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## Radio Spectrum Management for Future Wireless Communication Services

Tripathi, P.S.M.

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# RADIO SPECTRUM MANAGEMENT FOR FUTURE WIRELESS COMMUNICATION SERVICES



AALBORG UNIVERSITET

A DISSERTATION  
SUBMITTED TO THE DEPARTMENT  
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DOCTOR OF PHILOSOPHY



PURNENDU SHEKHAR MANI TRIPATHI  
CENTER FOR TELEINFRATRUTUR

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**Supervisor:**

Professor Ramjee Prasad, Aalborg University, Denmark

**Examination Committee:**

Associate Professor Morten Falch (Chairman)  
Department of Electronic Systems, Copenhagen  
Aalborg University, A.C. Meyers Vnge 15  
DK-2450 Copenhagen SV  
E-mail: falch@cmi.aau.dk

Professor Seshadri Mohan  
Systems Engineering Department  
University of Arkansas at Little Rock  
Little Rock, AR 72204, Arkansas  
USA  
E-mail: smseshmohan@gmail.com

Director Sudhir Dixit  
Communications and Media Services Comms (Americas)  
Hewlett-Packard Enterprise Services  
USA  
E-mail: sudhir.dixit@ieee.org

**Moderator:**

Associate Professor Albena D. Mihovska, Aalborg University, Denmark

**Date of Defence:**

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# Abstract

*Prior to the emergence of mobile communications, radio spectrum was mainly used by police and military and some other government agencies. In public domain, radio spectrum was related to broadcasting services. During this period, no one thought that radio spectrum had any revenue potential like any other natural resource and therefore, no specific regulations were required to manage radio spectrum. After emergence of mobile communications, we heard demand of radio spectrum for commercial use. With the passage of time, demand for radio spectrum started increasing from every users be it Defence, Police or industry.*

*Radio spectrum has now acquired an interesting status of omnipresence; be it in a developed country or a developing one, recognized the world-over as an important tool for the socio-economic development of the nation. It is well recognised that in every nation-state it represents between 1 and 3% of the gross domestic product, the total added value of goods and services in the economy. It becomes a bridge between business, defence, safety and to our social welfare. Considering the commercial impact of radio spectrum, the methodology of allocation of spectrum for commercial services has shifted to market determined method like Beauty Contest and Auction from earlier widely used First Come First Served (FCFS) method.*

*In recent years, technological innovation in the field of communications has placed increasing demands on radio spectrum. The demands of spectrum from existing traditional services such as broadcasting, mobile voice services, public safety services and defence have also grown. All these put together, placed a strain on the finite radio spectrum resource. The existing spectrum management is unable to meet the ever increasing demand of radio spectrum. As per current usage, no vacant spectrum is available below 5 GHz. The bigger question is that whether the spectrum is really exhausted, not available for new services. Studies on spectrum utilization have shown the different story. Studies show that spectrum is underutilized in most of the frequency bands at given time and location meaning that, part of the frequency band could be free and available at a particular time and location, although it has*

been allocated to some primary services. This unutilised spectrum is known as 'White Space'.

The concept of white space has further been broadened, when we talk about terrestrial TV broadcasting network. TV Broadcast services operate in VHF (54 MHz to 216 MHz) and UHF (470 MHz to 806 MHz) bands in analog and digital mode. Due to Multi frequency network, it is impossible to use entire spectrum at one location i.e. a part of allocated spectrum is used at one location and a big chunk of spectrum becomes unused at that particular location. This unused spectrum is known as TV White Space. At this point of time, it was felt that existing rigid radio spectrum management method is unable to tackle this underutilisation problem and flexibility in management of radio spectrum is desired. Accordingly, flexibility in spectrum management has been introduced through allowing spectrum trading, spectrum pooling and spectrum refarming, and making a part of spectrum de-licensed. This flexibility has further extended in new concepts namely dynamic spectrum access (DSA) and cognitive radio (CR) technology. The DSA is a method which allows wireless user to access the spectrum dynamically (instead of static) on time and location basis. Cognitive radio (CR) is the most promising technology which facilitates access spectrum dynamically.

With the passage of time, more and more services got converged with the advancement in the generation of mobile communications. Convergence demands more spectrum and high throughput. Presently we are in the 4th generation of mobile communication. The desire of greater mobility has envisaged 5th generation of mobile communication to provide upto 1Tbps link rate. To realise 5G vision, we need high amount of contiguous spectrum. We need to look towards mm-waves as well as to enhance the flexibility in the management of spectrum at the lower end.

The thesis provides an overview of radio spectrum management, its requirement, management at different level and various available methods for allocation of spectrum with a focus on radio spectrum management in India and present a new method of allocation of spectrum for commercial services particularly telecommunication services to enhance the spectrum utilisation as well as revenue through the auction of spectrum. The thesis also describes a detailed analysis of spectrum trading in telecom sector at operator level and discuss a scenario for spectrum trading at user level and gives a comprehensive study about 5G network and the spectrum requirements for 5G network. No regulation has so far been developed in India for deployment of cognitive radio. The thesis presents an analysis for deployment of cognitive radio in India.

Worldwide, radio spectrum manager has made regulations to exploit this TV White space. FCC, USA and Ofcom, UK have taken initiatives to ex-

*exploit TV white space by making regulations. Several other countries have also made regulations for utilization of TV white space based on the regulations made by the FCC and the Ofcom. However, no such regulations have been developed in India for utilization of TV white space. The thesis provides an overview of utilization of TV white space in different countries and present detailed analysis of status of TV white space in India, possible regulations for its utilization and applications in Indian scenario.*

*In summary, the thesis provides in-depth study of the Radio Spectrum Management with a focus on spectrum assignment for telecom sector, spectrum requirements for 5G network and utilisation of TV white space in India.*



# Dansk Resume

*Forud for fremkomsten af mobilkommunikation blev radiospektrum primært anvendes af politi og militær og nogle andre statslige organer. I det offentlige domne, blev radiospektrum relateret til radio- og tv-tjenester. I denne periode, ingen troede, at radiofrekvenser havde nogen indtægter potentiale som enhver anden naturressource, og derfor blev der ingen specifikke regler forpligtet til at forvalte radiofrekvenser. Efter fremkomsten af mobilkommunikation, har vi efterspørgslen af radiofrekvenser til kommerciel brug. Med tiden er efterspørgslen efter radiofrekvenser begyndte stigende fra hver brugere i det Forsvar, politi eller industri.*

*Radiofrekvenser har nu fået en interessant status allestedsnærværelse, det ses i et udviklet land eller et udviklingsland en, anerkendt verden over som et vigtigt redskab for den socio-økonomiske udvikling af nationen. Det er velkendt, at i hvert nationalstaten det repræsenterer mellem 1 og 3 % af bruttonationalproduktet, at den samlede merværdi af varer og tjenester i økonomien. Det bliver en bro mellem erhvervslivet, forsvar, sikkerhed og til vores sociale velfærd. I betragtning af den kommercielle virkning af radiospektrum, er metoden for tildeling af frekvenser til kommercielle tjenester flyttet til markedet bestemt metode som konkurrence og auktion fra tidligere udbredte først til melle (FCFS) metode.*

*I de senere år har den teknologiske innovation inden for kommunikation placeret stigende krav til radiofrekvenser. Kravene til spektret fra de eksisterende traditionelle tjenester såsom radio, mobil tale-tjenester, offentlige sikkerhedstjenester og forsvar er også vokset. Alle disse sat sammen, lagde en belastning på finite radiofrekvenser ressource. Den nuværende ledelse spektret er i stand til at imødekomme den stadigt stigende efterspørgsel af radiofrekvenser. Pr. nuværende brug, ingen ledig frekvenser til rådighed under 5 GHz. Det større spørgsmål er, hvorvidt spektret er virkelig udmattet, ikke tilgængelige for nye tjenester. Undersøgelser om udnyttelse af spektret har vist anden historie. Undersøgelser viser, at frekvensressourcerne underudnyttet i de fleste af de frekvensbånd ved en given tid og sted betyder, at en del af frekvensbåndet kan være gratis og tilgængelig på et bestemt tidspunkt og sted, selv om det er*



blevet tildelt nogle primære tjenester. Denne uudnyttede spektrum er kendt som "White Space".

Begrebet hvide rum er yderligere blevet udvidet, når vi taler om jord-baseret tv sendenet. TV-tjenester opererer i VHF (54 MHz til 216 MHz) og UHF (470 MHz til 806 MHz) bånd i analog og digital tilstand. Grundet Multi frekvens -netværk, er det umuligt at bruge hele spektret på et sted, dvs en del af den tildelte frekvenser anvendes på et sted og en stor luss af frekvenser bliver anvendt på det pågældende sted. Denne ubrugte spektrum er kendt som 'TV White Space'. På dette tidspunkt, var det opfattelsen, at de eksisterende stive radiofrekvensforvaltning metode er i stand til at tackle dette underforbrug problem og fleksibilitet i forvaltningen af radiofrekvenser er ønsket. Derfor har fleksibilitet i frekvensforvaltning blevet indført ved at tillade handel med frekvenser, frekvenser pooling og spektrum genopdyrkning, og gøre en del af frekvenser de-licens. Denne fleksibilitet er yderligere udvidet i nye koncepter, nemlig dynamisk spektrum adgang (DSA) og kognitiv radio (CR) teknologi. DSA er en metode, som muliggør trådløs brugeren adgang til spektret dynamisk (i stedet for statisk) om tid og sted basis. Kognitiv radio (CR) er den mest lovende teknologi, der letter adgangen spektrum dynamisk.

Med tiden, fik flere og flere tjenester konvergeret med advancement i generation af mobil kommunikation. Konvergens kræver mere spektrum og high throughput. I jeblikket er vi i 4. generation af mobil kommunikation. ønsket af større mobilitet har planlagt 5. generation af mobil kommunikation til at give op 1Tbps link sats. For at realisere 5G vision, vi har brug for høj mængde af sammenhængende spektrum. Vi er nødt til at kigge i retning mm-bølger samt at gøre fleksibiliteten i forvaltningen af frekvenser i den lave ende.

Afhandlingen giver et overblik over radiofrekvensforvaltning, sit krav, ledelse på forskellige niveauer og forskellige tilgængelige metoder til tildeling af frekvenser med fokus på forvaltning af frekvensressourcer i Indien og præsentere en ny metode til allokering af frekvenser til kommercielle tjenester især telekommunikationstjenester til at gøre spektret udnyttelse samt indtægter gennem auktionen af frekvenserne. Afhandlingen beskriver også en detaljeret analyse af handel med frekvenser i telebranchen på operatør niveau og diskutere et scenario for handel med frekvenser på brugerniveau og giver en omfattende undersøgelse om 5G netværk og behovet for frekvenser til 5G netværk. Ingen regulering er hidtil blevet udviklet i Indien til indstilling af kognitiv radio. Afhandlingen indeholder en analyse for indstilling af kognitiv radio i Indien.

På verdensplan har radiospektrum manager gjort regler for at udnytte dette TV White space. FCC, USA og Ofcom har UK taget initiativer til at udnytte TV hvide rum ved at gøre regler. Flere andre lande har også gjort regler for udnyttelse af TV hvide rum baseret på regler fastsat af FCC og Ofcom. Imidlertid er udviklet sådanne regler i Indien for udnyttelse af TV hvide rum.

*Afhandlingen giver et overblik over udnyttelsen af TV hvide rum i forskellige lande og nuvrende detaljeret analyse af status for TV hvide rum i Indien, mulige regler for dens anvendelse og applikationer i indiske scenario.*

*Sammenfattende Afhandlingen giver grundig undersøgelse af Radio Spectrum Management med fokus p frekvenstildelingen for telesektoren, behovet for frekvenser til 5G netværk og udnyttelse af TV hvide rum i Indien.*



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I dedicate this work to my parents without their encouragement and motivation, this dream could not be accomplished.

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# Dedication

Dedicated to Dr. Ashok Chandra to turn me into the person that, I am today

To my wonderful wife Dr. Ragini Tripathi for her love and affection at times of trauma and stress

To my beloved daughter Keya who makes everything worthwhile..



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# Chapter 1

## Introduction

## 1.1 Background and Motivation

Radio Spectrum is an essential raw material for wireless services. It is a vital input for many public, security and government services. Wireless communications technology has become a key element in modern society. In our daily life, devices such as TV remote controllers, cellular phones, personal digital assistants (PDAs), and satellite TV receivers etc. are based on wireless communications technology. Today the total numbers of users subscribing to cellular wireless services have surpassed the number of users subscribing to the wired telephone services[1]. Besides cellular wireless technology, cordless phones, wireless local area networks (WLANs), and satellites are being extensively used for voice and data oriented communications applications and entertainment services.

In coming days, spectrum demand is going to be increased manifold. The demands of spectrum from existing traditional services such as broadcasting, telecom services, public safety services and defence have also grown. The International Telecommunications Union (ITU)[2] Reports (ITU-R M.2078) titled "Estimated Spectrum Bandwidth Requirements for the Future Development of IMT 2000 and IMT-Advanced" [3] projects overall spectrum requirements for the future development of IMT-Advanced. The study considered two different scenarios, one representing the situation in small and and/or less developed countries (comprising lower traffic volume and slower development i.e. low market setting), and the other one representing the situation in large industrialized and densely populated countries (high market setting). The ITU report has projected a total spectrum requirement by the year 2020 would be 1720 MHz for high market and 1280 MHz for low market. Ericsson[4] has estimated that the mobile traffic data will grow by 12 fold by the end of the year 2018 in which the typical mobile PC will generate 11.0 GB, a tablet 2.7 GB, a smart phone around 2.0 GB per month and no significant growth will take place in fixed traffic data. The existing command and control method of spectrum management[5] is unable to meet the increasing demand of radio spectrum. There is a need to redefine the radio spectrum management to accommodate the demands of users.

ITU has defined 41 types of radiocommunication services and mobile services is one of them[6]. Mobile telecom services is a part of mobile services. Mobile telecom is one of the fastest growing sector in the world. The growth of any other industry has a direct or indirect link with telecom. Telecommunications along with Information Technology has greatly accelerated the growth of the economic and social sectors of a country and contributed significantly to the countrys economic growth. It can be seen that the global

telecom services market generated US\$ 1.4 trillion in the year 2009 despite the economic slowdown[7]. At the same length, spectrum demand in telecom sector is much higher as compared to any other radio communication services. The spectrum demand in other sectors is horizontal whereas in telecom sector, the demand is vertical because spectrum requirement for telecom services is subscriber dependent (figure 1.1). The requirement increases with increase in subscriber base.

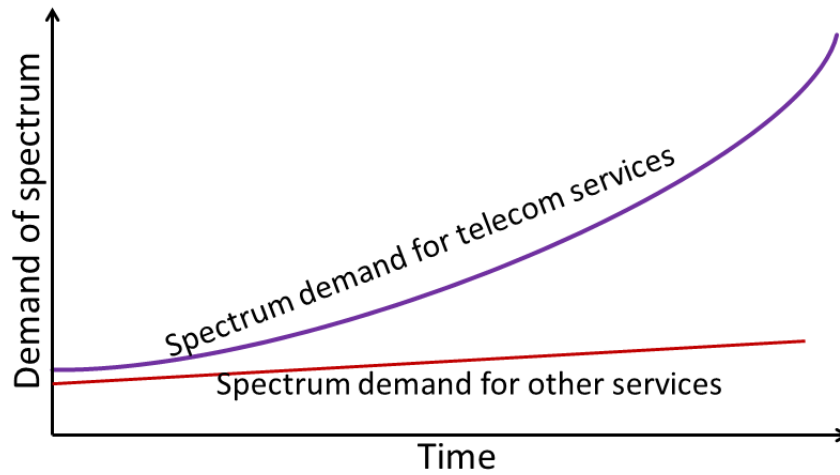


Figure 1.1: Demand of spectrum with respect to time

The advances in telecommunication have also changed the economic value of radio spectrum. Due to this economic change, the method of allocation of spectrum for commercial services have also shifted to market based methods [8] like Beauty Contest and Auction from earlier widely used First Come First Served (FCFS) method. However, these methods provide static allocation i.e. a part spectrum is allocated to an operator for a particular service in a area (a state or entire country) for a minimum of 10-20 years period of time. This static allocation guarantees the spectrum without any interference. However, it does not lead to efficient spectrum use and keeps spectrum underutilised.

Studies on spectrum utilization have been carried out in various countries, and it is reported that spectrum is underutilized in almost all the frequency bands at given time and location. It signifies that part of the frequency band could be free and available at a particular time and location. These unutilized parts of spectrum at any given time and location is called white space or spectrum hole [1, 9] (figure 1.2). This white space can easily be seen in the frequency bands assigned for terrestrial TV broadcasting services

due to multi-frequency networks concept.

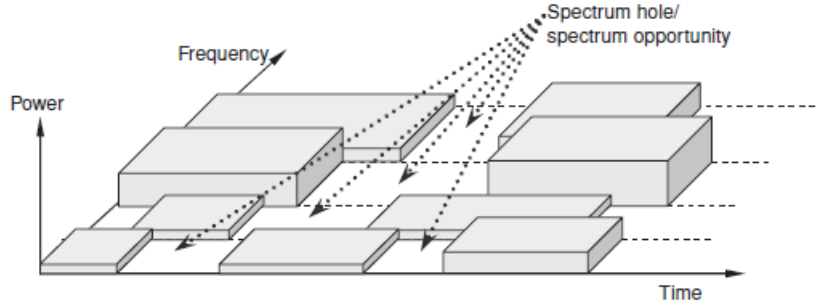


Figure 1.2: white space/spectrum hole [1]

The Dynamic Spectrum Access (DSA) and cognitive radio (CR) emerged due to underutilisation of radio spectrum[10]. The DSA allows wireless user to access the spectrum dynamically (instead of static) on time and location basis. Some steps like, delicensed frequency bands, spectrum trading and spectrum sharing etc. are few steps towards dynamic spectrum access. Over and above these steps, CR is the most promising technology which facilitate to access spectrum dynamically.

Currently, we are in the 4th generation of mobile communication[11], which provides data rates of 100 Mbps (high mobility)/1Gbps (low mobility). The desire of high data mobility has envisaged 5th generation of mobile communication to provide applications in every walks of human life and with a speed upto 1Tbps link rate at short distance or as system aggregate operating in burst mode and at least 250 Mbps to the end user for real time applications with coverage extending from a city, to a country, the continent and the world[12]. To realise 5G vision, we need high amount of contiguous spectrum. We need to look towards mm-waves as well as to enhance the flexibility in the management of spectrum at lower end.

## 1.2 Thesis Objectives

The thesis provides an overview of radio spectrum management at different level and various methods available for allocation of spectrum. A new method of allocation of spectrum for telecommunication services has been proposed to enhance the spectrum utilisation and revenue. It also provides a study on spectrum trading in telecom sector at operator and user prospective. The thesis also discuss dynamic spectrum management and cognitive

radio for exploiting TV white space, and to improve energy efficiency as well as spectrum efficiency.

### 1.3 Contributions of the Thesis

- A comprehensive study on the radio spectrum management, its requirement, management at different level and various available methods for allocation of spectrum.
- A new method of allocation of spectrum for telecommunication services to enhance the spectrum utilisation as well as revenue.
- A comprehensive study on spectrum trading with a focus on spectrum trading in telecommunication sector at operators and users perspectives.
- A comprehensive study on the dynamic spectrum access and cognitive radio on energy efficiency point, TV white space and its implementation in Indian scenario and requirement of spectrum for 5G Network.

### 1.4 Structure of the Thesis

The rest of the thesis is structured as follows:

**Chapter 2:**Radio spectrum is part of the electromagnetic spectrum. Radio spectrum ranges from 3 kHz to 3000 GHz. Radio spectrum being a natural scarce resource, can neither be created, nor destroyed. It is the use of spectrum which can be regulated so as to multiply its usage by technological means taking into account natural phenomenon of its capabilities and its constraints[13]. The nature of radio spectrum is so complicated that we have so far been able to utilise only a limited portion of the radio frequency spectrum. Due to complex nature, regulation of radio spectrum is entirely different from regulation of other activities or the term 'regulation' in general parlance. It is predominantly governed by the scientific features and physical laws of nature [13].

