in figure 6.3 obtained for above values indicate that mean number of SUs using the spectrum decreases as λ_p and/or μ_s increases. Similarly the deprivation rate shown in figure 6.4 is found for $\mu_s=0.6$ which increases as λ_p and/or μ_p increases. Now let λ_s vary and $\lambda_p=0.2$ and $\mu_p=0.4$, the results in figure 6.5 and 6.6 indicate that if (i) blocking rate increases as λ_s increases or μ_s decreases and (ii) utilization ratio increases as λ_s increases and or μ_s decrease.

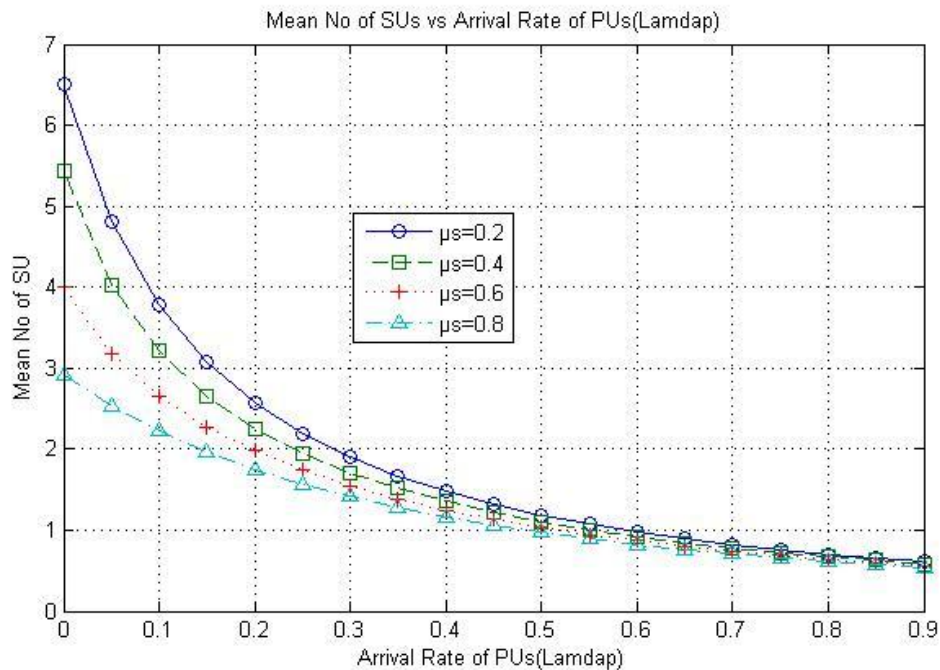


Figure 6.3: Mean number of SUs vs. Arrival Rate of PUs (λ_p)

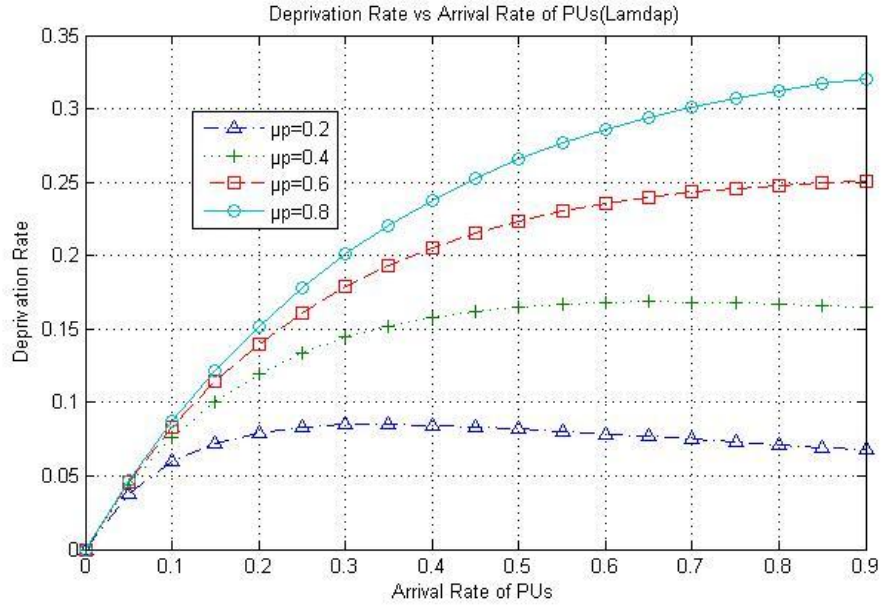


Figure 6.4: Deprivation Rate vs. Arrival Rate of PUs (λ_p)

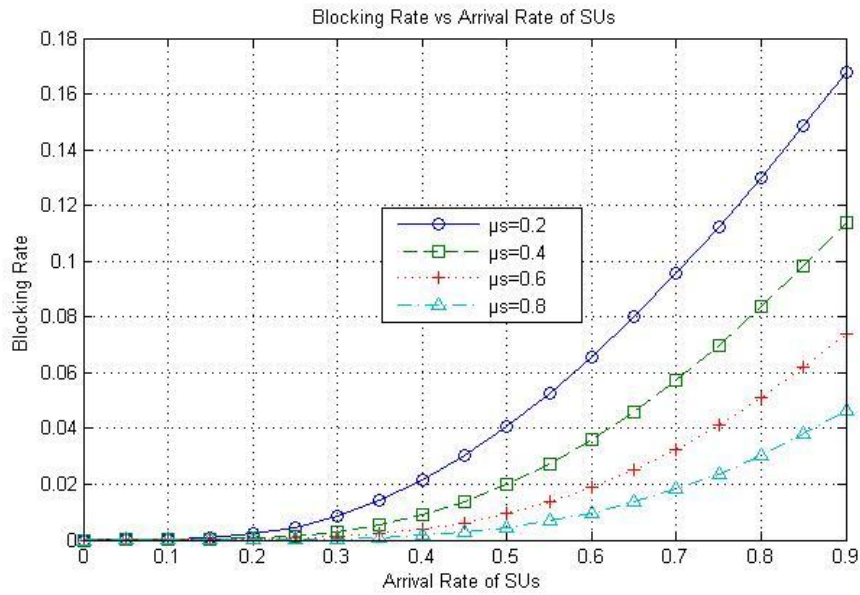


Figure 6.5: Blocking Rate vs. Arrival Rate of SUs (λ_s)

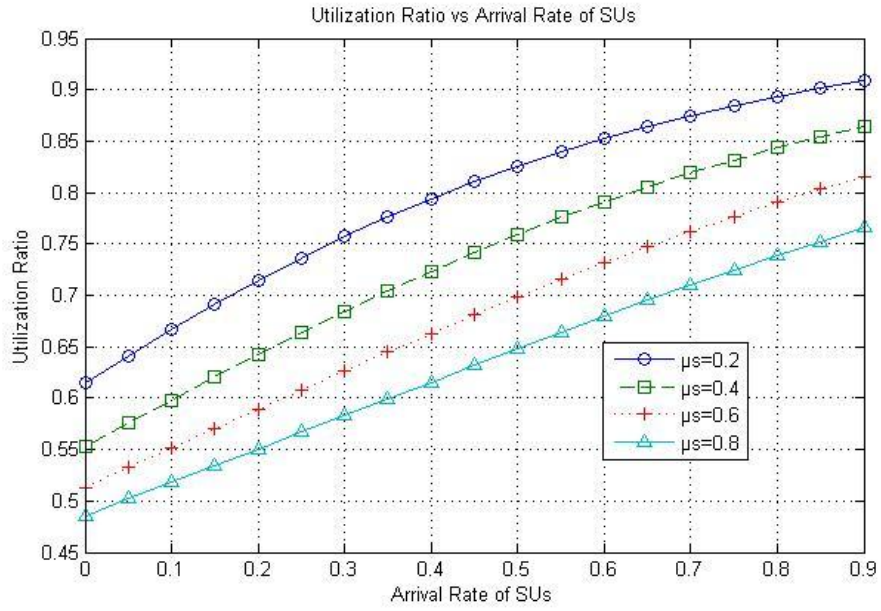


Figure 6.6: Utilization Ratio vs. Arrival Rate of SUs (λ_s)