This chapter provides basic concept of radio spectrum management, its history, goals of radio spectrum management and different levels of radio spectrum management. It also gives brief introduction about the management of radio spectrum in Denmark and India with a detailed analysis about allocation of spectrum for different radiocommunication services in national

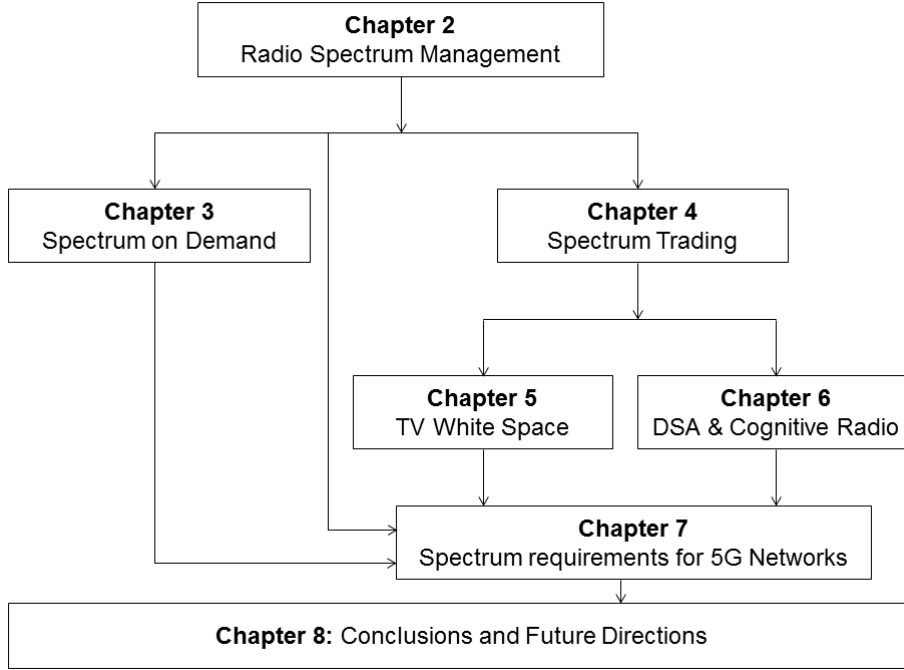


Figure 1.3: Structure of thesis

frequency allocation plan of India.

**Chapter 3:** The traditional method of spectrum management is 'Command and Control' [5]. Traditional method guarantees the interference free environment and separate spectrum allocation for each services and users. However, it does not ensure efficient spectrum utilisation. Once the spectrum has been assigned to a user, spectrum utilization cannot be questioned during the licensing period provided he fulfils the terms and conditions of the license.

The spectrum requirements for commercial and non-commercial services are different. Demand for spectrum for commercial services is increasing much faster rate as compared to non-commercial services. Broadcasting and Telecom services are considered commercial services. There is a basic difference between these two commercial services on spectrum point. The spectrum requirement for broadcasting services is customer independent, whereas spectrum requirement for telecom services is customer dependent. Spectrum demand for telecom services increases with increase in the number of customers. The spectrum requirement for broadcasting services does not vary with time. However, spectrum demands for telecom services are growing day

by day. Presently spectrum is assigned to telecom services through auction [8]. Under the traditional auction method, spectrum is assigned to the entire service area. There are cases, where operators are unable to utilize assigned spectrum blocks in the entire service area. They may be able to utilize in a part of the service area. Under such condition, spectrum in the remaining area becomes idle and cannot be utilized for any other purpose.

This chapter provides details about traditional method of radio spectrum management, its advantages and disadvantages. In this chapter, a new concept of spectrum assignment for telecom services titled 'Spectrum on Demand for telecom Services' has been discussed, which improve spectrum efficiency and earn more revenue as compared to traditional auction method.

**Chapter 4:** Currently, spectrum for commercial services is assigned through auction only. Auction is a cumbersome process, therefore, it cannot be conducted day to day basis on demand of service providers. It is difficult for an operator to get additional spectrum whenever he wants. Spectrum trading has recently been introduced by various administrations to solve this problem. Spectrum trading [14] is a new concept in which service providers are permitted to purchase spectrum from the market to fulfil their requirements. Spectrum trading is considered as economically efficient because trade will only take place if the spectrum is worth more to the new user. Spectrum trading has been allowed in the United States of America (USA) and several European Union (EU) countries.

This chapter describes the spectrum trading, its advantages and disadvantages. This chapter provides details provisions about spectrum trading in the USA and the EU countries. The chapter also describes a detailed analysis of spectrum trading in telecom sector at operator level and discuss a scenario for spectrum trading at user level. This chapter also provides an overview of possibilities of spectrum trading in India and concludes that necessary ingredients are present in India for spectrum trading and it could provide a boost to the Indian telecom sector.

**Chapter 5:** A large part of 1 GHz sub band has been allocated for TV broadcasting. This is a precious band from coverage point. It has been found that a large chunk of TV frequency band is unutilized at a given location and time. This unutilised spectrum is known as TV White Space[15]. It is wastage of precious natural resources. The idea of exploitation of idle TV spectrum at any location emerges after introduction of cognitive radio technology and dynamic spectrum access. TV white space has already been opened in the USA, the United Kingdom (UK) and several EU countries for low power equipment. The regulatory framework has already been in place



in these countries. TV white space has not yet been opened for unlicensed use in India. Doordarshan, a Public Service Broadcaster (named Prasar Bharti)[16], is the only terrestrial TV broadcaster in India, covers almost entire country. Therefore, a good amount of TV white space is available in India. This white space needs to be exploited.

This chapter provides a comprehensive study about TV White Space. Regulations have already been made for exploitation of TV white space in developed countries. This chapter provides an assessment of TV white space in India and a detailed analysis for the possibility of utilisation of TV white space in India.

**Chapter 6:** The existing static approach of spectrum management model is unable to cater the present and future requirement of spectrum. However, studies on spectrum utilisation reveals that a major part of assigned spectrum is unused at a given time and location[9]. To exploit this unused spectrum, spectrum should be managed dynamically instead of static. The concept of dynamic spectrum access has emerged to improve the spectrum utilization. The Dynamic Spectrum Access allowing the new user (unlicensed) to access spectrum which has already been allocated to another user (licensed). Spectrum trading, open spectrum and spectrum common are few steps towards dynamic spectrum management[10]. Cognitive radio is the best technology, which would help in managing radio resource in more simplified way. Dynamic spectrum management will provide conducive environment for implementation of cognitive radio based network.

This chapter gives a comprehensive study about dynamic spectrum access and cognitive radio and provides an analysis about spectrum and energy efficiency in cognitive radio networks. Cognitive Radio has not yet been permitted in India and other developing countries. This chapter gives a detailed analysis for possibility of utilisation of Cognitive Radio in India.

**Chapter 7:** The analysis made in preceding chapters, we concluded that sufficient unutilised spectrum is available in lower bands for new applications, and the cognitive radio is the best instrument to exploit unutilised spectrum in dynamic manner. However, the spectrum requirements for 5th generation (5G) network can not be met with this availability. The phenomenal growth in mobile data traffic calls for a drastic increase in network capacity beyond current IMT (3G/4G) networks. There is a call for the next generation mobile communication system i.e 5G. The 5G network envisages data speed of 1Tbps and beyond [12]. Presently, mobile communications are operating between 700 MHz to 2.6 GHz. These spectrum bands do not have the capacity to carry such enormous data. Millimeter (mm) frequency band

beyond 10 GHz is the obvious and the most preferred band for 5G[17].

The chapter 7 gives a comprehensive study about 5G network along with its intelligence unit WISDOM[18] and discuss the spectrum requirements for 5G network and concludes that mm-waves along with lower band spectrum will fulfill the spectrum requirements of 5G network. In this chapter, we also analysed frequency bands for 5G communication services.

**Chapter 8:** This chapter concludes the thesis by revisiting the objectives of the study and summarizing the main points. The chapter also highlights the scope of future extension in relation to this study.



## Chapter 2

# Radio Spectrum Management

## 2.1 Introduction

Radio spectrum is always around us in the form of invisible waves. Radio spectrum is used by countless technologies that affect most aspects of our lives. Radio spectrum is part of the electromagnetic spectrum. Radio spectrum ranges from 3 kHz to 3000 GHz. The radio spectrum has been divided into different bands as shown in figure 2.1.

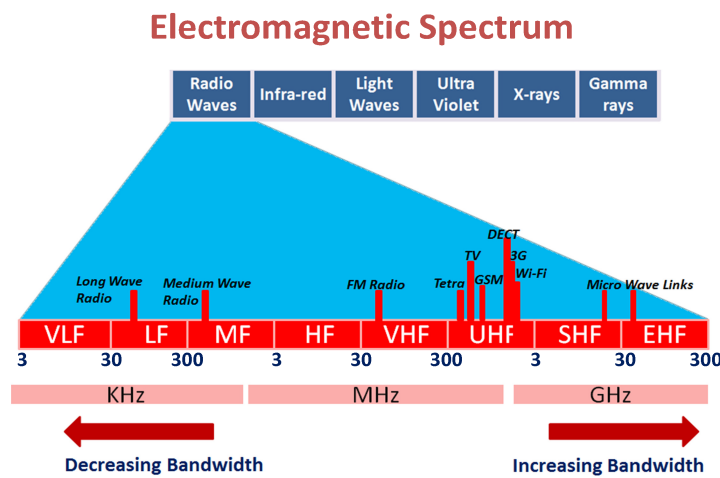


Figure 2.1: Radio spectrum usage

Radio spectrum can neither be created nor destroyed. It is the use of spectrum which can be regulated. The radio spectrum usage can be multiplied by technological means taking into account natural phenomenon of its capabilities and constraints. Regulation of radio waves is entirely different from regulation of other activities or the term 'regulation' in general parlance. It is predominantly governed by the scientific features and physical laws of nature. Radio frequency spectrum usage is shared amongst the various radio services and must be used efficiently, optimally and economically in conformity with the provisions of national and international laws [19]. Therefore, lack of appropriate radio regulatory mechanism will discourage radio innovation, usage and development of networks by service providers and other wireless users, who will believe that their investment is at risk and finally society would not get benefits what it could be.

Spectrum management is the process of regulating the use of radio frequencies to promote efficient use and gain a net social benefit [8]. Man-

agement of the spectrum is the combination of administrative and technical procedures with legal connotations necessary to ensure efficient operation of radiocommunication services without causing harmful interference. Efficient and effective spectrum management, therefore, is the art and science of carefully planning spectrum allocation in a coordinated manner without compromising national interests and efficiently assigning frequencies for the benefit of users at large with minimum scope of harmful interference [20]. There are forty-one different types of radiocommunication services, including safety services, viz., aeronautical, maritime, radionavigation, radiolocation, radio astronomy, meteorological, broadcasting, satellite broadcasting, fixed, fixed-satellite, mobile, mobile-satellite, space services, etc. In accordance with international treaties, all the frequency bands are shared amongst different types of radiocommunication services for a variety of applications and technologies by different countries. The need for an efficient radio regulation arises from every aspect i.e. natural, physical, economic and social as given below[19]:

- The radio spectrum is limited natural resource like water, oil etc. Unlike other natural resources, radio frequency spectrum is not consumed upon its usage.
- The radio signals are pervasive, i.e. they don't recognize man-made boundaries (including international borders).
- Two radio stations can communicate effectively only when they are operating on same frequency and on the other hand, if two or more radio stations are operating at the same frequency, within the same geographical area, at the same time, stations would experience mutual interference and make difficult to extract information. In other words, no two wireless transmissions can exist at the same frequency, at the same time and in the same geographical area.
- Radio frequency ranges from 3 KHz to 3000 GHz, but only limited portion of the radio frequency spectrum is useful for specific radiocommunication services due to the following reasons:
  - Propagation characteristics of different types of radio waves.
  - Availability of technology and equipment for different types of radio frequency spectrum applications.
  - The suitability of frequency bands for specific applications

- Unlike other natural resources, it cannot be owned but used and shared amongst various countries, services, users, technologies, etc without any element of exclusiveness. It is also liable to be wasted if it is not used optimally and efficiently.
- Rapid change in telecom world has made the radio spectrum one of the most valuable and vibrant resource for the economy of any country. Effective use of spectrum can make a big difference to a countrys prosperity, especially where communications are heavily reliant upon wireless technologies.
- Today radio has entered in all walks of life. Life without radio is difficult to imagine. Effective regulation helps to develop knowledgeable society and provide environment to extract benefits from radio spectrum as much as possible.

The effective management of radio spectrum will generate new revenues and business models and also enhance the efficiency and effectiveness of current services. Studies show that increased penetration of communications technology is strongly associated with growth. A 2009 World Bank study found that a 10% increase in broadband capacity was associated with a 1.3% increase in economic growth[21].

## 2.2 Goals of Radio Spectrum Management

The concept of spectrum management includes all activities related to planning, allocation, assignment, use, and control of the radio frequency spectrum [20]. The work of spectrum management becomes highly complex when it comes to simultaneously fulfil the demand for spectrum for 41 different radiocommunication services, each with its own unique requirements and characteristics. For example, navigational and communication needs in civil aviation and shipping can only be met by use of the radio spectrum, and that the same chunk of radio spectrum need to be available globally. Radio astronomy requires that certain part of the radio spectrum must not be used for any transmission (over a defined geographical area/ space).

The benefits derivable from the use of spectrum are, in general, not easily comparable, and also vary with technology, economic, social factors and several other considerations. For example, it is not an easy matter to determine whether a particular chunk of spectrum for Defence use is more purposeful than the use of the same chunk of spectrum for commercial public use which generates huge revenue and benefits millions of users. Therefore,

today's spectrum management has now been converted into a mechanism to fulfil the requirements of various radiocommunication services taking into account technical, economic, social and international obligations. We could say that the goals of spectrum management are to maximise the technical efficiency, economic efficiency and social welfare, and to make a right balance between these three goals (figure 2.2).

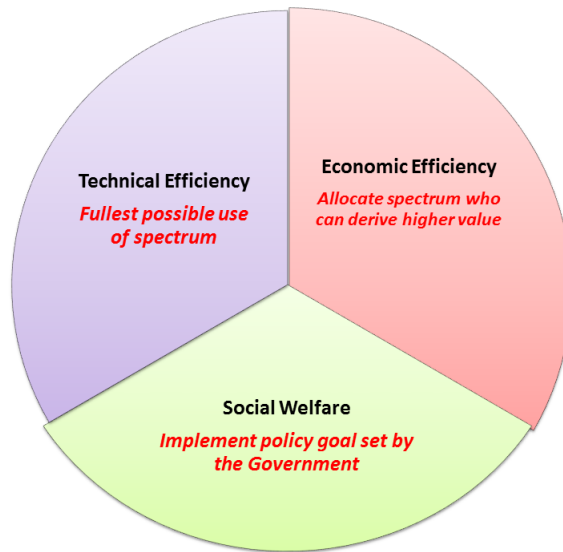


Figure 2.2: Goals of radio spectrum management

### 2.2.1 Technical efficiency

At the basic level, technical efficiency implies the fullest possible use of spectrum [22]. Technical efficiency involves providing interference free environment for various radio users, allocating spectrum to different radio services in equitable manner, making room for new services and to encourage users for use of more spectrum efficient technologies. It also refers to the need to tackle a host of related problems, such as use of faulty or non-standard equipment, the unauthorised or illegal use of frequencies, spill-over signals from neighbouring administrations, the use of inappropriate levels of power, finding the optimum location for antennas, and so on.

### 2.2.2 Economic Efficiency

Economic efficiency does not mean to maximise revenue. In general terms, economic efficiency means that allocate spectrum who can derive



higher value. It involves a judgement regarding the allocation of relatively scarce spectrum so that it should be put to use in the most productive way possible so that end users get at the lowest possible unit cost of production. Productivity changes with respect to time, so will the value of spectrum. Radio frequency bands should be priced in such a way that the right signals for future investments are sent to the market and open the door for new technologies. Economic efficiency has three dimensions relating to production, consumption and the use of resources over time [8].

- **Productive Efficiency** Services produced through spectrum usage should be at the lowest possible cost for inputs.
- **Allocative Efficiency** Spectrum should be allocated between different users/services in such a way that services produced should be optimal.
- **Dynamic Efficiency** Spectrum resources are used in such a way to encourage investment and innovation.

### 2.2.3 Social welfare

The main objectives of social welfare is to convey the policy goals set by the government, minimise the conflicts and rationalise the use of spectrum for the benefit of society. At the same time, it safeguards interests of spectrum use for efficient functioning of defence, emergency and other public services.

## 2.3 History of Radio Regulation

The history of radio regulation started from 24 May 1844, when Samuel Morse sent his first public message over a telegraph line between Washington and Baltimore [23]. Initially, it was limited within country boundaries but it crossed boundaries of countries within a very short span of time. There was no system of management of radio spectrum. As a result, wireless user can choose any frequency for transmission. As applications and services grew, interference became an increasing problem. It was felt that Spectrum is an inexhaustible natural resource and is a shared resource requiring coordination among all its users. The first International Telegraph Convention was signed by the 20 participating countries on 17 May 1865 and the International Telegraph Union was set up to enable subsequent amendments to this initial agreement[23]. This marked the birth of the todays International Telecom Union (ITU)[2].

To make a uniform regulation, the first international conference [24] was held in August 1903 in Berlin to consider an international convention for regulating maritime communications. The Berlin conference agreed upon the principles of radio spectrum management. One of major steps at the conference was the establishment of the International Bureau in Bern to register the operating frequencies of radio stations to control the spectrum occupancy and avoid mutual interference. The register of the occupied frequencies was named later "The Bern List". It was the first attempt to manage the radio frequency spectrum, worldwide.

The well-known Titanic maritime ship disaster in April 1912 attracted public attention about need of strict radio regulation was felt as inquiries alleged that another liner was nearby and could have helped had its radio operator been on duty to receive the distress signals of the 'Titanic'. After three months of disaster, the second radio conference was held in London and settled the problem of intercommunication between ships on the sea. The first Table of Frequency Allocations was also created in this conference by the International Radiotelegraph Union which contained allocation of the kilohertz range only [25].

The International Telephone Consultative Committee (CCIF) was set up in 1924, the International Telegraph Consultative Committee (CCIT) was set up in 1925. The International Radio Consultative Committee (CCIR) was established in 1927. The CCIR were made responsible for coordinating the technical studies, tests and measurements being carried out in the various fields of telecommunications and for drawing up international standards.

The next International Radiotelegraph Conference was held in Washington in 1927 [26]. The Union allocated frequency bands to the various radio services existing at the time to ensure greater efficiency of operation in view of the increase in the number of services using frequencies and the technical peculiarities of each service. The International Frequency registration Board and International Radio Consultative Committee, CCIR was also setup as fallout of this conference.

At the 1932 Madrid Conference [27], the Union decided to combine the International Telegraph Convention of 1865 and the International Radiotelegraph Convention of 1906 to form the International Telecommunication Convention. It was also decided to change the name of the Union to International Telecommunication Union with effective from 1 January 1934.

In 1947, ITU became part of United Nations on a provisional basis, from that date. The ITU as a UN specialized agency formally entered into force on 1 January 1949. The International Frequency Registration Board (IFRB) was established to coordinate the increasingly complicated task of managing the radio-frequency spectrum. The Table of Frequency Alloca-

tions, introduced in 1912, was declared mandatory. In 1956, the CCIT and the CCIF were merged to form the International Telephone and Telegraph Consultative Committee (CCITT)[23]. From this point of time, ITU is diligently working towards its commitment i.e. ***"ITU is committed to connecting all the world's people wherever they live and whatever their means"***[2].

## 2.4 Spectrum Management Level

The current spectrum allocation process operates at national, regional and international level as shown in figure 2.3.

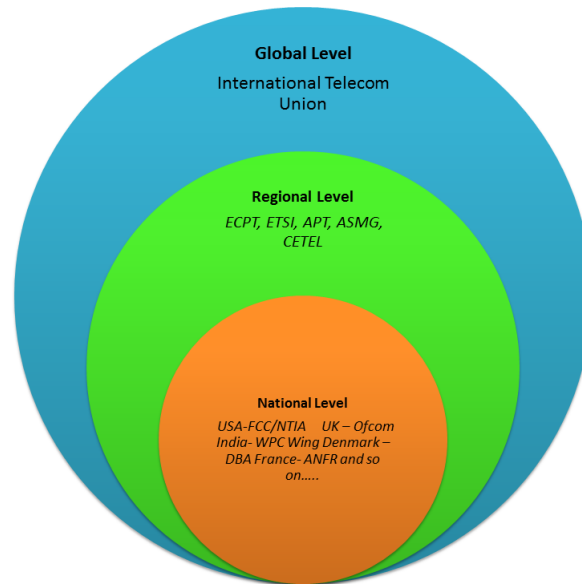


Figure 2.3: Spectrum management level

### 2.4.1 Spectrum Management at International Level

At international level, International Telecommunication Union, a specialised agency of the United Nations, is responsible for spectrum management. Although its first area of expertise was the telegraph, the work of ITU now covers the whole information and communications technology (ICT) sector, from digital broadcasting to the Internet, and from mobile technologies to 3D TV. ITU membership includes 193 Member States and more than 700 Sector Members and Associates [2]. Broadly, international bodies tend to set out high level guidance which national bodies adhere to in setting

more detailed policy. International coordination is essential in some cases because the zones of possible interference extend beyond national geographical boundaries and in other cases because users are inherently international, e.g. aviation and maritime. As the global focal point for governments and the private sector, ITU's role in helping the world communicate spans three core sectors (figure 2.4); ITU-R: Radio Communication Sector, ITU-D: Development Sector and ITU-T: Standardization Sector. ITU-T develops and maintains standards for telecommunication technology, ITU-D is to facilitate the implementation and operation of telecommunication technology in developing countries and ITU-R is responsible of managing the radio-frequency spectrum and satellite orbits and radiocommunication standardization.

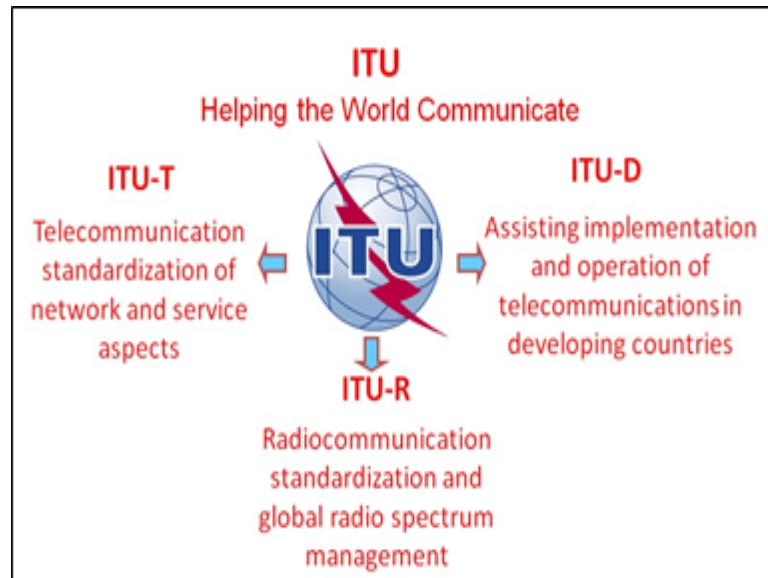


Figure 2.4: Three core sector of ITU [2]

### Radiocommunication Sector (ITU-R)

The radio spectrum management activities are associated with Radiocommunication sector of ITU [28]. ITU-R plays a vital role in the global management of the radio-frequency spectrum and satellite orbits - limited natural resources which are increasingly in demand from a large and growing number of services such as fixed, mobile, broadcasting, amateur, space research, emergency telecommunications, meteorology, global positioning systems, environmental monitoring and communication services - that ensure safety of life on land, at sea and in the skies. The ITU-R Mission is:

*"To ensure rational, equitable, efficient and economical use of the radio-frequency spectrum by all radiocommunication services, including those using satellite orbits, and to carry out studies and adopt recommendations on radiocommunication matter"*

ITU-R works with the aims to create the conditions for harmonized development and efficient operation of existing and new radiocommunication systems, taking due account of all parties concerned and to ensure interference free operations of radiocommunication systems. ITU-R works through ITU-R Study Groups & its working parties, Conference Preparatory Meetings, and World Radiocommunication Conferences.

### **World Radiocommunication Conference**

World Radiocommunication Conference (WRC)[29] is Supreme body in worldwide management and regulation of the RF spectrum. The WRC held periodically every 4 years. Last WRC was held in 2012 at ITU headquarter in Geneva, Switzerland and the next one is scheduled in 2015.

Under the terms of the ITU Constitution, a WRC revise the Radio Regulations and any associated Frequency assignment and allotment Plans and address any radiocommunication matter of worldwide character. The Radio Regulations is an intergovernmental treaty which coordinates and standardises the operation of telecommunication networks and services and advances the development of communications technology. The radio regulation define [30]:

- the allocation of different frequency bands to different radio services;
- the mandatory technical parameters to be observed by radio stations, especially transmitters;
- procedures for the coordination (ensuring technical compatibility) and notification (formal recording and protection in the Master International Frequency Register) of frequency assignments made to radio stations by national governments;
- other procedures and operational provisions.

### **Study Groups**

The work of Radiocommunication Sector of ITU (ITU-R) is organized in seven Study Groups (SGs)[31]:

- **Study Group 1 (SG 1):** Spectrum management

- **Study Group 3 (SG 3):**Radiowave propagation
- **Study Group 4 (SG 4):**Satellite services
- **Study Group 5 (SG 5):**Terrestrial services
- **Study Group 6 (SG 6):**Broadcasting service
- **Study Group 7 (SG 7):**Science services

Each study groups have different working parties which study specific topic of study group concern.

### Radio Regulations

ITU-R publishes Radio Regulations (RR)[6] for regulating and managing radio spectrum usage. The RR is an international treaty and set the framework for national regulating agencies to manage, regulate and license radio spectrum usage. RR provide basic principles and terminologies for managing radio spectrum. The RR have the following objectives:

- *to facilitate equitable access to and rational use of the natural resources of the radio-frequency spectrum and the geostationary-satellite orbit;*
- *to ensure the availability and protection from harmful interference of the frequencies provided for distress and safety purposes;*
- *to assist in the prevention and resolution of cases of harmful interference between the radio services of different administrations;*
- *to facilitate the efficient and effective operation of all radiocommunication services;*
- *to provide for and, where necessary, regulate new applications of radio-communication technology.*

The ITU divides world into 3 regions; Region 1 comprises Europe, the Middle East and Africa, Region 2 contains the Americas and Greenland and Region 3 consist India, Australia, the South Pacific and the Far Eastern countries. The RR contain definitions and spectrum allocation for 42 radiocommunication services, which are categorized based on operational, administrative and technical requirements for all the 3 regions. Based on the RR provisions, regulating agencies have to develop frequency allocation plan for usage of spectrum in their country. It is possible that a block of spectrum

is allocated to one or more of the services without referring to specific radio systems. Regulating agencies are free to choose any of them as per their requirements [32].

Figure 2.5 illustrates the process of global spectrum management in the ITU, in force since 1993. It forms a closed-loop system built around consensus-seeking through studies and negotiations in the study groups and WRC. The final product of study groups is Recommendations and handbooks, and WRC is Radio regulations.

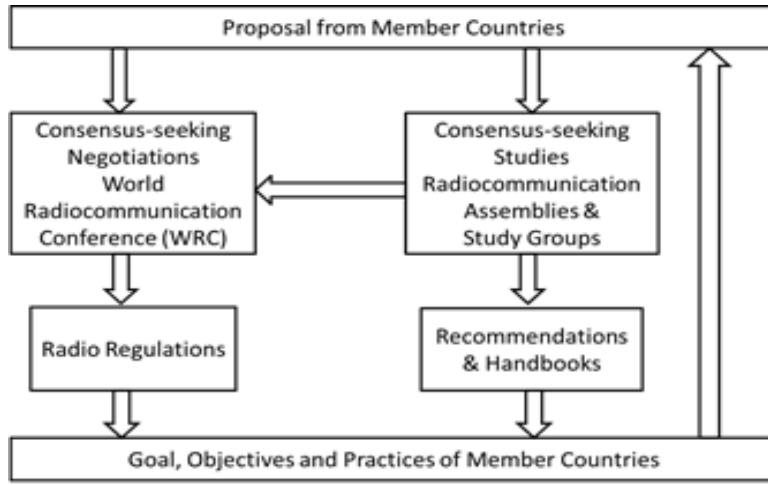


Figure 2.5: Spectrum management in ITU [28]

### 2.4.2 Spectrum Management at Regional Level

At regional level, there are several agencies which are working in different regions like CEPT, ETSI in Europe, APT in Asia, ASMG in Arab and CITEL in American countries. A list of regional establishment is given in table 2.1. These agencies mainly work towards the harmonization of spectrum for different services in their region and also play role in international co-ordination.

### 2.4.3 Spectrum Management at National Level

The Administrations world over have their own National Radio Spectrum Regulatory Authority. To cite with, the United States operates in a bifurcated spectrum management system where the Federal Communications Commission (FCC)[33] governs commercial wireless communications users and state and local government spectrum users. The FCC works towards

Table 2.1: Spectrum management agencies at regional level

Name	Function
<b>Europe: CEPT</b> (European Conference of Postal and Telecommunications Administrations) <a href="http://www.cept.org">www.cept.org</a>	The CEPT, formed in 1959, an organisation where policy makers and regulators from 48 countries across Europe collaborate to harmonise telecommunication, radio spectrum, and postal regulations to improve efficiency and co-ordination for the benefit of European society. The work of CEPT is conducted by three autonomous Committees: The Electronic Communications Committee (ECC), The European Committee for Postal Regulation (CERP) and The Committee for ITU Policy (COM-ITU)
<b>Asia: APT</b> (Asia-Pacific Telecommunity) <a href="http://www.aptsec.org">http://www.aptsec.org</a>	The APT was established in Bangkok in July 1979. The APT is an Intergovernmental Organization operates in the field of information and communication technologies (ICT). The APT covers 38 member countries, with 4 associate members and 130 affiliate members.
<b>Arab Countries: ASMG</b> (Arab Spectrum Management Group) <a href="http://www.asmg.ae">http://www.asmg.ae</a>	ASMG was established by the Arab Ministerial Council for ICT to cooperate and collaborate in the field of Spectrum Management and Coordinate among member states on all issues related to the Spectrum Management. The twenty two Arab States utilize this platform.
<b>American Countries: CITEL</b> (Inter-American Telecommunication Commission) <a href="https://www.citel.oas.org">https://www.citel.oas.org</a>	High-level specialized advisory body of the Organization of American States (OAS), leader in the region in all aspects involving telecommunications and information and communications technologies (ICTs)
<b>Caribbean Countries: ECTEL</b> (Eastern Caribbean Telecommunications Authority) <a href="http://www.ectel.int">http://www.ectel.int</a>	ECTEL was established in 2000 by the Governments of five Eastern Caribbean states (Commonwealth of Dominica, Grenada, Saint Christopher and Nevis, Saint Lucia, Saint Vincent and The Grenadines) to promote market liberalization and competition in telecommunications of the contracting states



six goals in the areas of broadband, competition, the spectrum, the media, public safety and homeland security, and modernizing the FCC. The other part is the National Telecommunications and Information Administration (NTIA)[34] regulates all Federal Government spectrum users and responsible for advising the President on telecommunications and information policies. The Office of Spectrum Management (OSM), part of NTIA, formulates and establishes plans and policies that ensure the effective, efficient, and equitable use of the spectrum both nationally and internationally.

Office of Communications (Ofcom)[35] is the communications regulator of UK and is responsible for radio spectrum management in United Kingdom. Ofcom regulates the TV and radio sectors, fixed line telecom and mobiles, plus the airwaves over which wireless devices operate.

In India the Wireless Planning and Coordination (WPC)[36] Wing of the Ministry of Communications and IT, is the National Radio Regulatory Authority responsible for Frequency Spectrum Management. In Denmark, Danish Business Authority is the regulator and responsible for radio frequency spectrum management.

The planning and physical assignment of radio spectrum to users is the responsibility of national regulatory authorities. For planning purposes, spectrum is divided into bands and channels that have varying sizes and bandwidth. In general, lower frequency bands have the smaller bandwidth capacity than higher frequency bands. This means that higher frequency bands can carry more information. In contrast, lower frequency bands have longer range and better penetration inside the building. These types of characteristics determine the suitability of frequency ranges for particular services. How the spectrum is partitioned between the different uses (allocation) and how and to whom licences are given for the use of channels or blocks of spectrum (assignment) are organised and managed by the national regulatory authority of the country. The three essential terms related to radio spectrum management are allocation, allotment and assignment. The definition of these three terms as per radio regulation of ITU[6] is given below:

- **Allocation:** Allocation of a frequency band in frequency table for the use by one or more than one radiocommunication services under technical considerations concerning the suitability of frequencies for certain applications, and political priorities between different types of applications. International Allocation is done by ITU, which reflect in Radio regulation (RR). National Allocation for different services in line with RR is done by national regulator, which reflect in National Frequency Plan.

- **Allotment:** Allotment of radio frequency channel in an agreed plan for use by one or more administrations of any services in one or more identified countries or geographical areas under specified conditions. Allotment is done by either regional level or at national level for use of frequency channel for specific use as defined in national frequency plan for commercial and non-commercial use.
- **Assignment:** Authorization given by an administration for a radio station to use radio frequency channel under specified technical conditions like power of signal, amount of bandwidth and type of modulation etc. This is done by national regulator for use of frequency channel for specific use in specific geographic location of the country for commercial and non-commercial use. There are several methodologies for assignment of spectrum namely FCFS, beauty contest, lottery and auction etc. Generally, FCFS method adopted when demand for spectrum within a particular band is considerably less than supply. When spectrum demand exceeds supply, beauty contest or auction is more suitable for assignment of spectrum.

## 2.5 Radio Spectrum Management in Denmark

The Danish Business Authority (DBA)[37] is responsible for radio spectrum management in Denmark. Earlier, it was managed by the National IT and Telecom Agency (NITA). Radio spectrum in Denmark is managed through a Radio Frequencies Act. The purpose of the act is to promote competition and efficient spectrum use and to ensure that essential public interest conditions are met. The Act include the issue, transfer and duration of licences, ensuring competition in the telecommunications sector, charges and fees, regulatory supervision by the Danish Business Authority, and use of spectrum for radio and TV. The DBA also supervises compliance with the Frequency Act and rules and terms laid down in pursuance of the Frequency Act. The Danish Business Authority lays down a frequency plan within the terms of the spectrum policy framework mandate and based on international cooperation in the field of radio frequencies, including the EU. The frequency plan contains an overview of how spectrum resources are to be deployed in Denmark.

The methodology (auction, public tender or first come, first served) of assignment of spectrum depends upon the type of usage (commercial or non-commercial) and scarcity. The DBA has adopted auction route for assignment of spectrum for IMT services. FCFS method is used to assign spectrum for other services. The spectrum allotments made are in synchronization with CEPT regulation. The Government has established Telecommunications Complaints Board where decision taken by DBA can be challenged.

Danish regulatory authority is more mature than Indian regulatory authority in respect of conducting auctions. First auction was conducted in the year 200 in 3.5 GHz band and the latest one was conducted in 2012 in the 800 MHz band. GSM band (900/1800 MHz band) has been refarmed. After refarming, 15 MHz was auctioned in 2010. A detail of auctions conducted by DBA is given in table 2.2. Spectrum usage charges is to be paid annually by service providers, which is based on a percentage of geographical coverage of the country.

Table 2.2: Spectrum auction held in Denmark

Frequency Band	Year of Auction	Amount of Spectrum (in MHz)
410 MHz(410-430)	2010	10+10(FDD)
450MHz (450-470)	2006 and 2010	10+10(FDD)
800 MHz(791-821/832-862)	2012	30+30(FDD)
900/1800 MHz	2010	5+5 (900 MHz,FDD), 10+10(1800 MHz,FDD)
2100 MHz(1920-1980/2110-2170 & 1900-1920)	2001	60+60(FDD) & 20(TDD)
2500MHz(2500-2570/2620-2690 & 2570-2620)	2010	70+70(FDD) & 50(TDD)

## 2.6 Radio Spectrum Management in India

In India, the Wireless Planning and Coordination (WPC)[20] Wing of the Ministry of Communications and IT is the National Radio Regulatory Authority responsible for Frequency Spectrum Management.

The WPC Wing, created in 1952, is the national radio regulatory nodal agency of the Government of India. The WPC Wing is responsible for plan-

ning, regulating and managing of the Radio Frequency (RF) spectrum and associated satellite orbits, including geo-stationary satellite orbit as well as licensing of wireless stations in the country under the Indian Telegraph Act 1885 (ITA 1885) and the Indian Wireless Telegraphy Act 1933 (IWTA 1933), a statutory requirement. WPC Wing also issues licenses to radio officers on board ships & Aircraft and conduct of proficiency examinations as per international regulations. It caters the needs of all wireless users in the country, government or private, security or non-security agencies. WPC Wing is also the national agency for all matters related to the Radio Communication sector of ITU and Asia-Pacific Telecommunity (APT). It is responsible for protection of overall national interests of all the user organisations and projecting the harmonized Indian views in various ITU foras after taking into account relative merits and priorities of various services; interpretation and suitable implementation of Radio Regulatory provisions. Radio monitoring, a regulatory and treaty requirement, is carried out by the Wireless Monitoring Organization of the WPC Wing. It is essentially technical in nature and its broad objectives are derived from the international treaty document Radio Regulations of the International Telecommunication Union[20].

### **National Frequency Allocation Plan**

For the management of spectrum at the national level, WPC Wing draws up a more detailed frequency allocation table than the one drawn up at the international level. In developing the detailed allocation table, WPC Wing goes even one step further and identifies the frequency spots in the channelling plan for more common radio systems/ networks. This detailed allocation table is essentially a road map showing where the radio industry in India would lead to. This allocation table is called National Frequency Allocation Plan (NFAP)[20], which gives the complete information on the allocation of the spectrum in India. NFAP has the following sections:

- International Frequency Allocation Table
- National Frequency Allocation Table
- Footnotes to International Frequency Allocation Table
- Remarks in the National Frequency Allocation Table
- Channeling Plan

NFAP is reviewed periodically in line with the Radio Regulations of the ITU in order to cater to newly emerging technologies taking into account

spectrum requirements of the government/private sector as well as to ensure equitable and optimum utilization of the scarce limited natural resource of RF spectrum. The provisions of NFAP protect the existing assignments under their existing status, unless and until it is decided to modify or relocate these assignments. All necessary technical, operational, regulatory and administrative measures are taken so as to avoid harmful interference. If we go through NFAP, spectrum allocation in different frequency bands is distributed between primary and secondary services. In an allocation, more than one primary and secondary service could be listed. When more than one services are listed having the same status (i.e. primary or secondary), the order of their listing does not indicate any relative priority among such services. As per radio regulation [6], listed secondary services in an allocation are allowed to operate subject to:

- a) shall not cause harmful interference to stations of primary services to which frequencies are already assigned or to which frequencies may be assigned at a later date

- b) cannot claim protection from harmful interference from stations of a primary service to which frequencies are already assigned or may be assigned at a later date

- c) can claim protection, however, from harmful interference from stations of the same or other secondary service(s) to which frequencies may be assigned at a later date

In general, Broadcasting and Telecommunication services are considered as commercial services and the remaining services are considered as non-commercial services. Generally FCFS method is used for assignment of spectrum for non-commercial services whereas market determined methods are used for commercial services. Spectrum allocation process is done in four steps as shown in figure 2.6.