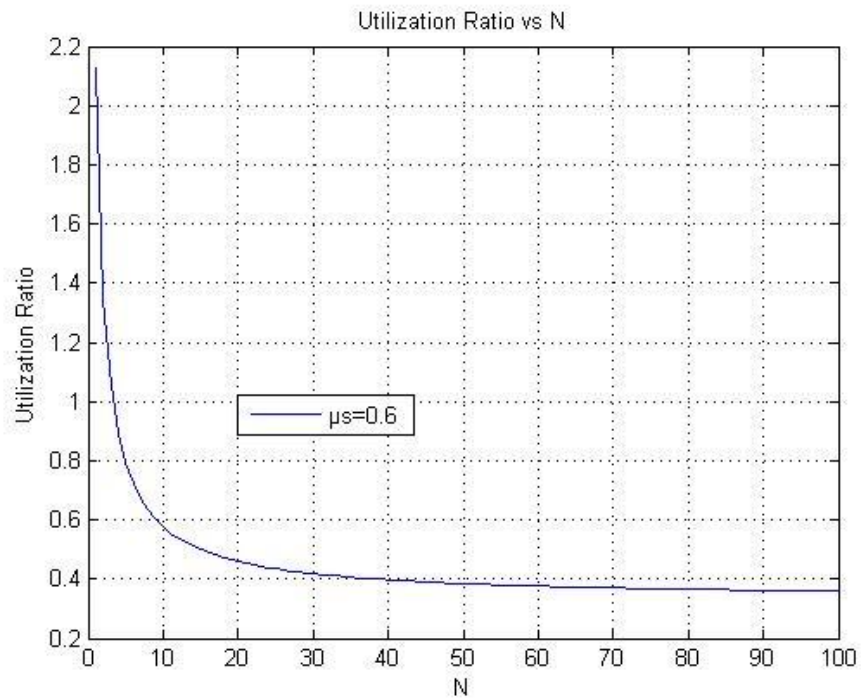


Figure 6.7: Utilization Ratio vs. N

Now we observed in figure 6.7 by letting N vary and setting $\lambda_p = 0.2$, $\mu_p = 0.4$ and $\lambda_s = 5$ that utilization ratio does not increase if we increase number of bands available to SUs. The simulation results are previously, described in [129].

Challenges in Implementing the Spectrum Sharing Scheme

In dynamic spectrum sharing, the role of SU is to use licensed spectrum opportunistically. According to this role, SUs coexist with PUs that is licensed to operate over given frequency bands. PUs does not cooperate with or even provide feedback to SUs. SUs continuously sense the spectrum and exploit spectrum holes for opportunistic communications. Orthogonal frequency-division multiplexing (OFDM) has been considered SUs transmission here due to its great flexibility in dynamically allocating the unused spectrum among the SUs and its ability to monitor the spectral activities of the PUs at no extra cost. However, it has been shown that employing OFDM also affects the performance of cognitive radio networks, e.g., causing mutual interference between the PUs and the SUs due to the nonorthogonality of their respective transmitted signals [130], [131].

As multiple SUs to share PU spectrum, PU to SU interference, SU to PU interference and SU to SU interference have to be considered. To maximize the total number of SUs who can be supported while guaranteeing the minimum SINR requirements of SUs and also protecting the PUs is the challenge in implementation point view.

6.5 Conclusion

The spectrum sharing is the important function of the spectrum management in Cognitive Radio Network. The primary secondary sharing has two forms: cooperation and co-existence. In the coexistence form of spectrum sharing, the PU is unaware of the SU, and there is no coordination or communication between PU and SU. The CTMC based spectrum sharing scheme is presented here has considered coexistence form of spectrum sharing in which there are two primary users and multiple secondary users. Here we consider a primary-prioritized Markov approach for dynamic spectrum access. In order to study the performance, the interactions between the primary users and the unlicensed users are modeled using continuous-time Markov chains. We have derived some statistics for the scheme. The performance analysis of DSA can be done with the help of derived statistics.

When PUs mean occupation time of spectrum increases the opportunity for the secondary users to access the spectrum decreases. Also in case of increase in frequency of arrival of PUs forces the SUs to vacate the spectrum and further decreases the mean number of SUs at spectrum. The blocking probability of SU depends upon the arrival rate of SUs and average usage time of SU. The increase in total number of SUs in the scheme does not improve spectrum utilization ratio.

Finally, the challenges in implementing the proposed scheme for maximizing the CRN performance are discussed.

7

Conclusions and Future Work

This chapter concludes the thesis and proposes the future work, which can be researched and build based on the ideas proposed. This thesis presents current radio spectrum utilization in India, and empirical modeling of spectrum utilization for cognitive radio potential. Studies of Cognitive access of TV white spaces and Digital dividend in India have been presented. Pros and cons of CR deployment while considering implications on spectrum management are also presented. A Continuous Time Markov Chain based spectrum sharing is proposed for performance evaluation of DSA Systems.

The presented work can be pursued and extended in multiple directions. As an extension of the present work, further long term studies need to be performed in those bands which are identified as less utilized to assess the feasibility of alternative services on the secondary basis in these bands. These extensive studies would enable us to identify the cyclic trends and potentially longer term trends in band by band spectrum utilization. The extensive parallel measurement can be performed in rich diversity of measurement scenarios of practical interest to assess the variations in spectrum usage in the environments with different user profiles, different population densities and different geographic characteristics. The outcome of these studies would facilitate to identify the frequency bands with low or no active utilization more accurately for opportunistic spectrum access.

Throughout our Pune measurement campaigns, we have kept the same set of measurement parameters of the spectrum analyzer. The study regarding the impact of each parameter e.g. resolution bandwidth, sensing time, and detector type on the spectrum occupancy of different wireless services can be the extension for the existing work. A more controlled and accurate measurement set up should be designed. The use of vector signal analyzer which has higher sampling rate and ability to detect the feature and coherent detection in measurement set up should be considered. This can improve the sensing performance of the measurement set up. The higher sampling rate can extract realistic occupancy patterns of a channel with high time accuracies. However the real time data collected with high sampling rate would be huge and may require longer time span to process. In addition, the measurement methodology should be improved to give realistic spectrum occupancy estimate.

We have not explored the spectrum utilization modeling in time domain and spatial domain. The long term measurement data should be used for the developing the more accurate empirical model in spatial and time domain. The developed models can be applied in design of cognitive radio network. Further it should be applied to improve the spectrum sensing performance of Cognitive radio. In adaptive spectrum sensing, the historical information of frequency usage from extensive measurement campaign can save the spectrum sensing time and energy of the Cognitive radio.

The interference study from white spaces devices operating in TV band on the protected services in the context of India is an unexplored area of research.

Finally, we propose to investigate specific use cases. For example, the proposal for wireless backhaul in India using TV white spaces can be explored. The issues of choice of communication technology, frequency planning, opportunity detection mechanisms need to be investigated and prototype should be tested. The generic research on the topics spectrum policy, spectrum rules, dynamic spectrum sharing techniques can be done. Despite the above mentioned limitations, useful and valuable results have been achieved which are summarized in next part.

In the initial part of this thesis, as a background we have introduced the spectrum access barriers. The spectrum scarcity and its causes are also highlighted. We have discussed the cognitive radio technology for Dynamic spectrum access and reviewed the current spectrum sensing techniques. Further the relevant literature survey is discussed.