From the NFAP, it is possible to calculate the amount of spectrum allocated to different types of radio services in India. The entire radio spectrum ranges from 30 KHz to 300 GHz are shared by different primary radio services and approximately 19.86% of this spectrum is also allocated to secondary services. The shared spectrum resources is given in the table 2.3. Space research services holds lion share of spectrum assigned for secondary services. Secondary services can operate on non-protection and non-interference basis.

The details given in table 2.3 are allocation only. It is not necessary that all the frequencies are assigned to users and in use. If we look at the table, we would find that satellite and science services are concentrated in the higher frequency bands. The lower bands are utilised mainly for aeronautical and maritime radio navigation and broadcasting services. The allocation made for these services are almost same in all the three regions as common frequencies

are required to communicate for navigation. Fixed and mobile services are scattered in each band. IMT services are concentrated in the UHF band (300 MHz to 3 GHz). Except mobile services, exclusive primary allocation is present for other services. Out of entire spectrum band, only 2.06 % is reserved for exclusive primary services. The lion's share is contributed by radio navigation services which present in each band. There is no exclusive allocation for mobile services. Exclusive allocation for fixed services is present below 30 MHz only, and for broadcasting services is present below 300 MHz. About 1.31 % of total spectrum is reserved for fixed and mobile services. Percentage of exclusive allocation in different bands to fixed, mobile and broadcasting services and to the combination of these three services is given in the table 2.4.

Telecom and broadcasting services are considered as commercial services. In the telecom sector, 2G, 3G and Broadband Wireless Access (BWA) services are running in India. Assigned spectrum to different telecommunication services is shown in figure 2.7.

In India, first phase mobile telephone service started with issue of 8 licenses for GSM services in the 4 metro cities of Delhi, Mumbai, Calcutta and Chennai to 8 private companies in 1994 through a beauty parade. Subsequently, 34 licenses for 18 Territorial Telecom Circles were also issued to 14 private companies during 1995 to 1998 through the single stage bidding process. During this period a maximum of two licenses was granted for GSM in each service area and these licensees were called 1st & 2nd cellular licensees. State owned Public Sector Undertakings (PSUs) Mahanagar Telephone Nigam Limited (MTNL)[38] and Bharat Sanchar Nigam Limited (BSNL)[39] were issued licenses for the provision of GSM as the third operator in various parts of the country. Further, 17 fresh licenses have been issued to private companies as fourth cellular operator in 2001, one each in 4 Metro cities and 13 Telecom Circles through a multi-stage bidding process. In 2010, first time auction was conducted for 3G and BWA services and 4-5 licenses for 3G services and 3-4 licenses for BWA services were issued. The auction was hugely successful. Recently three phases of auction were conducted for assignment of spectrum in the 900/1800 MHz band but this auction could be considered as a failure because spectrum sold on reserve price. The fourth round of auction for spectrum in the 900/1800 MHz is underway.

In broadcasting services, private operators are present only in FM broadcasting and satellite TV. Terrestrial TV and AM/SW/FM broadcasting is operated by state owned Public Sector Unit 'Prasar Bharti'[16].

## 2.7 Conclusions

Radio spectrum is a vital resource for wireless services. Today's society, radio spectrum has entered in all walks of life and also contributed significantly towards GDP of a country directly and indirectly. Therefore, its efficient and effective management is inevitable. Management of radio spectrum is operated at national, regional and international to make an interference free environment for wireless services. This chapter provided an overview of radio spectrum management at the international and regional level and also give a complete detail of spectrum management and frequency allocation in India and Denmark.

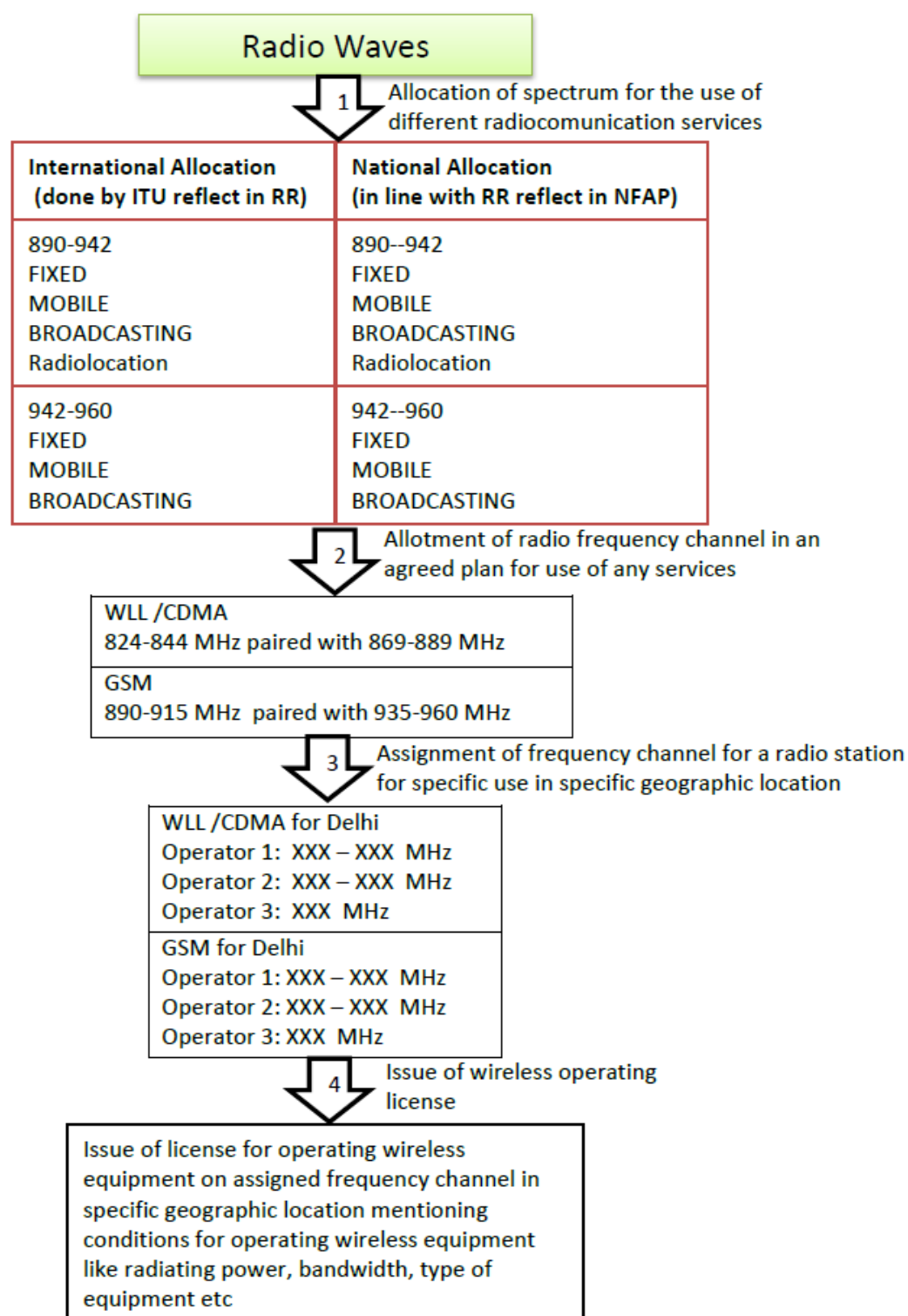


Figure 2.6: Spectrum allocation process in India



Table 2.3: Frequency resource allocated for each services in different frequency bands in percentage

Frequency Band	Fixed	Mobile	Broadcasting	Navigation	Sat. Services	Amateur	Others	Secondary
30KHz-300 KHz	47.2	0	0	38.9	0	0	0	47.3
300KHz-3 MHz	43.25	44.25	47.25	30	0	7.4	0.38	14.85
3MHz-30 MHz	49.95	22.9	16.75	25.5	0	12.22	2.78	15.23
30MHz-300 MHz	85	85	36.3	10.95	1.5	0.75	2.75	7.32
300MHz-3GHz	65.61	65.42	19.62	40.53	37.9	0	25.62	21.47
3GHz-30 GHz	84	79.37	2.96	22.6	77.7	0	15.78	39.1
30GHz-300 GHz	58.49	53.64	1.48	31.45	71.3	1.67	65.05	17.95

Navigation: include aeronautical, maritime, radiolocation, radio determination services etc.

Others: include space research, radio astronomy etc.

Satellite Services: all kind of satellite services

Table 2.4: Percentage of exclusive allocation for fixed, mobile and broadcasting services

Frequency Band	Fixed	Mobile	Broadcasting	Fixed & Mobile	Fixed, Mobile & Broadcasting
30KHz - 300 KHz	11.11	0	0	0	0
300KHz - 3 MHz	0	0	40	19.04	7.22
3 MHz-30 MHz	24.77	0	14.2	16.65	1.28
30 MHz-300 MHz	0	0	2.96	54.4	30.75
300 MHz-3GHz	0	0	0	16.8	6.8
3 GHz-30 GHz	0	0	0	4.95	0
30 GHz-300 GHz	0	0	0	0.75	0

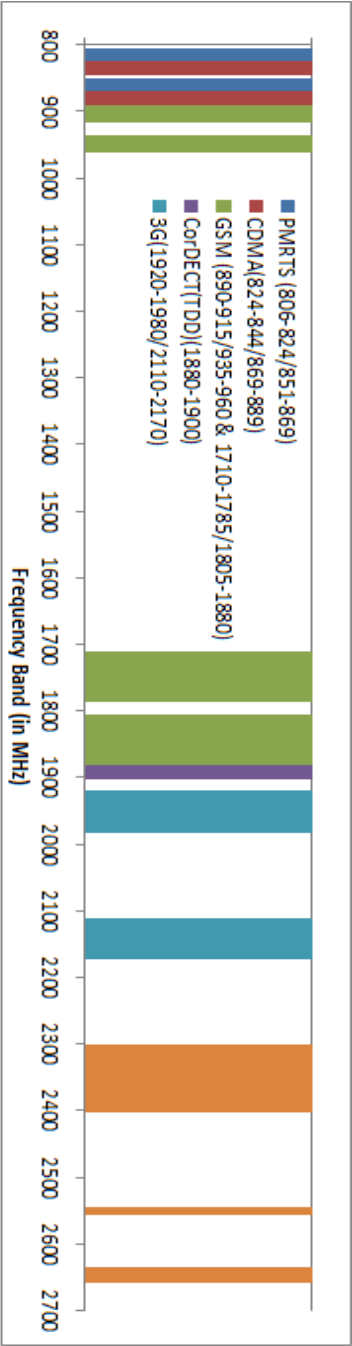


Figure 2.7: Spectrum assigned to telecom services in India

## Chapter 3

# Spectrum on Demand

### 3.1 Introduction

Life without mobile phone is difficult to imagine. Today, telecom services are affecting virtually everyones life and have become a major political topic and a significant contributor to national gross domestic product (GDP). The telecom services have been recognized the world-over as an important tool for the socioeconomic development of a nation. Pick up any newspaper and you will find an article somewhere relating to the telecom sector. If it is not in the technology section it would almost certainly be in the business section[40]. Starting from voice services, we are now experiencing massive growth in value added services short message service (SMS), multi-media services (MMS), Internet applications using wireless access protocol (WAP), mobile TV etc. After emergence of mobile telecom services, the dynamics of radio spectrum management have been changed. It is felt that traditional method of spectrum management would not work effectively to manage the spectrum demand of telecom sector. Several experiment has taken place in the management of radio spectrum and commercial approaches like beauty contest, auction has been adopted[8]. These steps ensure good revenue realisation but could not ensure efficient utilisation of radio spectrum. In this chapter, we discuss a new method of assignment of spectrum for commercial services which could provide additional revenue and ensures efficient spectrum utilisation.

### 3.2 Traditional Method - Command and Control

Radio spectrum management is an extremely important part of the wireless world. No wireless services can flourish without radio spectrum. Before the emergence of mobile communication, radio spectrum was in abundance. During the period, spectrum users were mainly police, military and some other government agencies. In the public domain, radio spectrum was related with broadcasting services only. The commonly used method for allocation of spectrum is known as Command and Control method (figure 3.1). In this method, radio spectrum is divided into spectrum bands that are allocated to specific services, such as mobile, fixed, broadcast, fixed satellite and mobile satellite services on an exclusive basis. Within this allocations, different spectrum blocks are assigned to users[5]. This command-and-control-based spectrum management framework guarantees that the radio frequency spectrum will be exclusively licensed to an authorized user (i.e. licensee)

and can use the spectrum without any interference. In short, command and control can be characterized by[8]:

- Divide the radio spectrum into different bands taking into account ITU-R radio regulation allocation table.
- Allocate these bands to specific radio communication services such as fixed, mobile, broadcasting and amateur etc.
- Decide the guard band and its width between the bands, if required.
- Decide the method for use of spectrum in each band
- Issue of license to spectrum users in each band for specific use under certain regulatory conditions.
- Assigned spectrum is non-transferrable in terms of services and users

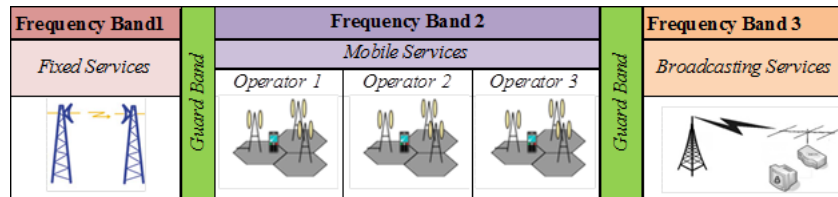


Figure 3.1: Command and control method

The command and control method is widely criticized for non-efficient use of spectrum. It has several advantages like it provides interference free environment due to rigid technical conditions, provision of guard band between the two allocations and separate spectrum allocation for each service and users. It plays an effective role in expansion of any services worldwide through co-ordination and harmonization. GSM service is the best example of the harmonization under command and control method. Another example is aeronautical and maritime services, where harmonized band is essential for operation. Harmonization also promotes economic efficiency by facilitating the development of common technical standards, and an international market for equipment and services enabling manufacturers to take advantage of economies of scale[41]. The advantages can be summarized as under:

- Less complicated process which reduce regulators burden
- Interference free environment due to rigid technical conditions

- Technical harmonization can be easily maintained which helps in expansion of any service worldwide.
- Low cost of equipment due to technical harmony
- Quality of services easy to maintain

The current practice of spectrum management ensure interference free environment to its license users but it does not ensure efficient use of spectrum[8]. Once the spectrum has been assigned to a user, spectrum utilization cannot be questioned during the licensing period provided he fulfill the terms and conditions of the license.

The basic objectives of spectrum management is maximizing the economic value and spectral efficiency derived from the spectrum. These objectives may be fulfilled some cases like GSM bands but it is very difficult to say that current practice achieves the full objective of a spectrum management in other bands. There have been many pieces of evidence that suggest that regulators are failing to achieve the objectives.

It promotes a kind of spectrum hoarding, where the user holds spectrum but unable to fully utilize it[8]. The entire spectrum especially below 3GHz has already been allocated to various users. No vacant spectrum is available as on date below 3GHz. A number of users, especially government sectors, use spectrum for short periods and most of the time lying vacant. Allocation of spectrum to some obsolete technologies like paging services etc, have resulted in spectrum being unused for over a long period. Due to regulatory restrictions, they cannot share spectrum with other services. Some applications, granted spectrum free or on nominal charges, such as aviation radar, have not modernized their radar systems for many decades despite the availability of much more spectrum efficient technologies. These factors create a sort of artificial spectrum scarcity. This scarcity becomes hindrance for new technologies coming into the market. It is difficult to allocate spectrum to any new services in the lower band. Allocation in higher band would increase infrastructure cost, consequently services would be more expensive to end users. Moreover, scarcity increases the market price of the spectrum, which make services bit more costly.

Spectrum allocated to one radio communication service cannot be replaced by other services even knowing that spectrum is underutilized. For example, terrestrial TV services, where at least 8 MHz of spectrum (Bandwidth of one channel) remain largely unused but licensing condition does not provide broadcaster to use this unused spectrum for other services. Another example is mobile telecom services, where a block of spectrum assigned for entire service area. While spectrum could be heavily used in urban areas,

it would be underutilized in rural areas. The operator cannot share this spectrum with other operators under the existing regime.

In addition to above, there are several other challenges before spectrum regulator like interference Management, international coordination, maintaining technology neutrality and harmonisation, provide safeguard to the wireless based public services and draw the economic efficiency from the spectrum in equitable manner. The current approach to spectrum management is becoming very difficult because of the increasing demands for more spectrums and meeting these challenges.

### 3.3 Methods for allotment of spectrum under Command and Control Method

The methods of license assignment[8] are FCFS, lottery, beauty contest or auction as shown in the figure 3.2. When spectrum demand is not high and available more than its requirement, FCFS method is used for assignment. On the other hand, when requirement is more than availability, assignment is made using lottery, beauty contest and auction method. These methods have their own advantages and disadvantages as given below:

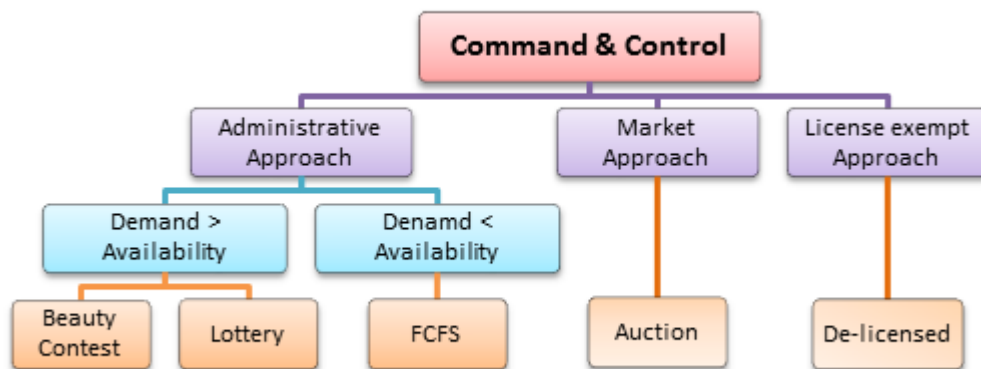


Figure 3.2: Command and control method of allocation of spectrum



### 3.3.1 Administrative Approach

#### First-come first-served

In FCFS method[42], request of applicants are attended in the order that they arrived without other biases or preferences. In this method, when a user wants spectrum for any particular radio service, he goes to the regulator for allotment of spectrum. Regulator evaluates the eligibility of the applicant and if the applicant meets the eligibility criteria, regulator allots the spectrum and charged a fixed amount from the applicant towards spectrum fee. This method is used when the number of applicants is very few and sufficient spectrum is available for allocation. FCFS methodology is inexpensive and takes very less time in the allocation of spectrum. However, it is not suitable for commercial applications as it does not give the true value of spectrum.

#### Lottery

Lottery system uses to assign spectrum on a random basis and usually at a zero price among qualified applicants. This method of allocation of spectrum was used during the 1980s by the USA and some other countries[43]. The lottery is less burdensome on the regulator and applicants not only in assigning spectrum quickly but also low cost to regulator and they are perceived as fair process as the every applicant has an equal chance of winning. It also provides a mechanism for selecting from among substantially equal applications in case of a tie breaker. Due to uncertainty over the result, lotteries attracted a large number of applications. USA adopted lottery system for allocation of cellular mobile licence 1980, where more than 400,000 applications were received[42]. Many lacked technical expertise and were seeking only speculative profit by resale, which resulted in revenue loss to the government and delay in the roll out of services. This method is considered as economically inefficient. Presently, this method is not used in any country.

#### Beauty Contest

It is quasi-judicial administrative process for selection of suitable applicants for allocation of radio spectrum. Bids are evaluated based certain criteria according to policy goals, like experience, total asset value, technical capabilities, business plan, geographical coverage and roll-out targets etc., and ranked on the basis evaluation (other than the price offered)[44]. The spectrum allocation follows these rankings. In some cases, a public hearing is also conducted where each contestant present its case before a government appointed committee. Most of the European Union countries

and Asian countries like Japan, Singapore, South Korea and Canada, the United Kingdom had adopted this method for award of license for 2G/3G mobile services[45]. The USA had also followed similar process until 1982 for allotment of spectrum for various wireless services and thereafter they were forced to adopt the auction method due to backlog in assigning spectrum.

Beauty contest is time consuming and expensive but it provides flexibility to government/regulator to ensure that spectrum is allocated to those who have qualified the certain standard as fixed by the Government according to their policy goals and criteria[45]. This method is normally influenced by some non-relevant factors and therefore, selection in beauty contest can be subjective, discriminatory and open to controversy as it does not tell that on what ground a firm is rejected. One example of this was the 3G allocation in Sweden in 2000, when some of the losers in the beauty contest process challenged the decision of regulator in the courts[46]. Lack of transparency is major issue attached with beauty contest and also provides no way of choosing among two or more licenses that are substantially equal which invites litigation and adds further delay. This method is also economically inefficient since assignment is made based on the factors which do not related to the economic value of spectrum. In addition to this, spectrum is awarded on the basis of promises about the future performance, which might be hard to enforce, leading to possible opportunistic behaviour and a credibility problem with beauty contest.

### 3.3.2 Market Approach

#### Auction

Auction[47] is a well known practice used for selling objects from very old age. An auction is a mechanism based on a pair of rules, namely the allocation rule that defines which good is allocated to whom and the payment rule that defines the charge of the auction winner(s). Deliverables in auction is heavily depends upon the fact that how the auction mechanism has been designed.

Spectrum auction[8] is a process whereby a government uses to sell the rights of spectrum over specific frequency band for certain duration. Auction is one of the efficient ways for allocation of spectrum to the bidder who value it most. A bid value signify the bidders valuation of the resource which shows that how efficiently bidder can utilise the public resource. Normally auctions are held with single dimension concept i.e. for maximising revenue but it can be made multidimensional attaching various policy goals along with maximising revenue. Multidimensional auction is most suitable for spectrum

auction. Therefore, auction achieves more than maximising revenue and generating efficient match of public resource to private firms. The regulator can adopt some criteria for awarding resource (spectrum) via auction as done in beauty contest. The terms and condition or rights of the winner is similar to the beauty contest or FCFS, the only thing which differ is bidders willingness to pay for the spectrum.

Auction is quick in delivery, more economical and more transparent as compare to beauty contest[45]. In auction, regulator has to come in advance explicitly about the criteria whereas in beauty contest, criteria are not explicitly known to contenders and also in auction bidder can know why they win or lost. Therefore, auction is less susceptible to legal and political controversy. Auction can generate a large chunk of money to the government.

### 3.3.3 Open (De-licensed) approach

De-licensed approach[5] is a kind of spectrum sharing, where unlimited number of unlicensed users shares an open frequency band with each other under certain technical conditions fixed by the regulator. Under open approach, no intervention from a regulator exists, it user comply with regulatory requirements. The open spectrum creates a fertile test bed for new wireless technologies and innovations. Majority of short range radars, Wi-Fi, Bluetooth, wireless LAN and cordless phones, are working efficiently in de-licensed spectrum bands despite considerable interference in these bands. There are some disadvantages are associated with unlicensed approach like congestion, considerable interference, reduction in QoS in de-licensed bands and loss of direct revenue to the government. De-licensed approach reduces the burden of regulators to assign spectrum for low power short range devices.

## 3.4 Spectrum Allocation for Commercial Services

The application of radio spectrum in general sense can be divided into commercial and non-commercial application[48]. The commercial applications are considered those services which earn revenue by utilising radio spectrum like telecom and broadcasting services(figure 3.3). Telecom and broadcasting sector cannot survive without radio spectrum and earn revenue through utilisation of spectrum. Contrary to commercial applications; non-commercial applications are those which do not earn revenue through utilisation of radio spectrum like an industry acquire wireless license to connect

its factory located in remote areas of the country with the corporate office, which is in a big city. Here, its earning does not depend upon utilisation of radio spectrum. Such types of application are considered as non-commercial applications. Spectrum utilized by the government departments like police, defence, public safety and other private sectors etc. is also considered as non-commercial applications. The spectrum assigned for non-commercial applications are normally either free of cost or on nominal charges whereas spectrum assigned to commercial applications involves huge money.

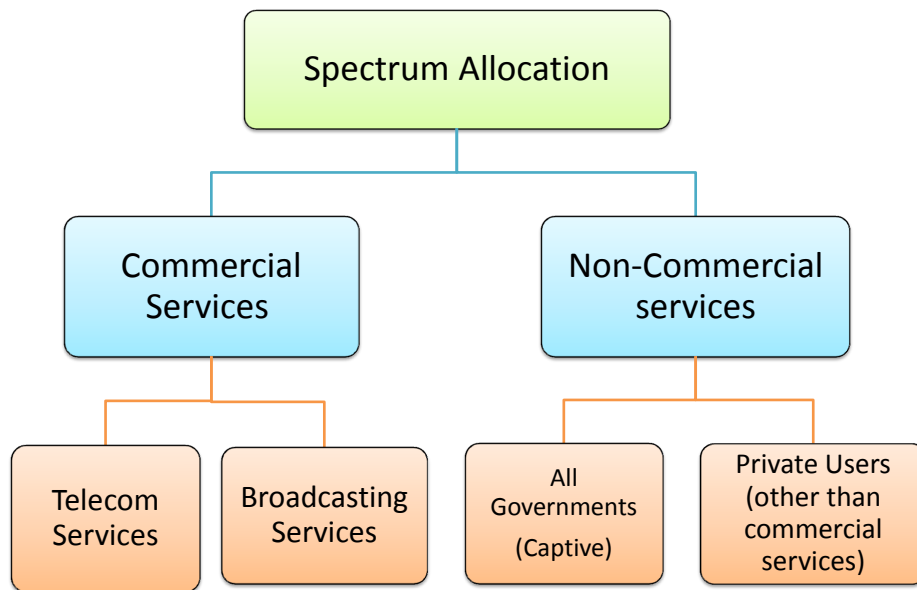


Figure 3.3: Division of commercial and non-commercial services

The spectrum requirements for commercial and non-commercial services are different. Demand for spectrum for commercial services is increasing much faster rate as compared to non-commercial services. Spectrum allocation for broadcasting and telecom services is given below:

### 3.4.1 Broadcasting Services

As per radio regulation [6], broadcasting services are operated in medium frequency (MF), high frequency (HF), very high frequency (VHF) and ultra-high frequency (UHF). The spectrum for broadcasting services in these bands

has been allocated long back by the ITU. Broadcasting services are still working in these allocated spectrum bands. With the passage of time, allocation in the UHF band i.e. 470-890 MHz for TV broadcasting has now been reduced in allocation due to digital switchover (DSO). Spectrum released through DSO has been proposed to allocate to telecom services.

The spectrum requirement for broadcasting services is customer independent. Once an operator established their network, no further spectrum would be required for running the services. Therefore, spectrum allocated for broadcasting services is sufficient to cater the requirements of the broadcasting sector.

### 3.4.2 Telecom Services

The journey of mobile communications commenced in the early 1980s as first generation (1G) with analog technology primarily for voice only. In early 1990s, second generation (2G) entered into market with digital technologies (GSM & CDMA) mainly for voice and data (SMS) services with a speed of 9.6 to 14.4 Kbps. The 2.5 generation (2.5 G) of technologies were a step further and supported data transmission along with voice with enhanced speed of 56 Kbps to 144 Kbps. 2.5 G facilitated enhanced multimedia and streaming video with limited web browsing. The third generation (3G) of mobile communications developed in late 1990s and facilitates enhanced multimedia and streaming video capabilities with transmission speed from 144 Kbps for vehicular speed, 384 Kbps for medium speed and 2Mbps for indoor and low speed. The present generation is fourth generation (4G) mobile communications with more than 100 Mbps peak data rate for high mobility communication (such as from trains and cars) and 1 Gbit/s for low mobility communication (such as pedestrians and stationary users)[11].

The demand of spectrum is increasing with convergence of more and more applications and desirability of greater mobility. Considering this fact, ITU has identified the following frequency band for International Mobile Telecommunications (IMT) services as shown in table 3.1 [49]:

Table 3.1: IMT bands

Frequency Band	Band Width
450-470 MHz	20 MHz
698-960 MHz	262 MHz
1710-2025 MHz	315 MHz
2110-2200 MHz	90 MHz
2300-2400 MHz	100 MHz
2500-2690 MHz	190 MHz
3400-3600 MHz	200 MHz
<b>Total</b>	<b>1177 MHz</b>

The above identified 1177 MHz spectrum is not sufficient to meet the telecom sector requirements. ITU has decided to identify new spectrum blocks, in addition to above, in different frequency bands for IMT services through Agenda item 1.1 for World Radiocommunications Conference 2015 (WRC-15) [50]

*"to consider additional spectrum allocations to the mobile service on a primary basis and identification of additional frequency bands for International Mobile Telecommunications (IMT) and related regulatory provisions, to facilitate the development of terrestrial mobile broadband applications, in accordance with Resolution 233 (WRC-12)"*

On the other hand, studies show that spectrum assigned for telecom services is not fully utilized [9]. This non-utilisation of spectrum could be attributed to current spectrum allocation policy for telecom services. The spectrum requirement for telecom service is subscriber dependent. The requirement increases with increase in subscriber base. The following three factors are responsible for telecom network capacity. The cell capacity can be altered by any of these three factors.

1. Amount of Spectrum
2. Spectral Efficiency per cell
3. Number of Cells

The spectral efficiency is related to radio access technology e.g. Global System for Mobile (GSM), Code Division Multiple Access (CDMA), Wideband Code Division Multiple Access (WCDMA), Long Term Evolution (LTE) and Worldwide Interoperability for Microwave Access (WiMAX) etc. The fundamental measure of spectral efficiency is the bits per second (bps) obtained relative to Hertz (Hz) of spectrum used (bps/Hz) for a given radio

access technology. Presently, LTE system has highest spectral efficiency with 2.4bps/Hz to 4.0 bps/Hz. High spectral efficiency is important for increasing network capacity, but, alone, it cannot address the increasing demand for cell capacity[51].

For a given access technology, network capacity could be enhanced by increasing either or both, cell site and amount of spectrum. The configuration of network and amount of spectrum decide that what level of demand network can meet. The traffic load at cell is measured in Erlangs B/Erlang C formula. The Erlang B/C formula is normally used to estimate voice call/data carrying capacity in the network[52]. For a given blocking probability, offered load in a network depends upon numbers of channel i.e. amount of spectrum.

There is an inverse relationship between the quantum of spectrum and the expenditure on network required to serve a particular level of demand[53]. A telecom service provider needs to install a new cell site due to capacity constraint or coverage constraint for a given amount of spectrum. The urban and rural areas have different population density. The capacity constraints would arise mainly in urban areas due to high population density and coverage constraints would be visible mainly in rural areas. The expenditure on network expansion could be reduced if additional amount of spectrum is made available to the telecom service provider. However, service provider will have to pay auction price for this additional spectrum. The auction price for acquiring additional spectrum would normally be lower than money required to be spent for expansion of network infrastructure to maintain same level of traffic.

Worldwide telecom services are running in 800, 900, 1800, 2100, 2300 and 2600 MHz. Recently, after completion of digital switchover 700 MHz band has also opened for telecom services. Initially, spectrum for telecom services was assigned through the FCFS method on nominal charges. With passage of time, assignment of spectrum for telecom services changed from FCFS to beauty contest and auction method. With this change, economic value of spectrum has also changed drastically. In auction, spectrum for telecom services in a service area (a part of country or entire country) is divided into blocks and these blocks are put to auction for 15-20 years of time. Whoever pays highest price, would own the spectrum block to run telecom services.

The amount of spectrum assigned for telecom services in different countries is not same. In European countries, mobile services typically use spectrum in the 800, 900, 1800, 2100 and 2600 MHz bands. Mobile services in a typical member state have access between 300 to 800 MHz of spectrum at frequencies below 3 GHz, and on average 4-5 operators are present in a country. Each operator holds approximately 100-200 MHz of spectrum

at frequencies below 3 GHz[17, 54]. Therefore, each operator has been assigned more than sufficient spectrum in European countries. On the other hand, countries like India, each operator holds approximately 8-15 MHz of spectrum at frequency below 3 GHz[20]. The initial assignment was made to operators in the range of 4.4 to 6.2 MHz of spectrum in 900/1800 MHz bands on FCFS method. This initial assignment of spectrum was sufficient to run the services. Telecom services are subscriber base services. The spectrum requirement increases with increase in subscriber base. Earlier, any additional spectrum assigned to operators was based on predefined subscriber base criteria. Presently assignment of spectrum for telecom services is made by auction method. If an operator wants additional spectrum, he could get through auction only.

In auction method, operator gets spectrum for the entire service area. However, traffic flow may not be same in the entire service area. The acquired spectrum becomes idle in some part of the service area due to low traffic flow, and the operator has to pay auction price for the entire service area. This creates inefficient use of spectrum, and additional capital investment by operators. Therefore, the existing method enhances spectrum scarcity, which further increase spectrum price in the market and makes services more expensive to end users.

### 3.5 Spectrum on Demand for Commercial Applications

It is well known fact that the demand/requirement of spectrum is not uniform in a service area. It varies with time and location depending upon traffic flow. In a telecom service area, traffic varies with location and time wise. At some point of time, traffic is very high and at some point of time traffic is low. Similarly, traffic is not same at every location of the city (Variation time wise). If we monitor spectrum usage during a day, we would find that highest spectrum utilisation takes place during peak hours, and less spectrum utilisation during non-peak hours (especially night time).

Similarly, cities with higher population density and commercial hub cities have high traffic flow whereas cities with low population density have low traffic flow (variation location wise in a service area). Even traffic flow is not same within a city. Traffic is normally high in commercial complex, airport, railway station and highly crowded areas of the city (variation in a city).

As shown in the figure 3.4, high traffic sites (A class cities) with high



traffic time zone utilise highest amount of spectrum and low traffic sites (C class cities) with low traffic time zone utilise the lowest amount of spectrum. In the remaining scenarios spectrum utilisation is neither high nor low. Therefore, spectrum utilisation is maximum in one case and partially utilised in the remaining cases in a service area. This creates an anomaly in spectrum usage with location and time in a service area.

City \ Time	Low Traffic Time zone	Medium Traffic Time zone	High Traffic Time zone
High Traffic (A Class cities)			Maximum Spectrum Requirements
Medium Traffic (B Class cities)			
Low Traffic (C Class cities)	Lowest Spectrum Requirements		

Figure 3.4: Spectrum requirement- time and location

As per the current practice, spectrum allocated to service providers is uniform in a service area irrespective of location and time despite that traffic flow with respect to time, and location would not be same. The entire spectrum at a given time/location may not be used by the service providers, but they have to pay spectrum usage charges and spectrum price for the entire acquired spectrum for a service area. This anomaly usually leads to an inefficient use of spectrum and costly services to the end user. This also creates artificial spectrum scarcity. However, such allocation makes the regulators job easy.

### 3.5.1 Proposed method

The operator needs a minimum quantum of spectrum to roll out the services in the service area. This minimum spectrum may be assigned to operators through auction for longer duration typically 15- 20 years for the entire service area. Spectrum beyond minimum quantum should be auctioned on location and time basis. The operator would buy spectrum as per their requirements which may vary with time and location.

For this purpose, divide the entire service area into small segments (may be at the district level) based on busy, medium and low traffic flow sense, and further divide duration on the traffic flow basis. Generally, traffic flow could be considered as high around in the morning and evening time

and low at night. At remaining period traffic flow could be considered as medium level. Based on these assumptions, a typical traffic flow variation in different kind of cities at different time period could be described as shown in table 3.2. After proper monitoring of spectrum usage, it can be easily derived that which city and what time, traffic is high, medium and low.

Table 3.2: Typical pattern of traffic flow in different cities

Time	City 1 (Class 'C')	City 2 (Class 'B')	City 3 (Class 'A')	City 4 (Class 'A')
00.00 to 4.00	Low	Low	Low	Low
4.00 to 8.00	Medium	Low	Low	Medium
8.00 to 12.00	High	Medium	High	Medium
12.00 to 16.00	Medium	Medium	High	High
16.00 to 20.00	High	High	High	High
20.00 to 24.00	Low	Low	Low	Low

The reserve price[8] is kept same for the entire service area in the traditional spectrum auction. Here reserve price is required to be fixed with respect to time and location. Generally, highly populated cities generate more traffic comparatively low populated cities. The cities can be classified either on population or on the traffic flow basis. The reserve price would be kept high for the cities (class 'A' cities) in a service area where traffic flow is high, and the cities (class 'C' cities) where traffic flow is low, the reserve price would be fixed low. Similarly time duration may be divided into high, medium and low traffic basis and reserve price would be fixed accordingly. Reserve price for the cities sketched in table 3.3 may be fixed as shown below:

Table 3.3: Typical pattern for reserve price

Time	City 1 (Class 'C')	City 2 (Class 'B')	City 3 (Class 'A')
00.00 to 4.00	Low (X1)	Low(Y1)	Low(Z1)
4.00 to 8.00	Medium(X2)	Low(Y1)	Low(Z1)
8.00 to 12.00	High(X3)	Medium(Y2)	High(Z3)
12.00 to 16.00	Medium	Medium	High
12.00 to 16.00	Medium(X2)	Medium(Y2)	High(Z3)
16.00 to 20.00	High(X3)	High(Y3)	High(Z3)
20.00 to 24.00	Low(X1)	Low(Y1)	Low(Z1)

Where,

$$Z(i) > Y(i) > X(i) \quad (3.1)$$

$$X(3) > X(2) > X(1) \quad (3.2)$$

$$Y(3) > Y(2) > Y(1) \quad (3.3)$$

$$Z(3) > Z(2) > Z(1) \quad (3.4)$$

Initially, allocation may be made for a longer period not more than a year. After monitoring traffic pattern, reserve price may be reviewed accordingly. It is a kind of spectrum trading, where trading will be done by the regulator itself not by the service providers.

### 3.6 Numerical Analysis

Consider a service area having 10 cities. A block of the spectrum has been auctioned for 20 years for the entire service area. The total amount realized by the regulator after auctioning one block of the spectrum is 200X. The average realized amount per annum per district would be X. Now another block of spectrum is to be auctioned considering as an additional spectrum block based on the proposed method. The entire service area will be divided into A Class (high traffic), B Class (medium traffic) and C Class (low traffic) in terms of location (city basis) and time (high, medium and low traffic period).

For numerical analysis purpose, we divided the time period into four different segments with each segment of six hours as shown in the table 3.4. We have taken medium city with medium traffic as a reference point, and its reserve price kept equal to revenue realized through the normal auction and increase (in multiple of 2) or decrease (in division of 2) the reserve price for remaining scenarios.

Table 3.4: Reserve price based on traffic

Time period zone	Class 'C'city	Class 'B'city	Class 'A'city
00.00-06.00 (Low)	X/16	X/8	X/4
06.00-12.00 (High)	X/4	X/2	X
12.00-18.00 (Medium)	X/8	X/4	X/2
18.00-00.00 (High)	X/4	X/2	X

We have taken three different scenarios in a service area for analysis of revenue realisation based on the above assumptions. In the first scenario,

spectrum sold in all the cities; the second one, spectrum is not sold in 50% of C class cities and the final one, spectrum sold a bit higher price in A & B class cities and spectrum is not sold in C class cities.