Although several spectrum occupancy measurement campaigns have been performed in the context of Cognitive radio mainly in USA and Europe, no such campaign has been conducted in India. To the best of our knowledge, the performed measurement campaigns have been the first wideband spectrum measurements in the context of Cognitive Radio in India. We have designed a wideband measurement set up for the spectrum usage evaluation. This thesis has presented the results of a broadband spectrum measurement campaign conducted in the frequency range 700–2746.7 MHz over a wide variety of scenarios in the metropolitan area of Pune and Mumbai, India. The investigated sites include indoor location, rural outdoor location and commercial outdoor location scenarios. To evaluate spectrum occupancy of different frequency bands allocated to wireless services in the measured band, short term spectrum measurement campaigns have been conducted. The longer time span measurement was performed to study the statistical characteristics of the spectrum usage. The obtained results have indicated that the actual utilization of spectrum is not uniform. It has been observed that some spectrum bands are subject to high occupancy levels while some others show moderate utilization levels, some are sparsely used and, in some cases, are not used at all. However, the overall level of utilization has been significantly low. Several allocated frequency bands for different services have shown potential for cognitive radio deployment. The spectrum measurements were performed at different locations and the spectrum occupancy evaluated for the different decision threshold which differentiate occupied or unoccupied channel. The measurement results have confirmed that the spectrum occupancy highly depends on measurement location and the selected decision threshold. For the indoor location many frequency bands have shown no spectrum activity for

longer time span compared to outdoor locations thus exhibiting the possibilities of secondary use of idle bands. The Mumbai measurement has shown low average spectrum occupancy of 6.62% may be due to following reasons.

1. The measurement location of Mumbai is in residential area of Mumbai suburban where usually spectrum activity is less.
2. The 10 dB noise margin we have selected as per ITU recommendation which was on higher side. This may have missed out the primary user activity.

The busy parts of Mumbai city will definitely show the higher average occupancy with reasonable noise margin. India has huge population and second largest number of mobile users in the world. Day by day the number of wireless users is increasing along with increase in multimedia and data services. This will put great demand on spectrum requirement. So there will be need of start of complex cognitive network in India in near future.

For the spectrum occupancy modeling, we have adopted an empirical approach using measurement data as basis for accurate model building. The stochastic duty cycle model based on the measurement has been used to extract relevant statistical properties of spectrum usage in frequency domain. The knowledge on high probability potential candidate bands for opportunistic spectrum access is derived from the duty cycle modeling. The statistical characteristics of spectrum usage are beneficial not only for spectrum sensing but also in dynamic allocation of frequencies to secondary users. The statistical and spectral occupancy results of GSM 900 and 1800 band leads to the conclusion that these bands are underutilized. The GSM uplink bands have considerable scope for cognitive radio operation. Further, we have discussed a number of wireless services that can be considered in the opportunistic bands which are probable for dynamic spectrum sharing.

Beta distribution has been assumed in the modeling the spectrum occupancy of the primary user in a licensed band. We have validated the beta distribution assumption of channel occupancy using our real time measurement. The Kolmogorov-Smirnov test is applied as a validation approach.

In subsequent part of the work, we introduced the concept of TV white space i.e. geographically unused TV spectrum. We have presented the current situation of TV band in India. We have

performed TV band measurement in urban and rural area to assess the potential for CR operation. We have designed measurement set up TV band occupancy evaluation. It has been observed from the results that the TV spectrum is underutilized showing ample scope for the CR operation. We have proposed regulatory reforms like spectrum refarming and unlicensed operation in TV band for efficient utilization TV spectrum. The cognitive access of unused wireless TV spectrum is considered to be an excellent opportunity to provide wireless broadband connectivity to rural area. We have studied the technical and regulatory requirements for the possible Cognitive Radio operation in TV white space frequency band in US and Europe. Three potential cognitive techniques (sensing, geo-location database and beacon) are considered for white space devices. Spectrum sensing only cannot provide adequate protection to the incumbent services, taking into account current technologies. Currently, Geolocation database approach for the cognitive radio operation seems to offers the best short-term solution for incumbent detection and interference avoidance. We have made some effort to translate the existing requirements of CR operation in TVWS for the Indian scenario. We have proposed generic requirements for the use of the TV white space for cognitive access. We have proposed last mile connectivity to the small village population through wireless broadband network using TVWSs. The major CR/TVWS ongoing standardization activities related to cognitive access to TVWS are discussed.

We have also accessed the post deployment of the cognitive radio scenario of spectrum regulation in India. CR/DSA paradigm can provide benefits like simpler, dynamic and efficient spectrum management, scope for innovations, easier to introduce new applications and flexible spectrum access. However, problems like interference control, hardware device certification, and hidden node problem may prevail under CR/DSA paradigm.

Our measurement results are the valuable inputs for the regulatory body of India to take accordingly certain decisions such as spectrum refarming and spectrum sharing in certain bands for efficient spectrum utilization. We have proposed spectrum refarming in the terrestrial TV broadcasting band based on the spectrum occupancy results in the frequency bands of GSM services. We found the highest spectrum occupancy in these bands showing the popularity and demand of these services in India. The high utilization of the spectrum in cellular band, growing number of mobile subscribers and the benefits of the mobile services experienced show the need of an additional spectrum for mobile services for the future development. We proposed the

digital dividend spectrum for the IMT advanced services to fulfill the demand of additional spectrum for mobile services. We believe that the digital dividend is the excellent opportunity for the wireless broadband penetration in the rural area of India.

The digital dividend is the spectrum freed after switchover from the analogue TV transmissions to spectrum efficient digital TV transmission. During the switch over, the double transmission i.e. the analogue and digital TV transmission period need to be shortened to get the immediate benefits of the digital dividend and minimize the period with additional spectrum required during the switchover for double transmission. There are different interests in the use of the digital dividend; however, most of the stakeholders agree that the digital dividend can be the efficient solution for the spectrum requirement of the IMT-Advanced mobile services. There is a strong need of global frequency harmonization in the IMT-Advanced services via generic terminal layout, which will provide substantial socio-economic benefits for society at large. To achieve this in the India, access to the spectrum should be given by auctioning the digital dividend spectrum as soon as possible after spectrum refarming. We have discussed the 700 MHz band plan agreed consensually, by the APT members which includes the FDD based frequency arrangement, and the TDD based frequency arrangement in the ITU WP 5D meeting.

In the next part of thesis, we have presented the Continuous Time Markov Chain (CTMC) analysis for dynamic spectrum access in licensed bands for cognitive radios. We have investigated a basic spectrum sharing scheme in which primary users coexist with multiple primary users representing the coexistence form of spectrum sharing. The CTMC analysis model has been constructed and obtained some important statistics which are beneficial in analyzing the performance of the DSA systems.