A graph of normalized revenue realization for different combination of cities in a service area based on the above reserve price has been shown in figure 3.5. We consider that spectrum sold on reserve price only.

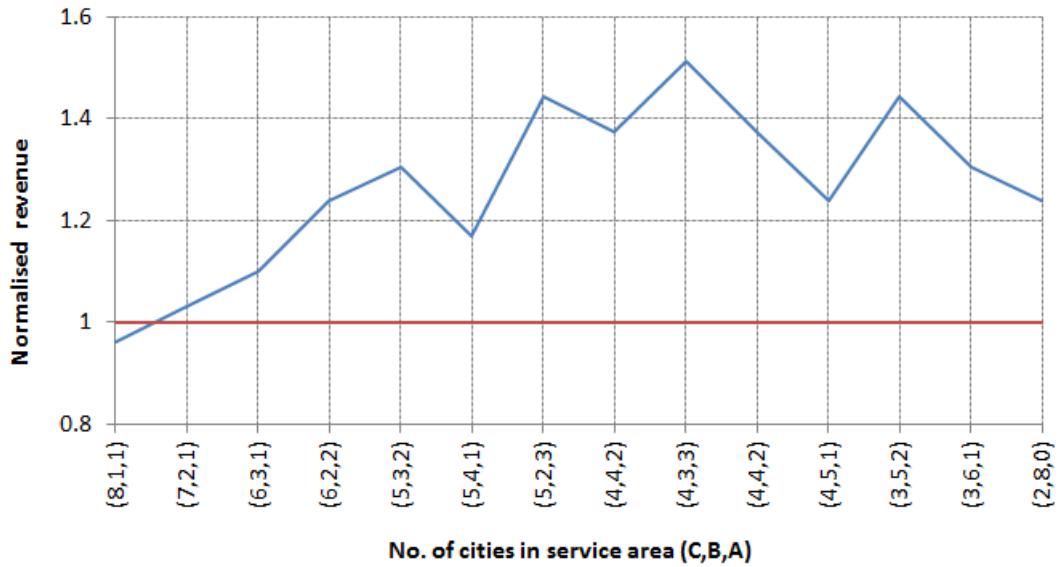


Figure 3.5: Normalized revenue realization at different type of cities combination

It shows that revenue realization for a service area, which has more than one medium traffic and high traffic level cities, would be higher than the normal auction process even if spectrum sold on reserve price subject to spectrum sold in all cities.

It may not be possible that additional spectrum demand exists in each and every cities in a service area. We take other scenarios where spectrum is not sold in C class cities. In the second scenario, we assume that spectrum could not be sold in 50% of C Class cities and in the remaining areas, spectrum sold on reserve price only. With this assumption, a graph of normalized revenue realization for different combination of cities in a service area based on the reserve price is shown in figure 3.6.

The graph indicates that revenue realization would be higher than the normal auction process if the service area has minimum two A class city and two B class city or more than 50% of the cities fall under class B.

In the third scenario, we assume that spectrum could not be sold in Class C cities, and spectrum sold in class A and class B cities at 5% and 2%

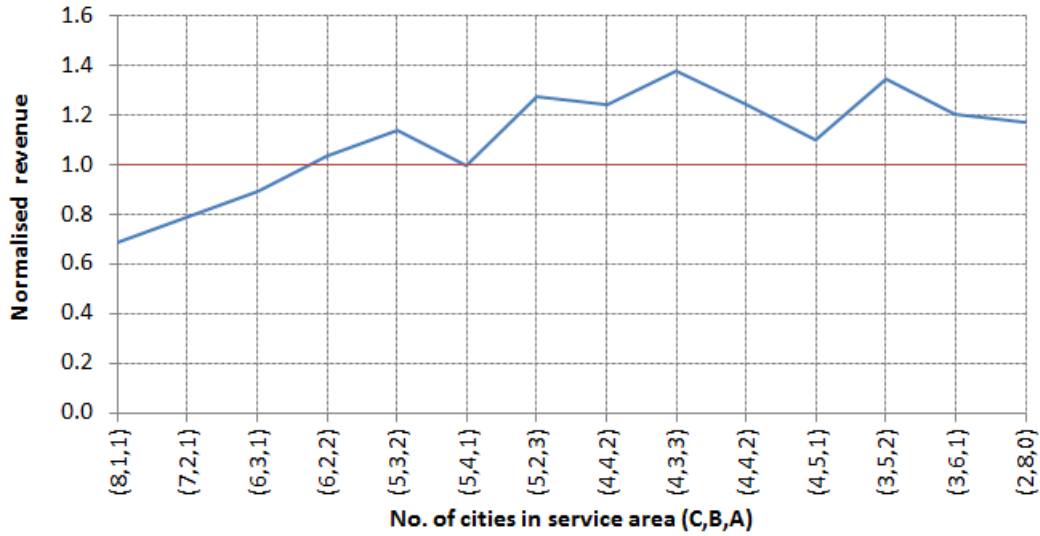


Figure 3.6: Normalized revenue realization when spectrum in 50% of class C cities not sold

higher than the reserve price respectively. With this assumption, a graph of normalized revenue realization for different combination of cities in a service area based on the reserve price is shown in figure 3.7. The graph indicates that revenue realization would be higher than the normal auction process if the service area has a minimum two-three A class and B class city. It is anticipated that auction price, especially for A class and B class cities may go beyond the assumption made in third scenario.

The second and third scenarios indicate that those service areas which do not have much traffic; such type of spectrum assignment may not be beneficial. It might be possible that spectrum demand in low traffic service may not go beyond a minimum quantum. Therefore, this type of spectrum assignment is good for those service areas where traffic flow is high. Such type of assignment is useful for developed countries, where traffic is high in most of the cities and excess spectrum has been assigned to the operators.

We take a typical case of a service area which has a combination of 5 C class, 3 B class and 2 A class cities. We plot the graph with variable reserve price (figure 3.8) for normalized revenue realization. The X is the average revenue realization for per annum per district in a service area. This X has been taken as the reserve price for B class city with a medium traffic flow period.

The plot shows that revenue realization will go down if we take reserve price below 'X' for 'B' class city with medium traffic flow period. The plot

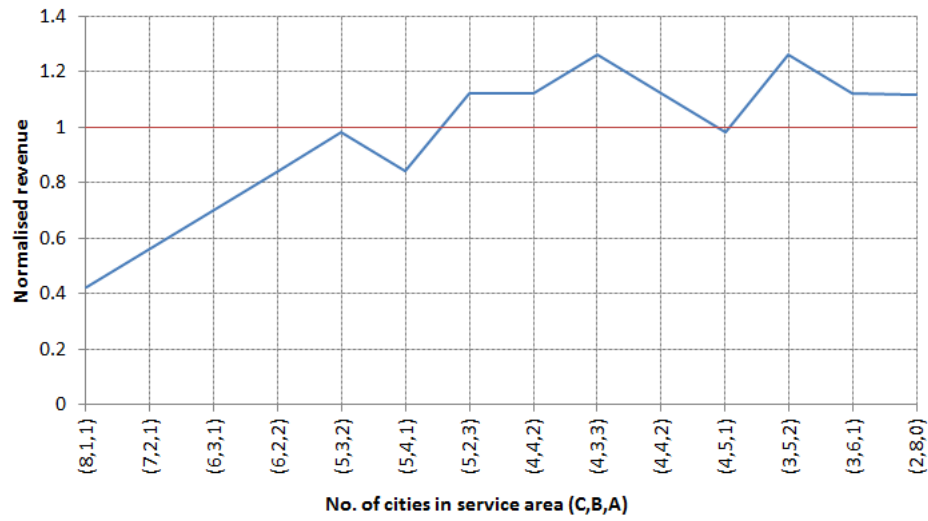


Figure 3.7: Normalized revenue realization when spectrum not sold in class C cities with incremented price for A & B cities

shows the high revenue realization at a high reserve price, but practically high reserve price may not yield high revenue realization as it may restrict the entry of operators in the auction. Therefore, reserve price should be kept around 'X' for typical service area case. The regulator would certainly get additional revenue in comparison to the traditional spectrum auction method. This also ensures higher spectrum utilization.

We take the Denmark as a case study for spectrum on demand. Denmark is well developed country and having a good telecom infrastructure. The overall teledensity is more than 100% and mobile penetration was stood 146% in 2012 which is one of the highest penetrations across the Europe. The mobile broadband penetration was 82% by the end of 2011.

There are four telecom operators namely M/s TDC, Telenor, Telia and 3 (Hutchison Whampoa). These operators are providing services in 900, 1800, 2100 and 2600 MHz band. Denmark consists five regions namely, Capital Region, Mid Jutland, North Jutland, Zealand and South Denmark. Based on the population, cities under these regions have been divided into Class A (population more than 65,000), B (population between 45,000 to 65,000) and C (population below 45,000) cities as given in table 3.5:

Consider that the first spectrum block has been assigned to operators by the traditional auction method, and an additional block is to be assigned through proposed method in all the five regions of the country. We calculate average revenue realisation in all the five regions based on the discussed three cases. The percentage of average revenue realisation in three different cases

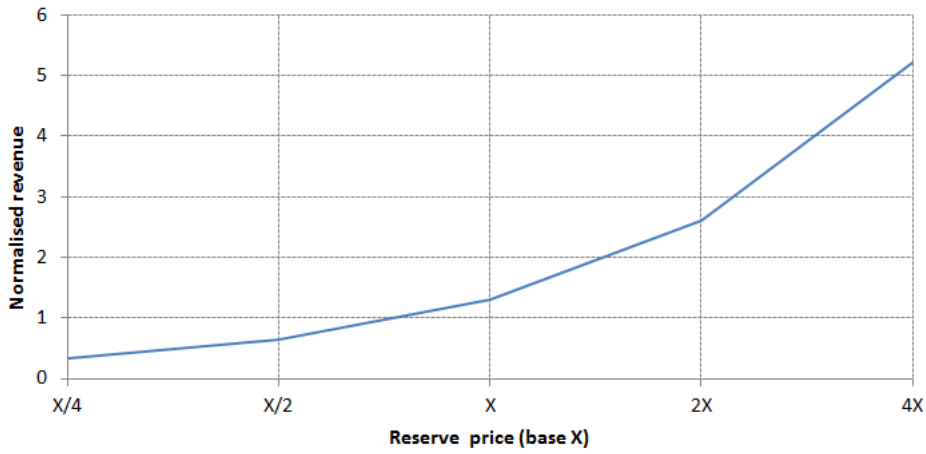


Figure 3.8: Variation of normalized revenue realization with reserve price

is given in table 3.6.

Table 3.6: Possible revenue realisation in different regions of Denmark

Region	No. of cities				Case 1	Case 2	Case3
	Class 'A'	Class 'B'	Class 'C'	Total			
Hovedstaden [Capital Region]	4	11	15	30	21.46	4.27	-11.20
Midtjylland [Mid Jutland]	6	6	7	19	55.59	42.93	32.95
Nordjylland [North Jutland]	2	2	7	11	18.75	-3.13	-23.45
Sjælland [Zealand]	4	5	8	17	37.50	21.32	7.29
Syddanmark [South Denmark]	5	6	11	22	34.38	17.19	2.05
<b>Total</b>	<b>21</b>	<b>30</b>	<b>48</b>	<b>99</b>	<b>33.33</b>	<b>16.67</b>	<b>2.03</b>

The above analysis shows that above scheme would be highly beneficial in Mid Jutland, Zealand and South Denmark in all the three cases. No doubt first case in which entire spectrum sold would be the better situation. In case 2, where spectrum could not be sold in 50% of class C cities could be considered an optimum situation whereas case 3 is an extreme case. If we take overall revenue realisation for entire country in case 2, we see that average revenue realisation would be more than 16% from the traditional method of auction and ensure efficient spectrum utilisation.

Table 3.5: No. of class of cities in different regions of Denmark

Region	No. of cities			
	Class 'A'	Class 'B'	Class 'C'	Total
Hovedstaden [Capital Region]	4	11	15	30
Midtjylland [Mid Jutland]	6	6	7	19
Nordjylland [North Jutland]	2	2	7	11
Sjælland [Zealand]	4	5	8	17
Syddanmark [South Denmark]	5	6	11	22
Total	21	30	48	99

The proposed method is complex in regulation, and required strict monitoring system to ensure that operators would adhere to purchased time slot. However, proposed method would ensure to enhance revenue and optimum utilisation of spectrum. The main advantages are:

- No additional burden on service providers for spectrum charges
- Service providers have already made tariff plan based on time concept like less charges in the night and high charges during peak hour. Allocation of spectrum based on the traffic may further reduce tariff.
- Efficiency of spectrum will be enhanced. During low time and low traffic cities, spectrum can be allocated to other services.
- It will enhance the revenue to the Administration in comparison to existing one time auction for a longer period for the entire service area basis.

## 3.7 Conclusions

The chapter provided an overview of existing command and control method of spectrum management. Under the traditional method, spectrum for commercial services is allotted through FCFS, Beauty contest and Auction. Auction is most preferable method for allocation of spectrum. The traditional method of The traditional auction method of assignment of spectrum for commercial services is not highly spectrum efficient and revenue



generator. We have presented a new concept of assignment of spectrum for telecom services. Allocation of spectrum at a location and time basis would provide additional revenue to regulator and ensures high spectrum utilization. The proposed method is highly beneficial in developed countries, where teledensity is high and spectrum utilisation is not optimum.

## Chapter 4

# Spectrum Trading in Telecom Sector

## 4.1 Introduction

The traditional Command and Control method does not ensure efficient use of spectrum though provides interference free environment and plays an effective role in the expansion of many services (like GSM) worldwide through co-ordination and harmonization. This method was considered good when few players were in the market and there was no dearth of usable spectrum.

In the change scenario, this approach is under pressure as it does not lead to efficient spectrum use. However, it could be justified in some way that it successfully avoids interference and played an effective role in expansion of few services through co-ordination and harmonization. The emergence of new technologies and services, need for greater mobility, greater capability of market players and blurring the boundaries between different services and technologies has put a great pressure on radio frequency spectrum manager for efficient and economical use of spectrum. Regulators were forced to adopt market mechanism for assignment of spectrum. Spectrum Auction was the first step in this direction. Auction allot spectrum who value its most. While introducing auction method, the FCC pointed out in 1999 that "efficient spectrum markets will lead to use of spectrum for the highest value end use" [33]. The second step in this direction is the creation of secondary market for spectrum i.e. to allow licensees to trade spectrum, owned by them, between each other as per their requirements to enhance the efficiency of spectrum. This concept is known as spectrum trading [8].

## 4.2 Spectrum Trading

Spectrum trading is a market based mechanism where buyers and sellers determine the assignments of spectrum and its uses [14]. In spectrum trading, seller transfers the right of spectrum usage, in full or part, to the buyer while retaining the ownership in exchange of money. Spectrum trading is considered as economically efficient because trade will only take place if the spectrum is worth more to the new user than former it was in the old user [55]. In case a user fails to derive benefits from spectrum, user could manage the cost of spectrum through trading, which paid during the auction for acquiring spectrum. Trading is technically considered as part of a spectrum sharing. However, trading differs in terms of usage right, where the total usage right transferred to the seller for a specified period and spectrum is available for exclusive use to licensee after the trade whereas in sharing, seller gets temporary right of spectrum usage, exclusive rights rests with the

seller and spectrum may not be available for exclusive use [56]. Spectrum can be traded for providing the same type of services. Such trades do not have any complications and can be easily managed. The example is the transfer of spectrum between two GSM operators to provide the same services. In case of liberalised spectrum, spectrum trading may take place for providing any services with any technology subject to interference limits.

Spectrum trading, when combined with liberalization, may help to remove the artificial scarcity of the spectrum as trading facilitates to acquire spectrum more readily from the market and liberalization facilitates new technologies/ services to enter in the market. Trading also provides incentives to transfer underused spectrum to those who can utilise it better and address issue of the fragmented spectrum through consolidation of spectrum[57]. These factors provide consumers with a greater choice with the competitive market, new services & technologies. The unit of trading can be licensing parameters namely the bandwidth, the geographical area and the duration. This leads to the possibility of partial transfer usage right in terms of bandwidth, area or time.

The major concern with spectrum trading is the risk of increased interference. Liberalisation facilitates to coexistence of different technologies in one frequency band, which may increase the level of harmful interference within the band. In some countries, regulator sets the initial limit for interference parameters namely, in band emission and out of band emission. Another solution is to keep an adequate guard band between two different technologies as per international practice but this may lead to inefficient use of spectrum. In any case, some reduction in quality of services may exist. However, such reduced technical efficiency could be compensated by increased economic efficiency[58].

It is expected that spectrum trading may enhance competition in the market as it would be easier for players to gain access to spectrum. However, there is a risk of spectrum hoarding by big players which may create instability in the market, and reduce the level of competition. This issue could be tackled by imposing a cap on spectrum holding and market shares, suspending licenses for inefficient use of spectrum. A relatively higher annual spectrum usage charge also need to be imposed to discourage spectrum hoarding.

It has been experienced that trading activities are seen low in the high priced bands even scarcity is high. It would not be economically viable for the user to buy such spectrum from the secondary market unless the user has some future plan and good standing in the market. Spectrum trading activities in low priced spectrum bands are usually high. Therefore, low priced and high scarcity spectrum bands are more vulnerable for spectrum

trading.

### 4.2.1 Transfer and lease of spectrum

Both terms represent spectrum trading. Under transfer, with the consent of regulator, entire license rights and obligations will transfer to a new user i.e. buyer and seller will no longer be able to use spectrum. Seller license will be revoked and a new license needs to be granted to buyer. Regulator involvement is necessary in revoking old license and issue new license. Under the of spectrum, the seller can enter into a contract with buyer for transfer right for spectrum usage in a specific area, certain time period or part of bandwidth without intervene of the regulator. The seller will continue to be registered holder of spectrum and responsible for regulatory compliance as applicable. Three types of leasing is possible (Figure 4.1) namely swapping, partial transfer/lease and full transfer.

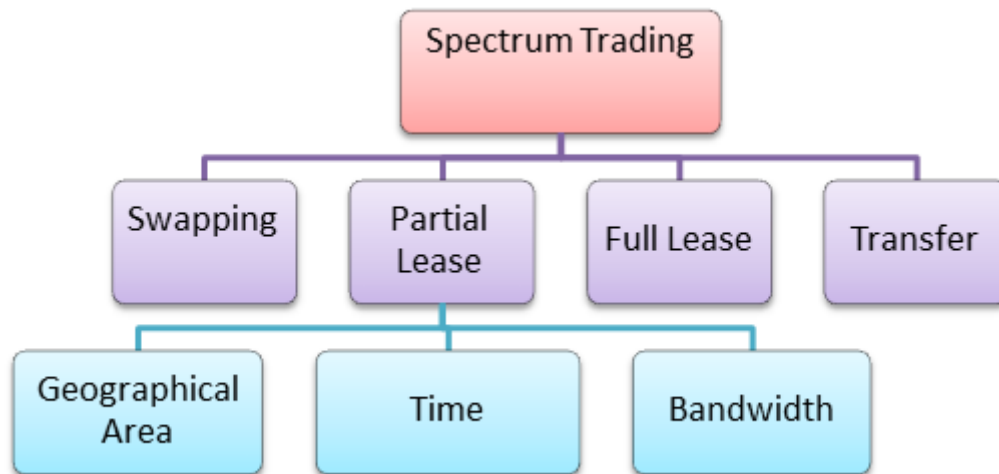


Figure 4.1: Spectrum trading

In swapping, buyer may make its spectrum holding contiguous by swapping spectrum block with sellers spectrum block as shown in figure 4.2. In this process, buyer would get the benefit in terms of technical efficiency, and seller may get some money without any enhancement in technical efficiency.

In partial lease, the seller may sell partial right for lease of spectrum in a certain geographical area, time period or part of bandwidth in the entire service area as shown in figure 4.2. In full transfer, the seller lease spectrum in all the three dimensions. In this process, seller would get financial benefits and buyers network efficiency would get enhanced and may consolidate larger market shares.

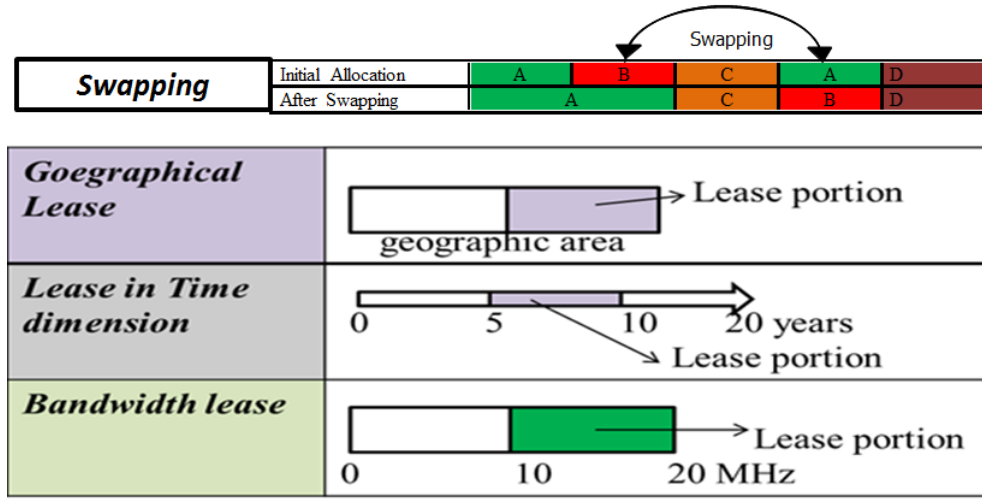


Figure 4.2: Swapping and partial lease in three dimensions

#### 4.2.2 Spectrum Trading in other Countries

Spectrum Trading has first been implemented in New Zealand and Australia. Thereafter, USA, UK, El Salvador, Guatemala and many European countries have introduced spectrum trading in specific bands, which are in demand for commercial use.

In the USA, the FCC has allowed spectrum trading, subject to its approval, to gain access to licensed spectrum by entering into spectrum leasing/transfer with licensees in most wireless radio services. The existing rules provide flexibility for some licensees to trade all or a portion of spectrum through lease or transfer to other existing licensees. Rules also allowed lease unused/entire spectrum to a new licensee without transferring rights. The FCC has also allowed public safety users to lease out their spectrum to each other. The FCC is also in favour of the concept spectrum broker, a third party whose business is only in spectrum selling and buying business[59]. The USA market is more mature and spectrum trading is highly successful.

In Europe, secondary trading is permitted under European Commission (EC) legislation. Almost all the EU states have allowed spectrum trading from 2006 onwards. Trading is permitted in all the bands, which is used commercially like PMR, fixed links, IMT bands, broadcasting and satellite bands etc. Trading rules may differ to some extent from country to country. Country specific partial trade in frequency, location and time are allowed, like some countries allowed partial trade in frequency but prohibit trade in location wise. In all countries, intents of trading are required to be informed to the authority. After authority consent, usage rights could be transferred.

Data in EU shows that trading is not very much successful. Maximum trading took place in PMR band, which have a high number of users and licenses whereas few trading took place in mobile bands, where number of licenses are less. The authorities in EU countries are hoping that trading will achieve its target with the passage of time[60].

### 4.2.3 Spectrum Trading in Denmark

Denmark was the first country in EU, which allowed trading in 1997 followed by Switzerland in 1998. The salient features of spectrum trading in Denmark are given below [57]:

- Spectrum trading is allowed in all GSM bands, 2.1 GHz, 3.5 GHz, 10.5 GHz, 26-29 GHz bands. Spectrum in these bands has been assigned through market mechanisms, auction or public tender
- Default duration for the granted usage is 15 years
- Usage rights can be traded partially for bandwidth and geographical area. No partial trade is allowed for time.
- Reference of usage right (frequency licence number) that will be transferred is required at notification of intent to trade
- Information about the license namely license number, frequency, geographical area etc. Needs to publish prior to the transaction
- Approval of transaction by the Authority is required for the trading part of the licence issued after an auction
- Transaction is required to be made public, which contains information like, identity of parties, reference of original authorization and new authorization, date at which transfer becomes effective, geographic area, frequency band and expiration date.
- Trade may be refused there is unpaid payment for a licence issued following an auction, licence holder cannot guarantee obligations on the provision of services with remaining spectrum.

Spectrum trading has been allowed long back in most countries but the market has not been successful in Australia, New Zealand and European countries because operators in these countries hold good amount of spectrum in each band, and lack of sufficient participation. The activity level is very high in the USA where mobile operators have bought spectrum from each other as well as from broadcasters and other niche spectrum holders.

### 4.3 Analysis of Spectrum Trading

There are three factors which could play a role in spectrum trading; subscriber base, spectrum holding and average revenue per user (ARPU). With the help of these three factors, we have derived two metrics for analyzing spectrum trading i.e. Subscribers per unit spectrum (SPS) and ARPU per unit spectrum (APS).

SPS is the ratio of total number of subscribers and assigned spectrum. This quantifies that how many subscribers handled by the operator on unit spectrum. High SPS indicates the operators market is stable and could be the probable buyer in the secondary market.

$$SPS = \frac{No.of\,Subscribers(N)}{AssignedSpectrum(S)} \quad (4.1)$$

APS is the ratio of ARPU (average revenue per user) and assigned spectrum. This quantifies that how much operator is earning on per user per unit of spectrum. High APS indicates the operators market is stable and could be the probable buyer in the secondary market.

$$APS = \frac{ARPU}{AssignedSpectrum(S)} \quad (4.2)$$

If the total revenue is  $R$  and number of users is  $N$ . The  $APS$  metrics can be written as,

$$\begin{aligned} APS &= \frac{R}{N.S} \\ &= \frac{R}{\left(\frac{N}{S}\right)S^2} \\ &= \frac{R}{(SPS).S^2} \end{aligned} \quad (4.3)$$

The above equation shows that there is a inverse relationship between the two metrics  $APS$  and  $SPS$ .

$$APS \propto \frac{1}{SPS} \quad (4.4)$$

If we differentiate Eq. 4.1 and 4.3, we would get,

$$\frac{\partial SPS}{SPS} = \frac{\partial N}{N} - \frac{\partial S}{S} \quad (4.5)$$



$$\frac{\partial APS}{\partial S} = \frac{\partial R}{R} - \frac{\partial N}{N} - \frac{\partial S}{S} \quad (4.6)$$

The analysis of Eq. 4.5 and 4.6, shows that revenue affects only to *APA* metric. Any change in subscriber base affects both the metrics. If the subscriber base increases, *APA* decreases but *SPS* increases and vice-versa if there is no change in revenue and quantum of spectrum. The relationship between *APS* and *SPS*, as mentioned in 4.4, has been shown in figure 4.3. Based on the relation, the following five scenarios is possible in a typical telecom service area.

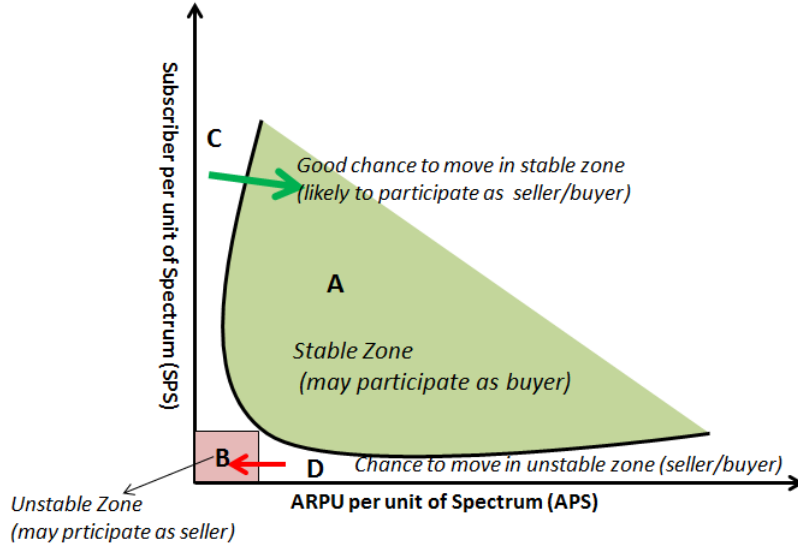


Figure 4.3: Different aspects of spectrum trading

**Both metrics are on higher side:** It signifies that the operators market is stable and has a good share in the market. Depending upon business strategy, the operator may need additional spectrum from the market for further expansion. Such operators could be probable buyers in the secondary spectrum market.

**Both metrics are on lower side:** It signifies that the operators market is unsteady. Not much subscribers in respect of assigned spectrum and average revenue. It means that spectrum is not being fully utilized. Such operators could be probable seller. In case of lowest metrics, it would be difficult for operator to survive without merger or selling spectrum unless their future business plan would be highly aggressive.

**Both metrics moderate:** In this case, operators business is running properly. Additional spectrum may not be required. The possibilities are

less to enter in the market. However, depending upon business strategy, the operator may go for buy of spectrum.

**SPS is high, APS is low:** Such condition is difficult to exist as a high subscriber normally gives better ARPU. If it happens, there would be a flaw in business strategy. The operator needs to relook at its business plan as there is a good chance to maximize APS. Such operators, if exist, less likely to participate in trading.

**SPS is low, APS is high:** There is a chance that the operator may move towards the lowest metrics side. It would be better for operator to relook at business strategy and participate in spectrum trading in the areas where the subscriber base is low and try to consolidate the position in the areas, where base is strong.

The above possibilities have been depicted in the figure 4.3. Operators fall under category A high SPS and APS, a probable buyer and category B low SPS and APS, probable seller. Category C high SPS and low APS and category D low SPS and high APS, these two may go for selling as well as buying depending upon their business plan.

Based on the above classifications, we would analyse the possibilities of spectrum trading between 2G GSM operators in two distinct telecom service area of India. All the data taken from Telecom regulatory Authority of Indian (TRAI) indicator report (January to March 2013)[61] and Cellular Operator Association of India (COAI) report for quarter ending March 2013[62]. The ARPU figure for some of the operators was not available so an average value of ARPU was taken for these operators for analysis purpose.

## 4.4 Indian Telecom Sector

The Indian telecom journey began in 1994, when telecom sector was opened for private sector. The first private sector wire-line and cellular licenses were issued in 1995. From then on, Indian telecom has seen several milestones crossed and many missteps that provided valuable lessons. The telecom industry has witnessed a phenomenal growth in the last decade with 898.02 million phone connections with overall teledensity of 73.32 at the end of March, 2013. Today, India is the second largest and fastest growing telecom market in the world in terms of the number of wireless connections. The growth is predominately in the wireless sector, which contributes 96.64% (867.80 million) of total phone connections [61].

Telecom services are operating in 800 MHz (CDMA), 900 MHz/1800 MHz (GSM), 2.1 GHz (3G) and 2.3 GHz/2.5 GHz (BWA) in India [20]. India is geographically 5th biggest country with 3.23 million  $km^2$ . The country has

been divided into 22 service areas for the purpose of telecom services. These service areas have further been divided into various categories viz. Metro, A,B and C based on the population, traffic pattern and revenue generations capacity. Service providers have been given a license for providing telecom services in these service areas. The Indian telecom scenario is bit unusual, if not unique, in terms of the number of operators and assigned spectrum. India is one of the few countries where CDMA and GSM both the technologies are in operation for mobile telecom services. Presently, 15 operators are providing different telecom services in India, out of which 8 are providing in all TSAs (6 in GSM and 1 each in CDMA & BWA). The average spectrum hold by each operator is between 10-20 MHz across all bands (i.e. 800, 900, 1800, 2100 MHz paired bands), about one-fourth of the international average [61][63]. A total of 310 MHz spectrum across the bands has been allocated for telecom services. There are no pan India presence in CDMA and 3G services except Public Sector Unit (PSU) BSNL[39]/MTNL[38]. BSNL is operating in all TSAs except Delhi and Mumbai, where MTNL is operating. A detail of no. of operators, average spectrum holding etc. is given in table 4.1 (BSNL/MTNL considered as one operator).

Table 4.1: Details of no. of operators and average spectrum holding

Services	No. of Operators			Frequency Band	Total Spec- trum (in MHz)	Average Al- location to an Operator (in MHz)
	Partial Pres- ence	Pan India	Total			
2G(CDMA)	4	1	5	800 MHz	20+20	2.5+2.5 to 5.0+5.0
2G (GSM)	6	6	11	900/1800 MHz	80+80	4.4+4.4 to 18.0+18.0
3G	4	1	5	2.1 GHz	25+25	5.0+5.0
BWA	1	2	3	2.3/2.4/2.5/ 2.6 GHz	60.0 (TDD)	20.0
<b>Total</b>	<b>14</b>	<b>10</b>	<b>24</b>		<b>310 MHz</b>	

The Indias telecom sector growth is hampering due to excessive fragmentation of spectrum holdings. Presently, spectrum has been de-linked with the operating license. Any additional spectrum, if required by the operator, will have to buy from the market. Merger & acquisition (between two or

more than two companies) is one solution to get additional spectrum but the process is complicated involves coordination with 2-3 different government departments and take considerable time. They can buy additional spectrum through auction but auction can be conducted when free spectrum is available with regulator. Therefore, it is almost impossible for an operator to get additional spectrum in the changed regulatory environment. Spectrum trading could be an option by which an operator can acquire additional spectrum from other operators without going into much complexity.

#### 4.4.1 Telecom Service Area 1

This TSA has a maximum number of operators, and the spectrum has been assigned in a highly fragmented manner. The operators, except two who won spectrum in the recently concluded auction, do not own contiguous 5 MHz spectrum in entire TSA. In some case, the operator has not been assigned spectrum in the entire service area i.e. partial spectrum has been assigned. Percentage of market share and assigned spectrum are given in figure respectively. Subscriber data show that operator 1, 2, 3, 5, 7 & 8 have good market share (figure 4.4).

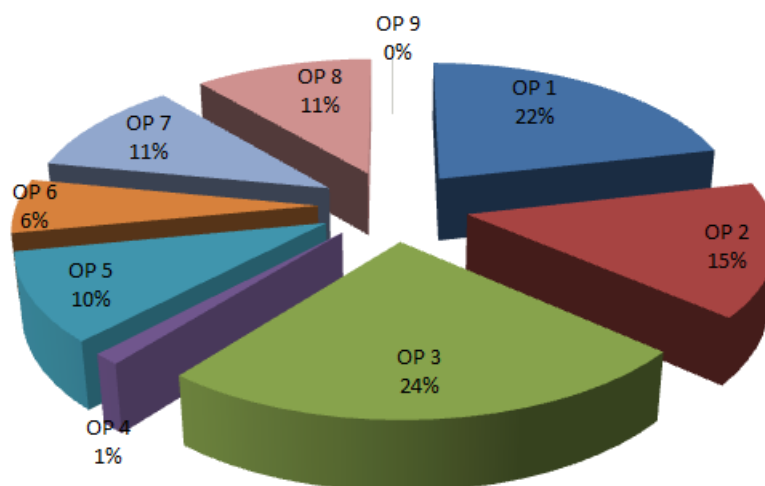


Figure 4.4: Operators market shares in TSA 1

Out of which operator 3 is leader with 24% of market share. Market share by operator 4, 6 & 9 is on the lower side. The maximum spectrum has been assigned to operator 7 with 10.0 MHz and lowest spectrum has

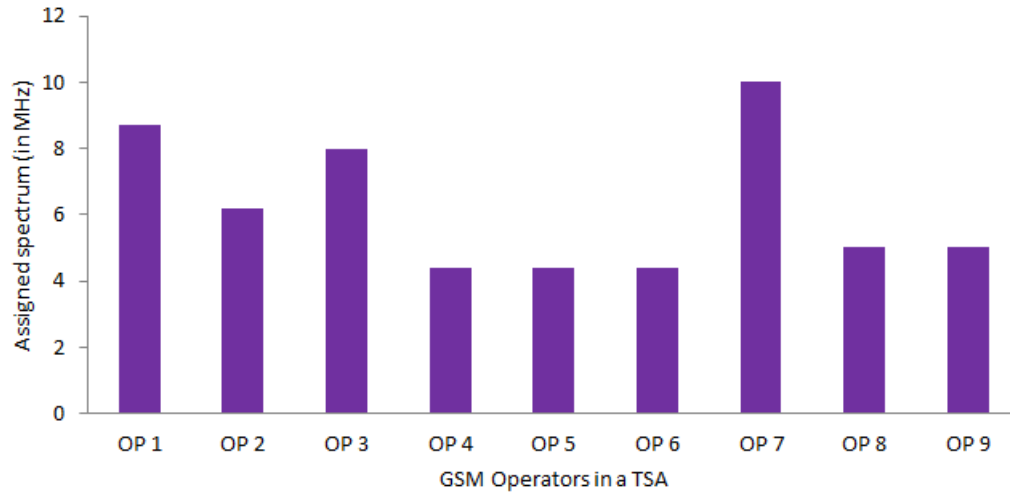


Figure 4.5: Operators spectrum shares in TSA 1

been assigned to operator 4,5 & 6 with 4.4 MHz (figure 4.5). Operator 8 & 9 have 5.0 MHz contiguous spectrum which they won in the recently concluded March 2013 auction.

The SPS analysis (figure 4.6) shows that operator 4 & 9 has lowest subscribers per MHz. If we look at APS analysis (figure 4.7) for operator 4 & 9, APS is moderate for Operator 4 and lowest for operator 9. There is a good chance that operator 4 and 9 may sell their spectrum. Operator 1, 2 & 3 has high value of SPS and APS, they have a stable market and may enter into the market to buy spectrum.

The operator 6 & 7 has low SPS and moderate APS, there is a chance that this operator may drift towards risk zone. The operator 7 may go to sell a part of the spectrum or try to increase market share with an aggressive marketing strategy. On the basis of SPS data, operator 5 & 8 has a good subscriber base per MHz spectrum. The operator 6, SPS is third lowest and APS is second lowest, may try to sell a part of spectrum in those areas where its market is not strong. The some of established players may need spectrum in areas where they dont have spectrum. Such players may try to buy spectrum from other players. Therefore, the TSA has good potential for spectrum trading for swapping (to make spectrum contiguous) and buying spectrum for consolidation of market and launch of new services.