References

- [1] Akshay Mishra, Gaurav Varshney and Abhay Karandikar, "Analysis of the 3G and BWA Auctions in India" in *Proceedings of ITS India 2012*.
- [2] D. C. Sicker and C. Doerr, "The 700 MHz Auction," in *Proc. of IEEE Workshop on Networking Technologies for Software Defined Radio Networks (SDR), in conjunction with IEEE Conference on Sensor, Mesh and Ad Hoc Communications and Networks (SECON)*, San Francisco, CA, USA, June 2008.
- [3] E. van Damme, "The Dutch UMTS Auction in Retrospect," CESifo Group, Tech.Rep., May 2001.
- [4] J. M. Peha, "Sharing Spectrum Through Spectrum Policy Reform and Cognitive Radio," in *Proceedings of the IEEE*, vol. 97, no. 4, pp. 708–719, April 2009.
- [5] Spectrum Policy Task Force, "Final Report" Federal Communications Commission, Washington, D.C., USA, Tech. Rep., ET Docket No. 02-135, November 2002.
- [6] M. A. McHenry, "NSF Spectrum Occupancy Measurements Project Summary," Shared Spectrum Company, Tech. Rep., August 2005.
- [7] I. F. Akyildiz, W.-Y. Lee, M. C.Vuran, and S. Mohanty, "Next generation/dynamic spectrum access/Cognitive Radio wireless networks: a survey," *Elsevier Computer Networks Journal*, vol. 50, no. 13, pp. 2127–2159, September 2006.
- [8] M. M. Buddhikot, "Understanding Dynamic Spectrum Access: Models, Taxonomy, and Challenges," in *Proc. of IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, Dublin, Ireland, April 2007, pp. 649–663.
- [9] Q. Zhao, and B. Sadler, "A Survey of Dynamic Spectrum Access," *IEEE Signal Processing Magazine*, vol. 24, no. 3, pp. 79–89, May 2007.
- [10] F. K. Jondral, "Software-Defined Radio - Basics and Evolution to Cognitive Radio," *EURASIP Journal on Wireless Communications, and Networking*, vol. 5, no. 3, pp. 275–283, August 2005.
- [11] R. Bagheri, A. Mirzaei, M. E. Heidari, S. Chehrazi, M. Lee, M. Mikhemar, W. K.Tang, and A. A. Abidi, "Software-Defined Radio Receiver: Dream to Reality," *IEEE Communications Magazine*, vol. 44, no. 8, pp. 111–118, August 2006.
- [12] U. Ramacher, "Software-Defined Radio Prospects for Multistandard Mobile Phones," *IEEE Computer*, vol. 40, no. 10, pp. 62–69, October 2007.
- [13] J. Mitola, "Cognitive Radio for Flexible Mobile Multimedia Communications," in *Proc.of IEEE International Workshop on Mobile Multimedia Communications (MoMuC)*, San Diego, CA, USA, November 1999, pp. 3–10.

- [14] R.W. Brodersen, A. Wolisz, D. Cabric, S.M. Mishra, D. Willkomm, Corvus: a cognitive radio approach for usage of virtual unlicensed spectrum, Berkeley Wireless Research Center (BWRC) White paper, 2004.
- [15] J. Mitola III, "Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio," *PhD. Dissertation Royal Institute of Technology*, Stockholm, Sweden, May 2000.
- [16] S. Haykin, "Cognitive Radio: Brain-empowered Wireless Communications", *IEEE Journal on Selected Areas Communication*, 23(2):201-220, February 2005.
- [17] ET Docket No. 03-108, March 11, 2005.
- [18] "Definitions of Software Defined Radio (SDR), and Cognitive Radio System (CRS)," *ITU- R SM.2152*, 2009, <http://www.itu.int/publ/R-REP-SM.2152-2009/en>.
- [19] I. F. Akyildiz, W.-Y. Lee, M. C. Vuran, and S. Mohanty, "A Survey on Spectrum Management in Cognitive Radio Networks," *IEEE Communications Magazine*, vol. 46, no. 4, pp. 40–48, April 2008.
- [20] O. Ileri, D. Samardzija, and N. B. Mandayam, "Demand Responsive Pricing and Competitive Spectrum Allocation via Spectrum Server," *Proc. IEEE DySPAN 2005*, Nov. 2005, pp. 194–202.
- [21] D. Cabric, S. Mishra, and R. Brodersen, "Implementation issues in spectrum sensing for cognitive radios," in *Proc. Asilomar Conf. on Signals, Systems, and Computers*, vol. 1, Pacific Grove, California, USA, Nov. 2004, pp. 772–776.
- [22] F. H. Sanders, "Broadband Spectrum Surveys in Denver, CO, San Diego, CA, and Los Angeles, CA: Methodology, Analysis, and Comparative Results," in *Proc. of IEEE Symposium on Electromagnetic Compatibility*, 1998.
- [23] M. A. McHenry, P. A. Tenhula, D. McCloskey, D. A. Roberson, and C. S. Hood, "Chicago Spectrum Occupancy Measurements & Analysis, and a Long-term Studies Proposal," in *Proc. of Workshop on Technology, and Policy for Accessing Spectrum (TAPAS)*, Boston, USA, August 2006.
- [24] R. I. C. Chiang, G. B. Rowe, and K. W. Sowerby, "A Quantitative Analysis of Spectral Occupancy Measurements for Cognitive Radio", in *Proc. of IEEE Vehicular Technology Conference (VTC)*, Dublin, Ireland, April 2007.
- [25] M. Wellens, J. Wu, and P. Mähönen, "Evaluation of spectrum occupancy in indoor and outdoor scenario in the context of cognitive radio," in *Proc. of International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, Orlando, FL, USA, August 2007, pp. 420–427.
- [26] M. Islam, G. L. Tan, F. Chin, B. E. Toh, Y.-C. Liang, C. Wang, Y. Y. Lai, X. Qing, S. W. Oh, C. L. Koh, and W. Toh, "Spectrum Survey in Singapore: Occupancy Measurements and Analyses," in *Proc. of International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, Singapore, May 2008, pp. 1-7.

- [27] M. Wellens, and P. Mähönen, “Lessons Learned from an Extensive Spectrum Occupancy Measurement Campaign and a Stochastic Duty Cycle Model,” *Springer Mobile Networks and Applications*, Special Issue on Advances in Wireless Testbeds and Research Infrastructure, vol. 15, no. 3, pp. 461-474, June 2010.
- [28] Lopez-Benitez, M.; Umbert, A.; Casadevall, F.; “Evaluation of Spectrum Occupancy in Spain for Cognitive Radio Applications,” in *Proc. of Vehicular Technology Conference, VTC Spring*, 26-29 April 2009, pp. 1-5.
- [29] Miguel López-Benítez, and Fernando Casadevall, “Spectrum Occupancy in Realistic Scenarios, and Duty Cycle Model for Cognitive Radio,” *Journal of Advances in Electronics and Telecommunications*, Vol. 1, No. 1, April 2010, pp. 26-34.
- [30] M. López-Benítez, F. Casadevall, “Methodological aspects of spectrum occupancy evaluation in the context of cognitive radio,” in *Proceedings of the 15th European Wireless Conference (EW 2009)*, Aalborg, Denmark, May 17-20, 2009, pp. 199-204.
- [31] V. Blaschke, H. Jakel, T. Renk, C. Kloeck, and F. K. Jondral, “Occupation measurements supporting dynamic spectrum allocation for cognitive radio design,” in *Proc. of International Conference on Cognitive Radio Oriented Wireless Networks and Communications (CROWNCOM)*, Orlando, FL, USA, August 2007.
- [32] Dennis A. Roberson and Cynthia S. Hood and Joseph L. LoCicero and John T. MacDonald, “Spectral Occupancy and Interference Studies in support of Cognitive Radio Technology Deployment” in *Proceedings of the 1st IEEE Workshop on Networking Technologies for Software Defined Radio Networks (SDR’06)*, 25–25 Sept. 2006, pp. 26–35.
- [33] Zhe Wang and Sana Salous, “Spectrum Occupancy Analysis for Cognitive Radio,” *London Communications Symposium*, University College London, 2006.
- [34] Dinesh Datla, Alexander M. Wyglinski, and Gary J. Minden, “A Spectrum Surveying Framework for Dynamic Spectrum Access Networks”, in *IEEE Transactions on Vehicular Technology*, vol. 58, no. 8, October 2009.
- [35] J. Ma, G. Y. Li, and B. H. Juang, “Signal Processing in Cognitive Radio,” *Proceedings of the IEEE*, vol. 97, no. 5, pp. 805–823, May 2009.
- [36] D. Cabric, A. Tkachenko, and R. W. Brodersen, “Experimental Study of Spectrum Sensing based on Energy Detection, and Network Cooperation,” in *Proc. of Workshop on Technology, and Policy for Accessing Spectrum (TAPAS)*, Boston, MA, USA, August 2006.
- [37] R. Tandra, and A. Sahai, “SNR Walls for Signal Detection,” *IEEE Journal of Selected Topics in Signal Processing*, vol. 2, no. 1, pp. 4–17, February 2008.
- [38] H. V. Poor, “An Introduction to Signal Detection, and Estimation”, 2nd ed. Berlin, Germany: Springer-Verlag, 1994.

- [39] H. Urkowitz, "Energy detection of unknown deterministic signals," *Proc. of the IEEE*, vol. 55, pp. 523–531, Apr. 1967.
- [40] H. Tang, "Some physical layer issues of wide-band cognitive radio systems," in *Proc. IEEE Int. Symposium on New Frontiers in Dynamic Spectrum Access Networks*, Baltimore, Maryland, USA, Nov. 2005, pp. 151–159.
- [41] J. Proakis, *Digital Communications*, 3rd edition, McGraw-Hill.
- [42] A. Sahai, N. Hoven, R. Tandra, "Some Fundamental Limits on Cognitive Radio", *Proc. of Allerton Conference*, Monticello, Oct 2004.
- [43] W. A. Gardner, "Signal interception: A unifying theoretical framework for feature detection," *IEEE Transactions on Communications*, vol. 36, no. 8, pp. 897–906, August 1988.
- [44] S. Shankar, C. Cordeiro, and K. Challapali, "Spectrum agile radios: utilization, and sensing architecture," in *Proc. IEEE Int. Symposium on New Frontiers in Dynamic Spectrum Access Networks*, Baltimore, Maryland, USA, Nov. 2005, pp. 160–169.
- [45] R. Tandra, and A. Sahai, "SNR walls for feature detectors," in *Proc. of IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks (DySPAN)*, Dublin.
- [46] R. J. Matheson, "Strategies for spectrum usage measurements," in *Proceedings of the IEEE International Symposium on Electromagnetic Compatibility (EMC 1988)*, Aug. 1988, pp. 235–241.
- [47] Kishor Patil, Ramjee Prasad, Knud Skouby, "A Survey of Worldwide Spectrum Occupancy Measurement Campaigns for Cognitive Radio," in *Proceedings of International conference on Devices and Communication (ICDeCom)*, Ranchi, India, 2011.
- [48] Radiocommunication Bureau, "HANDBOOK Spectrum Monitoring," *International Telecommunication Union (ITU)*, 2002.
- [49] Kishor Patil, Knud Skouby, Ashok Chandra, Ramjee Prasad, "Spectrum Occupancy Statistics in the Context of Cognitive Radio," in *Proc. of 14th International Symposium on Wireless Personal Multimedia Communications (WPMC'11)*, Brest, France November 2011.
- [50] F.K. Jondral, "Cognitive radio: A communications engineering view," *IEEE Wireless Communication*, vol. 14, pp. 28–33, Aug. 2007.
- [51] A. D. Spaulding and G. H. Hagn, "On the definition, and estimation of spectrum occupancy," *IEEE Transactions on Electromagnetic Compatibility*, vol. 19, pp. 269–280, Aug. 1977.
- [52] Petrin and P. G. Steffes, "Analysis and Comparison of Spectrum Measurements performed in Urban and Rural Areas to Determine the Total Amount of Spectrum Usage," in *Proc. of International Symposium on Advanced Radio Technologies (ISART)*, Boulder, CO, USA, March 2005, pp. 9–12.

- [53] National Frequency Allocation Plan NFAP-2011.
- [54] Telecom Regulatory Authority of India, 2007, Consultation paper on “Issues Relating to Mobile Television Service” *Paper No.9/2007*. Available on: <http://www.trai.gov.in>.
- [55] W. Zhang, A. Sadek, C. Shen, and S. Shellhammer, “Adaptive spectrum sensing,” in *Information Theory and Applications Workshop (ITA)*, Feb. 2010.
- [56] Rhode and Schwarz portable spectrum analyzer R&S FSH 3 manual
- [57] FSH Remote software manual
- [58] Kishor Patil, Knud Skouby, Ashok Chandra, Ramjee Prasad, “Spectrum Occupancy Statistics in the Context of Cognitive Radio,” in *Proc. of 14th International Symposium on Wireless Personal Multimedia Communications (WPMC'11)*, Brest, France November 2011.
- [59] S. J. Shellhammer, A. K. Sadek, and W. Zhang, “Technical Challenges for Cognitive Radio in the TV White Space Spectrum,” ITA 2009.
- [60] C. Stevenson, G. Chouinard, Z. Lei, W. Hu, S. Shellhammer, and W. Caldwell, “IEEE802.22: The First Cognitive Radio Wireless Regional Area Network Standard,” *Comm. Magazine*, Vol. 47, No.1, January 2009, pp. 130–138.
- [61] Federal Communications Commission, “In the Matter of Unlicensed Operation in the TV Broadcast Bands (ET Docket No. 04-186) and Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band (ET Docket No. 02-380): Second Memorandum Opinion and Order.” Federal Communications Commission, Washington, D.C., USA, , September 2010.
- [62] J. Zander, J. Kronander, A. Achtzehn, M. Nekovee, K. W. Sung, and S.L. Kim, “QUASAR Scenarios for White Space Assessments and Exploitation,” in *Proc. 9th International Symposium on EMC (EMC Europe 2010)*, Wroclaw, Sept. 2010.
- [63] Bacchus, R.B.; Taher, A.J.; Zdunek, K.J.; Roberson, D.A., "Spectrum Utilization Study in Support of Dynamic Spectrum Access for Public Safety," *New Frontiers in Dynamic Spectrum Access Networks, DySPAN 2010*, 4th IEEE Symposium, Singapore, April 2010.
- [64] Yang Wang, “Cognitive Radio for Aeronautical Air-Ground Communications”, *IEEE Aerospace and Electronic Systems Magazine*, June 2010, pp.18-23.
- [65] K. W. Sung, E. Obregon, and J. Zander, “On the Requirements of Secondary Access to 960-1215 MHz Aeronautical Spectrum,” in *Proc. IEEE DySPAN*, Aachen, May 3–6, 2011.
- [66] Jitin Bajaj, Woosong Kim, Soon Y. Oh, Mario Gerla, “Cognitive Radio Implementation in ISM Bands with Microsoft SORA” *22nd Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC' 11)*, Toronto, Canada, Sep. 11-14, 2011

- [67] P. F. Marshall, "Closed-form analysis of spectrum characteristics for CR performance analysis," *IEEE DySpan*, Chicago, IL, 2008, pp. 1-12.
- [68] C. Ghosh, S. Roy, M. B. Rao, and D. P. Agrawal, "Spectrum occupancy validation and modeling using real-time measurements," in *Proceedings of the 2010 ACM workshop on CR networks*, ser. CoRoNet '10, 2010, pp. 25-30.
- [69] P. M. Lee. *Bayesian Statistics: An Introduction*. Oxford University Press, Third Ed., 2004.
- [70] A. Stuart, K. Ord, and S. Arnold. *Kendall's Advanced Theory of Statistics*, 2A. London, pp. 25.37 U25.43, 1999.
- [71] Joseph W. Mwangoka, Paulo Marques, and Jonathan Rodriguez, "Exploiting TV White Spaces in Europe: The COGEU Approach" *IEEE Dynamic Spectrum Access Networks (DySPAN 2011)*, in Aachen, Germany.
- [72] M. Nekovee, Quantifying the availability of TV White Spaces for cognitive access in the UK, *IEEE ICC 2009*, June 2009, Dresden, Germany.
- [73] Federal Communications Commission, "In the Matter of Unlicensed Operation in the TV Broadcast Bands (ET Docket No. 04-186) and Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band (ET Docket No. 02-380): Third Memorandum Opinion and Order." Federal Communications Commission, Washington, D.C., USA, ET Docket No. 12-36, April 2012.
- [74] Ofcom, Statement on Cognitive Access to Interleaved Spectrum, 1 July, 2009.
- [75] Ofcom, TV White spaces: A consultation on white space devices requirements, 22 November, 2012.
- [76] Balmuralidhar.P, "Regulatory aspects and opprtunities of white spaces in India" in *proc.of Wirelss Vitae 2010*, Chennai, February 2010.
- [77] Kishor Patil, Ramjee Prasad, Knud Skouby, "Cognitive Access to TVWS in India: TV Spectrum Occupancy and Wireless Broadband for Rural Areas", in *Proc. of 15th International Symposium on Wireless Personal Multimedia Communications (WPMC'12)*, in Taipei, Taiwan, September 2012.
- [78] Kishor Patil, Ramjee Prasad, Knud Skouby, "Spectrum Measurement and Analysis of TV Band in Support of Cognitive Radio Operation in India", in *Proc. of 3rd International conference on Wireless VITAE 2013*, New Jersey, USA, June 2013.
- [79] R. Thanki, "The economic value generated by current and future allocations of unlicensed spectrum," available at http://www.ingeniousmedia.co.uk/websitefiles/Value_of_unlicensed_-_website_-_FINAL.pdf, September 2009.
- [80] Siddharth Shetty , Akshay Mishra and Abhay Karandikar, "Proposal for TV White Space towards National Frequency Allocation Plan (NFAP) 2010"

- [81] Federal Communications Commission, “In the Matter of Unlicensed Operation in the TV Broadcast Bands (ET Docket No. 04-186) and Additional Spectrum for Unlicensed Devices Below 900 MHz and in the 3 GHz Band (ET Docket No. 02-380): *Notice of Proposed Rule Making*,” Federal Communications Commission, Washington, D.C., USA, Tech. Rep. ET Docket No. 04-113, May 2004.
- [82] B. Scott and M. Calabrese, “Measuring the TV "White Space" Available for Un-licensed Wireless Broadband,” Free Press and New America Foundation, Tech.Rep., November 2005.
- [83] M. Mishra and A. Sahai, “How much white space is there?” Electrical Engineering and Computer Sciences, University of California at Berkeley, Berkeley, CA,USA, *Tech. Rep. UCB/EECS-2009-3*, January 2009.
- [84] L. Berlemann and S. Mangold, *Cognitive Radio and Dynamic Spectrum Access*. Chichester, United Kingdom: John Wiley & Sons Ltd., 2009.
- [85] R. Dhillon and T. Brown, “Models for analyzing cognitive radio interference to wireless microphones in TV bands,” in *Proc. of IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks, DySPAN*, Chicago, IL, USA, October 2008.
- [86] S. K. Jones and T. W. Phillips, “Initial Evaluation of the Performance of Prototype TV-Band White Space Devices,” Federal Communications Commission, Office of Engineering and Technology, Laboratory Division, Technical Research Branch, Tech. Rep. FCC/OET 07-TR-1006, July 2007.
- [87] S. K. Jones, T.W. Phillips, H. L. V. Tuyl, and R. D.Weller, “Evaluation of the Performance of Prototype TV-Band White Space Devices, Phase II,” Federal Communications Commission, Office of Engineering and Technology, Laboratory Division, Technical Research Branch, Tech. Rep. FCC/OET 08-TR-1005, October 2008.
- [88] <http://www.fcc.gov/encyclopedia/white-space-database-administration>
- [89] ECC Report 159, Technical and operational requirements for the possible operation of cognitive radio systems in the ‘white spaces’ of the frequency band 470-790 MHz, Cardiff, January 2011.
- [90] K.G. Shin, H. Kim, A. Min, and A. Kumar. “CRs for Dynamic Spectrum Access: From Concept to Reality”. *IEEE Wireless Communication Magazine (IEEE WCM)*, Vol. 17, No. 6. December, 2010.
- [91] C.Stevenson, G. Chouinard, Z. Lei, W. Hu, S. Shellhammer, and W. Caldwell, “IEEE802.22: The First CR Wireless Regional Area Network Standard,” *Comm. Magazine*, Vol. 47, No.1,January 2009, pp. 130–38.
- [92] S.Filin, T. Baykas, M.Azizur Rahman, H.Harada, “Performance Evaluation of IEEE 802.19.1 Coexistence System” in *Proc. of IEEE International Conference on Communications (ICC)*,Kyoto, June 2011.

- [93] R Chandrashekar, Secretary, Department of Telecommunication, and Chairman, Telecom Commission, "Connecting the Panchayats in the country" an exclusive interview with eGov magazine.
- [94] Office of the Registrar General and Census Commissioner, Ministry of Home Affairs, Govt. of India, http://censusindia.gov.in/Census_And_You/area_and_population.aspx
- [95] DTU, "New Technologies and Their Impacts on Regulation" Module 7 of ICT Regulation Toolkit.
- [96] Maziar Nekovee, "Impact of Cognitive Radio on Future Management of Spectrum" *Proc. CrownCom 2008*, Singapore, May 2008.
- [97] Peter Anker, "Cognitive Radio, the Market and the Regulator" *IEEE DySPAN 2010*, Singapore.
- [98] Kishor Patil, Ramjee Prasad, Knud Skouby, "Frequency Usage and Digital Dividend in India", in *monograph series of Scientific Journal of the University of Szczecin*, 2013.
- [99] <http://www.trai.gov.in>
- [100] David Lewin, Val Jervis, Chris Davis, Ken Pearson, "An assessment of spectrum management policy in India," December 2008. Available at [http://www.aegissystems.co.uk/download/2021/spectrum%20management%20\(india\).pdf](http://www.aegissystems.co.uk/download/2021/spectrum%20management%20(india).pdf)
- [101] "Estimated Spectrum Bandwidth Requirements for the Future Development of IMT-2000 and IMT-Advanced," 47 Report ITU-R M.2078. Available at <http://www.itu.int/publ/R-REP-M.2078-2006/en>.
- [102] Digital terrestrial Television Action Group (DigiTAG) "Analogue Switch Off Handbook learning from the experiences in Europe", 2008.
- [103] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, "Reaping the full benefits of the digital dividend in Europe: a common approach to the use of the spectrum released by the digital switchover," *COM (2007)700*, Dec. 2007. <http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=CELEX:52007DC0700:EN:NO> .
- [104] Anders Henten, Reza Tadayoni and Iwona Windekilde, "Spectrum war – The battle for the digital dividend spectrum" " In *Proceeding of the 18 Biennial ITS conference*, Tokyo, Japan.
- [105] How should digital dividend be used? EBU view. Available at <http://www.ebu.ch>.
- [106] Arif Khan, "Digital Dividend to Digital Opportunity". Available at [http://cmai.asia/sppt/Presentation%20to%20CMAI_COAI%20eventEricsson%20\[Compatibility%20Mode\]\).pdf](http://cmai.asia/sppt/Presentation%20to%20CMAI_COAI%20eventEricsson%20[Compatibility%20Mode]).pdf)
- [107] Recommendation ITU-R M.1645

- [108] “WRC 07 Decisions secure wireless future” *Journal of ITU News*, No.10, pp.28-34, 2007.
- [109] Proposal from GSMA to JTG-India. Available at <http://www.wpc.dot.gov.in/jtgindia.asp>.
- [110] TEMA proposal for 700 MHZ band plan.
Available at <http://www.wpc.dot.gov.in/jtgindia.asp>.
- [111] AUSPI’s proposed band plan for 698-806MHz.
Available at <http://www.wpc.dot.gov.in/jtgindia.asp>
- [112] Ericsson Proposal on allocation of spectrum in UHF band in India.
Available at <http://www.wpc.dot.gov.in/jtgindia.asp>
- [113] Proposed Frequency Arrangement for UHF Band 698 – 806 MHz, Nokia Siemens Networks / Nokia – India. Available at <http://www.wpc.dot.gov.in/jtgindia.asp>
- [114] COAI proposal for the 700MHz band.
Available at <http://www.wpc.dot.gov.in/jtgindia.asp>
- [115] Proposal from WiMAX Forum. Available at <http://www.wpc.dot.gov.in/jtgindia.asp>
- [116] Doordarshan’s Proposal for JTG-India on 698-806 MHz Band.
<http://www.wpc.dot.gov.in/jtgindia.asp>
- [117] APT Report on “Implementation Issues Associated with Use of the Band 698-806 MHz by Mobile Services” *No. APT/AWG/REP-24*, September 2011.
- [118] CEPT Report 22 on “Technical considerations regarding harmonization options for the Digital Dividend “and “Technical Feasibility of Harmonizing a Sub-band of Bands IV and V for Fixed/Mobile Applications (including uplinks), minimizing the Impact on GE06” 1 July 2008
- [119] Siriginidi Subba Rao, Bridging digital divide: *Efforts in India Telematics and Informatics*, Vol. 22 (2005) issue 4, pp 361–375.
- [120] http://www.gsmworld.com/our-work/public-policy/spectrum/digital-dividend/digital_dividend.htm
- [121] “Trends in Accessibility of Services and Networks”, P. Tournassoud.
http://www.alcatel-lucent.com/enrich/v2i12008/article_c1a5.html
- [122] <http://www.ctia.org/advocacy/research/index.cfm/AID/10538>. See also, International Association for Wireless Telecommunications Industry, New York City, 2009.
- [123] J. M. Peha, “Approaches to Spectrum Sharing,” *IEEE Communications*, Feb. 2005.
Available at www.ece.cmu.edu/~peha/wireless.html.

- [124] B. Wang, Z. Ji, and K.J.R. Liu. "Primary-prioritized Markov approach for dynamic spectrum access," *2nd IEEE International Symposium on New Frontiers in Dynamic Spectrum Access Networks*, vol.1 and 2, pp.495-503, 2007.
- [125] X. Zhu, L. Shen and T.-S. P. Yum, "Analysis of cognitive radio spectrum access with optimal channel reservation," *IEEE Commun. Letters*, vol. 11, no.4, pp.304-306, Apr. 2007.
- [126] P.K. Tang, Y.H. Chew, L.C. Ong, M.K. Haldar, "Performance of secondary radios in spectrum sharing with prioritized primary access," *IEEE MILCOM 2006*, vol.1-7, pp.1273-1279.
- [127] Y. Xing, R. Chandramouli, S. Mangold, and S. Shankar, "Dynamic spectrum access in open spectrum wireless network," *IEEE J. Sel. Areas Commun.*, vol. 24, pp.626-636, Mar. 2006.
- [128] Li-ke Wang; Yi-hua Zhu, "A spectrum sharing scheme for cognitive radio networks", in *Proc. International Conference on Communications and Networking in China, ChinaCOM 2009*, 26-28 Aug. 2009, pp1 – 4.
- [129] Kishor Patil, Madhukar Deshmukh, Horia Cornean, "CTMC based spectrum sharing scheme for Cognitive Radio Networks", in *Proc. of 8th International Conference on Communications (COMM 2010)*, Bucharest, Romania, June 2010.
- [130] T. Weiss, J. Hillenbrand, A. Krohn, and F. Jondral, "Mutual interference in OFDM-based spectrum pooling systems," in *Proc. IEEE VTC*, May 2004, vol. 4, pp. 1873–1877.
- [131] B. Farhang-Boroujeny and R. Kempter, "Multicarrier communication techniques for spectrum sensing and communication in cognitive radios," *IEEE Commun. Mag.*, vol. 46, no. 4, pp. 80–85, Apr. 2008.
- [132] M. Wellens, J. Riihijarvi, and P. Mahonen, "Empirical Time and Frequency Domain Models of Spectrum Use," Elsevier Physical Communication, Special issue on Cognitive Radio: Algorithms & Systems Design, vol. 2, no. 1-2, pp. 10-32, March-June 2009.
- [133] A. Clauset, C. R. Shalizi, and M. E. J. Newman, "Power-law distributions in empirical data," accepted for publication in *Society for Industrial and Applied Mathematics (SIAM) Review (SIREV)*, available online at <http://arxiv.org/abs/0706.1062v2> [Cited on: 5th March 2009], revised in February 2009.
- [134] CEPT Report 22 on "Technical considerations regarding harmonization options for the Digital Dividend" and "Technical Feasibility of Harmonizing a sub-band of Bands IV and V for Fixed/Mobile Applications (including uplinks), minimizing the Impact on GE06" 1 July 2008.
- [135] Guidotti, A., Guiducci, D. ; Barbiroli, M. ; Carciofi, C. ; Grazioso, P. ; Riva, G. . "Coexistence and Mutual Interference between Mobile and Broadcasting Systems." *IEEE 73rd Vehicular Technology Conference (VTC Spring)*. 15-18 May 2011. Budapest, 2011. P.1-5.

- [136] Kratochvíl, T., Říčný, V. "Simulated Testing of the Interferences Influence on the DVB-T Signal," In Proceedings of the 19th International Conference Radioelektronika 2009. Bratislava (Slovakia), 2009, p. 107 - 110.
- [137] Šakić, K., Grgić S. "The Influence of the LTE system on DVB-T reception," In Proceedings of the 52nd International Symposium ELMAR-2010, Zadar (Croatia), 2009, p. 235-238.
- [138] Denny Setiawan, Dadang Gunawan, Djamhari Sirat, "Interference Analysis of Guard Band and Geographical Separation between DVB-T and E-UTRA in Digital Dividend UHF Band," Proc. ICICI-BME 2009, Bandung, Indonesia, November 23-25, 2009.

List of Publications

Journal contributions relevant to the thesis at hand

- **Kishor Patil**, Ramjee Prasad, Knud Skouby, “Frequency Usage and Digital Dividend in India”, in *monograph series of Scientific Journal of the University of Szczecin*, No. 767, vol. no. 1, page 537 – 553, June 2013. **(Published)**

Conference contributions relevant to the thesis at hand

- **Kishor Patil**, Madhukar Deshmukh, Horia Cornean, “CTMC based spectrum sharing scheme for Cognitive Radio Networks”, in *Proc. of 8th International Conference on Communications (COMM 2010)*, pp.509-512, Bucharest, Romania, June 10-12, 2010. **(Published)**
- **Kishor Patil**, Ramjee Prasad, Knud Skouby, “A Survey of Worldwide Spectrum Occupancy Measurement Campaigns for Cognitive Radio,” in *Proc. of International conference on Devices and Communication (ICDeCom)*, pp. 89-83, Ranchi, India, February 24-26, 2011. **(Published)**
- **Kishor Patil**, Knud Skouby, Ashok Chandra, Ramjee Prasad, “Spectrum Occupancy Statistics in the Context of Cognitive Radio”, in *Proc. of 14th International Symposium on Wireless Personal Multimedia Communications (WPMC'11)*, pp.486-490, Brest, France, October 3-7,2011. **(Published)**
- **Kishor Patil**, Ramjee Prasad, Knud Skouby, “Stochastic Duty Cycle Model Based on Measurement for Cognitive Radio”, in *Proc. of 15th International Symposium on Wireless Personal Multimedia Communications (WPMC'12)*, pp.128-13, Taipei, Taiwan, September 24-27, 2012. **(Published)**
- **Kishor Patil**, Ramjee Prasad, Knud Skouby, “Cognitive Access to TVWS in India: TV Spectrum Occupancy and Wireless Broadband for Rural Areas”, in *Proc. of Global Wireless Summit (GWS 2013) Special Session*, New Jersey, USA, June 24-27, 2013. **(Selected and presented)**
- **Kishor Patil**, Ramjee Prasad, Knud Skouby, “Spectrum Measurement and Analysis of TV Band in Support of Cognitive Radio Operation in India”, in *Proc. of 3rd International conference on Wireless VITAE 2013*, New Jersey, USA, June 24-27, 2013. **(Selected and presented)**
- **Kishor Patil**, Snehal Barge, Ramjee Prasad, Knud Skouby, “Evaluation of Spectrum Usage for GSM band in Indoor and Outdoor Scenario for Dynamic Spectrum Access”, in *Proc. of International Conference on Advances in Computing, Communications and Informatics (ICACCI-2013)*, Mysore, India, August 22-25, 2013. **(Selected and presented)**
- Madhukar Deshmukh, **Kishor Patil**, Flemming Frederiksen, Knud Skouby, Ramjee Prasad, “Wireless Broadband Network on TVWS for Rural Areas: an Indian

Perspective”, in *Proc. of 16th International Symposium on Wireless Personal Multimedia Communications (WPMC’13)*, in New Jersey, USA, June 24-27, 2013. **(Selected and presented)**

Journal contributions in addition to the research presented in this thesis

- **Kishor Patil**, Knud Skouby, Ramjee Prasad, “ Resource Allocation during Efficient Spectrum Handoffs in CR Network” **(Submitted to Supervisors)**

Contribution of Publications

Paper 1: A Survey of Worldwide Spectrum Occupancy Measurement Campaigns for Cognitive Radio

In this paper, measurement challenges and methodological aspects are discussed. Also we reviewed past measurement campaigns performed by different research groups and analysis of empirical results. We further provide a spectrum occupancy measurement framework for the proposed spectrum measurement in India.

Paper 2: Spectrum Occupancy Statistics in the Context of Cognitive Radio

This paper reports the spectrum occupancy measurements conducted in the frequency band from 700 MHz to 2700 MHz in an outdoor environment in the suburban of Mumbai, India. The measurement results of two weekdays campaign shows considerably low occupation with great potential for dynamic usage of spectrum. Further we discuss CR potentials based on the measurement results.

Paper 3: Stochastic Duty Cycle Model Based on Measurement for Cognitive Radio.

In this paper we report the outcomes of the spectrum occupancy measurements conducted in Pune, India at different locations in the frequency band 700-2746.6 MHz. There are three contributions of this paper. First, we report the results of the spectrum occupancy measurement showing the impact of the measurement location on the spectrum occupancy. Second, we present the stochastic duty cycle model based on measurement to identify the potential for CR in the measured band. Third, we discuss the suitable wireless services in the identified band for CR.

Paper 4: Spectrum Measurement and Analysis of TV Band in Support of Cognitive Radio Operation in India

TV White Spaces constitutes the major portion of the VHF and UHF TV band which is geographically unused after digital switchover. The most important regulatory trend in the context of Dynamic Spectrum Access (DSA) is the Cognitive access of TV white Spaces. Through spectrum measurement campaign we have estimated the spectrum utilization of TV band in Pune, India. We have designed the measurement set up and methodology for the measurement campaign. Our spectrum occupancy analysis provides the realistic view on the spectrum opportunities in India for (i) spectrum refarming of TV band; (ii) Cognitive Radio operation in TV band. Also we have stressed on the need of quantitative analysis of TVWSs availability and compatibility studies for protection of incumbent services for CR access of TVWSs in India. Also this paper reviews the state-of-the-art in standardization of cognitive access to TVWS.

Paper 5: Cognitive Access to TVWS in India: TV Spectrum Occupancy and Wireless Broadband for Rural Areas

The digital transition of TV transmission will make available some TV frequencies which are to be geographically unused called as TV White Spaces. The important regulatory trend in the context of Dynamic Spectrum Access (DSA) is the Cognitive access of TV white Spaces. In this context, we have performed spectrum measurements of TV band in Pune, India. Our result shows poor spectrum utilization in TV band, and good potential for Cognitive radio operation. Digital switchover in India will generate golden opportunity for empowering rural India. As majority of India's population lives in rural part of India, we have proposed wireless broadband access to rural areas using TV White Spaces (TVWSs). This will help in bridging the digital divide by offering governance, banking, and health services online in the rural areas.

Paper 6: Frequency Usage and Digital Dividend in India.

This paper presents the spectrum utilization results of mobile telecom services particularly, GSM from the spectrum occupancy measurement campaign conducted in Pune, India. We observed the highest occupancy rate in the 2G cellular telecom services band showing demand mobile telecom services is high in India, and so for the spectrum. The results of our measurement campaign endorses the decision of India to identify the 698-806 MHz band (700 MHz band) for the International Mobile Telecommunications (IMT) services which is also in the line of ITU initiative of global harmonization in IMT band. Further, we discuss about the switchover plan from analogue to digital Television (TV) in India, and resulting digital dividend spectrum (700 MHz band) from spectrum re-farming, which could be the solution for the spectrum requirement for mobile telecom services in India. The views of the different stakeholders about 700 MHz band plan is presented. Finally, the two harmonized frequency arrangement for IMT systems agreed by the Asia Pacific Telecommunity (APT) for 700 MHz band is discussed.

Paper 7: CTMC based spectrum sharing scheme for Cognitive Radio Networks.

In this paper a spectrum sharing scheme is proposed, in which there are two primary users and multiple secondary users who share frequency spectrum with the primary users. A continuous time Markov chain (CTMC) analysis model is presented to derive the statistics of the proposed scheme. Numeric experiments are presented to examine impacts of various parameters on the derived statistics of the proposed scheme.

Paper 8: Evaluation of Spectrum Usage for GSM band in Indoor and Outdoor Scenario for Dynamic Spectrum Access

This paper describes the GSM band measurement conducted at different locations. In this paper, we report detailed measurement results of GSM band including statistical as well as spectral occupancy details obtained from measurement campaign conducted in Pune, India for indoor and

outdoor scenarios. The results can be further used as an input for spectrum regulator for considering Cognitive Radio (CR) operation in GSM band.

Paper 9: Wireless Broadband Network on TVWS for Rural Areas: an Indian Perspective.

The focus of the paper is to assess the availability of geographically interleaved spectrum, also known as television spectrum white spaces (TVWS) and proposing the wireless network scenarios for rural broadband connectivity.

Contribution of Publications to Thesis Chapters

Sr. No.	Publications	Ch.1	Ch.2	Ch.3	Ch.4	Ch.5	Ch.6	Ch.7
1	A Survey of Worldwide Spectrum Occupancy Measurement Campaigns for Cognitive Radio		√					
2	Spectrum Occupancy Statistics in the Context of Cognitive Radio		√					
3	Stochastic Duty Cycle Model Based on Measurement for Cognitive Radio			√		√		
4	Spectrum Measurement and Analysis of TV Band in Support of Cognitive Radio Operation in India				√			
5	Cognitive Access to TVWS in India: TV Spectrum Occupancy and Wireless Broadband for Rural Areas				√			
6	Frequency Usage and Digital Dividend in India					√		
7	CTMC based spectrum sharing scheme for Cognitive Radio Networks						√	
8	Evaluation of Spectrum Usage for GSM band in Indoor and Outdoor Scenario for Dynamic Spectrum Access			√				
9	Wireless Broadband Network on TVWS for Rural Areas: an Indian Perspective.				√			

Curriculum Vitae

Kishor P. Patil (Life member of Computer Society of India and ISTE) received the Bachelor degree in Electronics engineering from Amravati University in 1987 and the Master of Electronics Engineering from Gulbarga University in 2000. Currently he is pursuing his Ph.D. in wireless communication at Center for TeleInFrastructure (CTIF), Aalborg University, Denmark. Currently he is working as an associate professor in Sinhgad Academy of Engineering, Pune. His main research interests are in the area of spectrum occupancy modeling for Cognitive Radio, Cognitive Radio Networks, TV White Space availability in India, and regulation and policies for Cognitive Radio in the Indian context.