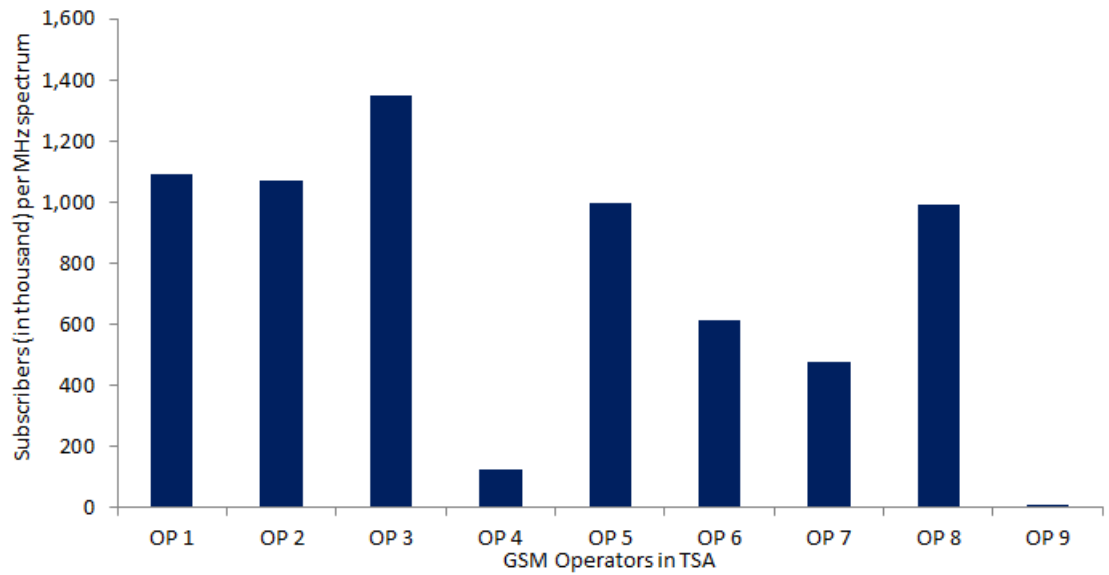


Figure 4.6: SPS analysis for TSA 1

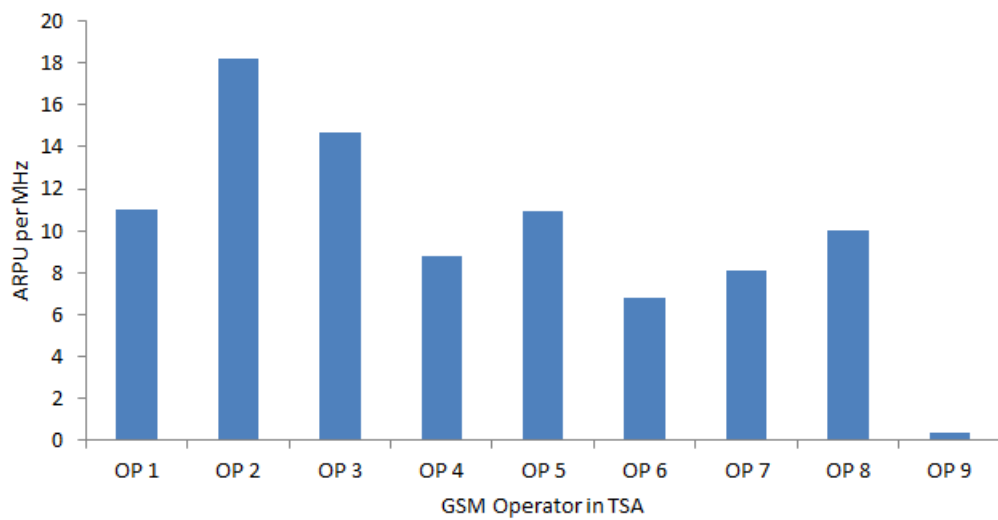


Figure 4.7: APS analysis for TSA 1

### 4.4.2 Telecom Service Area 2

Now we take another TSA, where spectrum has been assigned contiguously and number of operators are 8. We will show that such TSA may not have much potential for trading as all the operators have a good of share of market and their SPS and APS value is also good. Percentage of market share and assigned spectrum are given in figure respectively. Subscribers data shows (figure 4.8) that all the operators have an almost equal market share except operator 1 & 4.

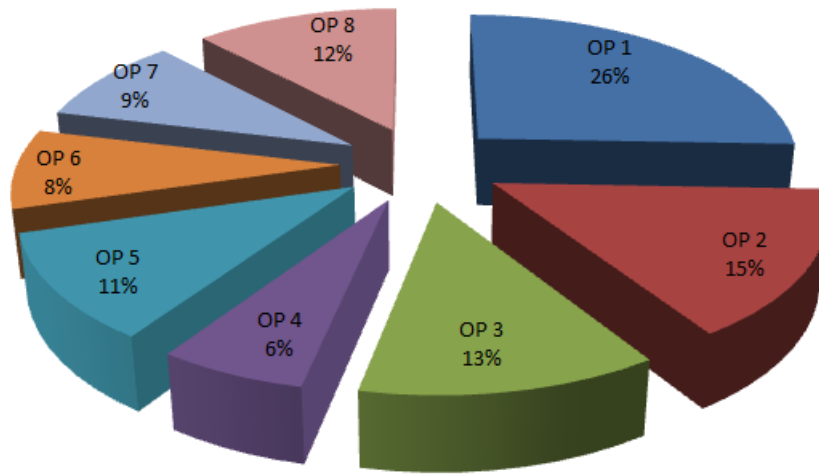


Figure 4.8: Operators market shares in TSA 2

Operator 1 is the leader of the TSA whereas operator 4 has a lowest subscriber base. Maximum spectrum (12.4 MHz) has been assigned to the operator 7 and minimum one (4.4 MHz) has been assigned to operator 3, 4, 5 & 6 (figure 4.9).

SPS analysis (figure 4.10) shows that operator 1, 3, 5 & 6 has high SPS value, operator 2, 4 & 8 has moderate SPS value and operator 7 has lowest SPS value. APS data (figure 4.11) shows that except operator 7, remaining have good APS value.

This TSA does not have good ground for spectrum trading. Only operator 7 can go for selling spectrum in the secondary market whereas the remaining operators may try to buy the spectrum. A high value of spectrum in the secondary market is expected in this TSA as only one operator could sell spectrum. However, spectrum trading is possible for swapping to make assigned spectrum contiguous.

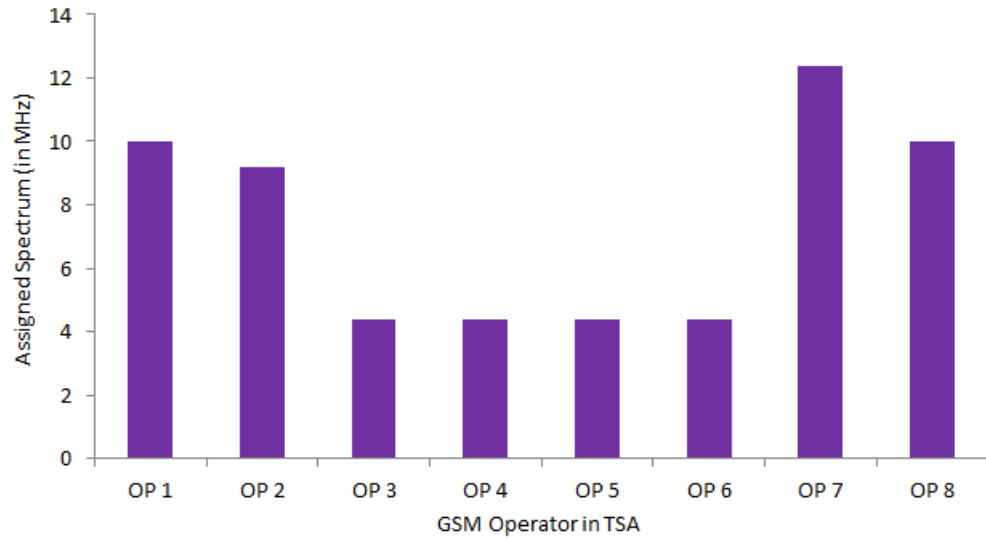


Figure 4.9: Operators spectrum shares in TSA 2

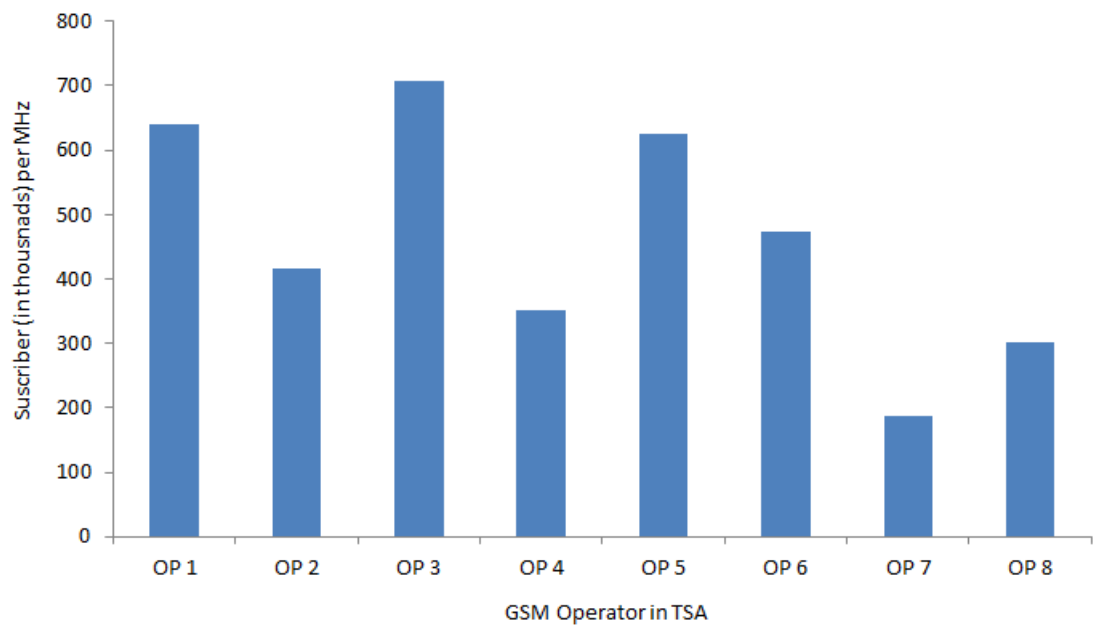


Figure 4.10: SPS analysis for TSA 2



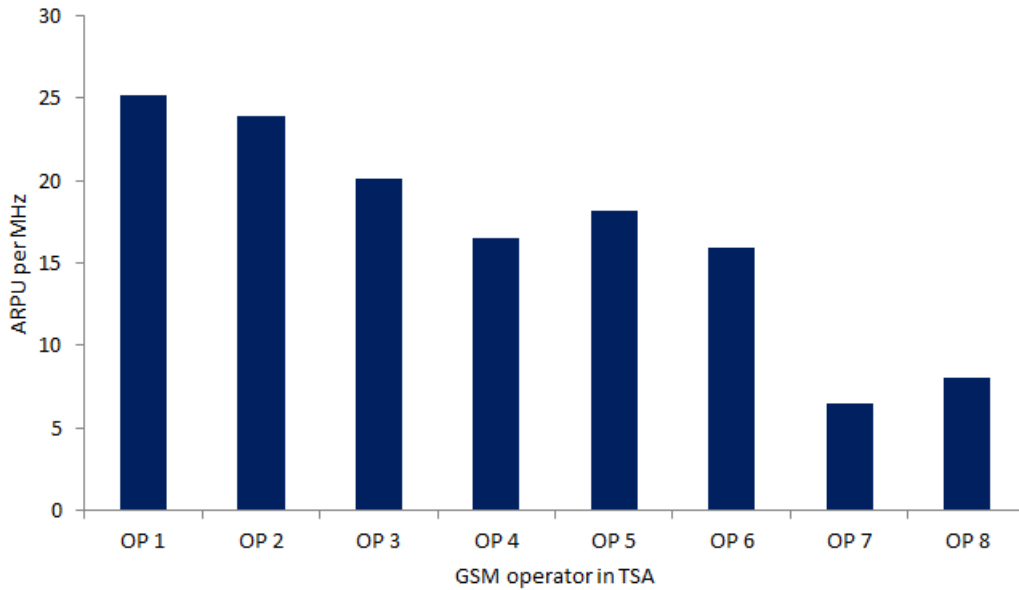


Figure 4.11: APS analysis for TSA 2

## 4.5 Spectrum Trading at User level in Primary Network

Spectrum trading in the telecom sector at operator level would take place only when the market is not fully grown, and operators do not have sufficient spectrum (according to their subscriber base) to run the services. Once the operators manage sufficient spectrum from the market through buy or sell of spectrum, no further spectrum trading would take place. This can be seen in the European market, where operators have sufficient spectrum and few trading took place in the telecom sector. The spectrum trading in the telecom sector will be more useful when it would be introduced at the users level. It has been experienced that a user needs a better quality of services if he wants to make a voice call or video streaming, however, he may not need the same QoS for internet access or data transfer. In the present scenario, user is forced to take services of one operator for the different variety of usages and bound to pay tariffs as decided by that operator. The users, who are near to the transmitting station, get better signal strength and the users, who are away from the transmitting station, get degraded signal strength. The degradation depends upon how far a user is from the transmitting station in a cell. But users have to pay the same price irrespective of quality of services.

It is difficult for users to change operator instantaneously according to the requirements to get better services. However, the situation could be changed if spectrum trading is applied at the user level.

The concept of spectrum trading at the user level is that users are free to choose any operators according to the requirements at any given time and location, like a user wants to make voice calls or live video coverage, he may choose an operator which offers better QoS and so on. Users device is equipped with spectrum sensing ability to search for a vacant channel along with signal strength and price. Based on the signal strength and price, user will decide which operators channel is suitable for him and select accordingly. This would be benefited to both operators and users. The user would get the option to choose operators as per his requirements, and operator would get differential revenue according to quality of services i.e. High QoS would give high revenue, and low QoS would give low revenue. Spectrum trading at the user level would force operators to improve their services, which would also increase overall revenue of the operators.

The spectrum trading at user level has been depicted in figure 4.12 in which three operators are providing services at a location, and a user is free to choose any of the operators based on the signal strength. For simulation purpose, we have taken three different price rates for high, medium and low signal strength in a preliminary environment, where a user selects a channel based on the signal strength. We have assumed this differential price rates are 1.2 for high signal strength (SNR level more than 10 dB), 1.0 for medium signal strength (SNR level less than 10 dB and higher than 6.0 dB) and 0.8 for low signal strength (SNR level less than 6.0 dB and higher 0 dB). The operator positions are fixed at T1 (0, 0), T2(0,-500m) and T3 (0,500m) and transmitting signal with 20W transmit power. Users are surrounded in an area of 1000 m radius around centre.

In first stance, we have assumed that out of the total users, the first one third users would go for high signal strength, the second one third users would go for medium signal strength and the last one third users would go for low signal strength. Overall, users have been divided into three categories, where the first group is ready to pay higher price, the second group and the third group is ready to pay medium price and low price respectively. If 90 users present, the first 30 users (1 to 30) connect to one of the operators if SNR level is a more than 10dB. Similarly, the second 30 users (31 to 60) connect to one of the operators if SNR level is between 10dB to 6.0 dB, and the last 30 users (61 to 90) connect if SNR level is between 6.0 dB to 0.0 dB. In case, a user received signal from more than one operator meeting the required SNR level, the order of precedence for connection will be T1 than T2 and finally T3. If received signal does not meets the required SNR level,

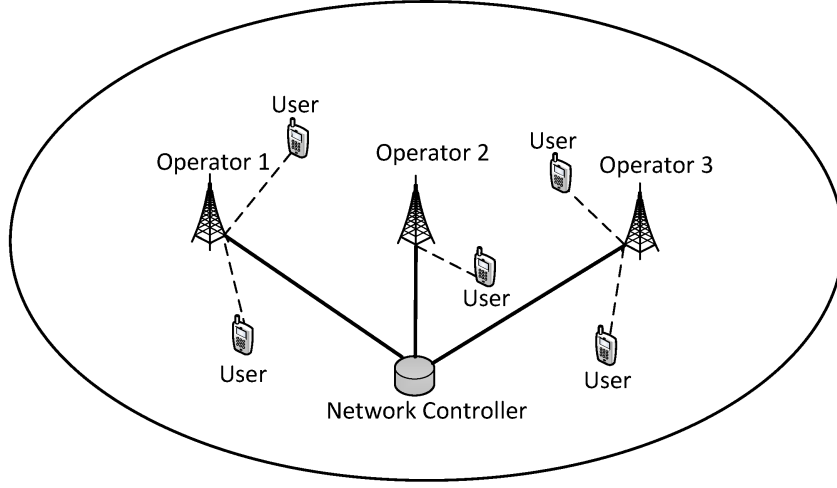


Figure 4.12: Model for spectrum trading at user level

user would not be connected to any of the operators. In this scenario, it is possible that some of the users may not get connected due to non-meeting of SNR criteria. The average revenue has been determined in two conditions; the first one is average revenue per user (irrespective of actual connections). We also assumed one third of total active users connected with each operator in absence of spectrum trading regime for comparison purpose and revenue earned from each user is 1.0 i.e. total revenue earned by one operator would be the one third of total number of users. This is considered as normalised revenue. The second one is that average revenue with respect to actual numbers of connected user i.e. average revenue per active user.

$$\text{NormalisedRevenue} = \frac{\text{Totalrevenue}}{\text{Totalnumberofusers(active + inactive)}} \quad (4.7)$$

$$\text{Averagerevenueperactiveuser} = \frac{\text{Totalrevenue}}{\text{Totalnumberofactiveusers}} \quad (4.8)$$

The figure 4.13 shows average revenue per active user and normalised revenue at different number of users. Normalised revenue is the ratio of total revenue earned by the operators under spectrum trading regime and in absence of spectrum trading. It can be seen that the average revenue per active user is approximately 1.0. However, if we take the total number

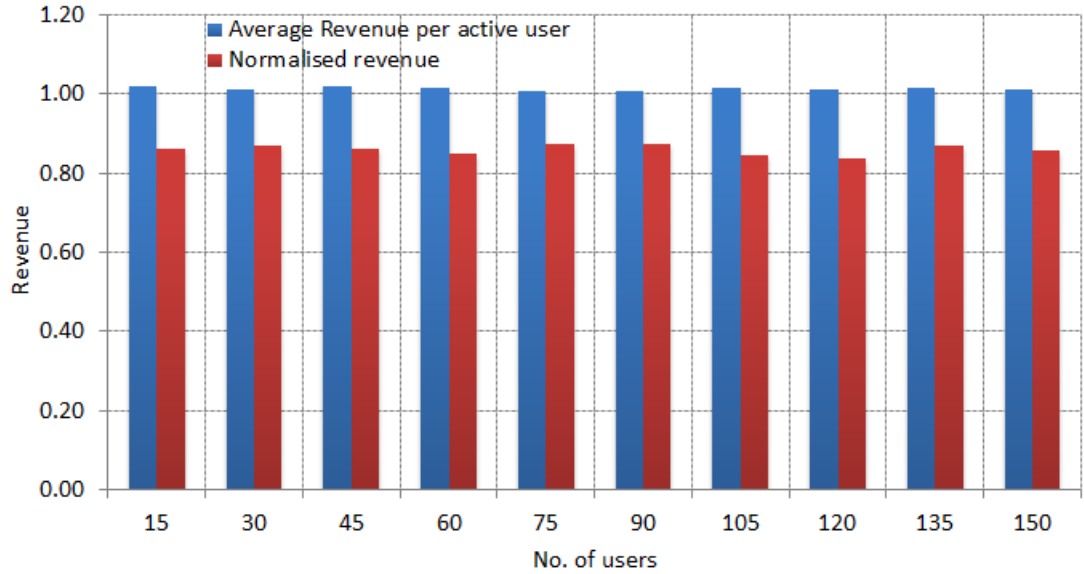


Figure 4.13: Revenue realisation at different number of users

of users into account, the average revenue per user i.e. normalised revenue is approximately 0.82. Both the values are almost same irrespective of the number of users. This shows that overall numbers of active user are less under spectrum trading regime.

If we go at the operator level, we would find that the average normalised revenue for all the three operators is different in both the conditions as shown in figure 4.14. It can be seen that the normalised revenue for operator 1 is more than 1.0 and the average revenue per active user is about to 1.0. The situation is not same for operator 2 and 3. The average normalised revenue decreases, if we move from operator 1 to 3 due to order of preference. As stated earlier, the first preference will be given to operator 1 if a user gets required SNR level from all the three operators (1, 2 & 3) or two operators (1 & 2 or 1 & 3).

Similarly, operator 2 will get preference, if a user gets required SNR level from operator 2 & 3. Least priority has been given to operator 3. However, if we look at average revenue per active user, it is more than 1 for all the three operators and lowest is with operator 1. This shows that number of users connected with operator 1 is highest and the total revenue is also highest for operator 1. This clarified that the operator, who provides better services, would get preference and can earn more revenue under spectrum trading regime.

It is possible that a user gets high category signal strength from all

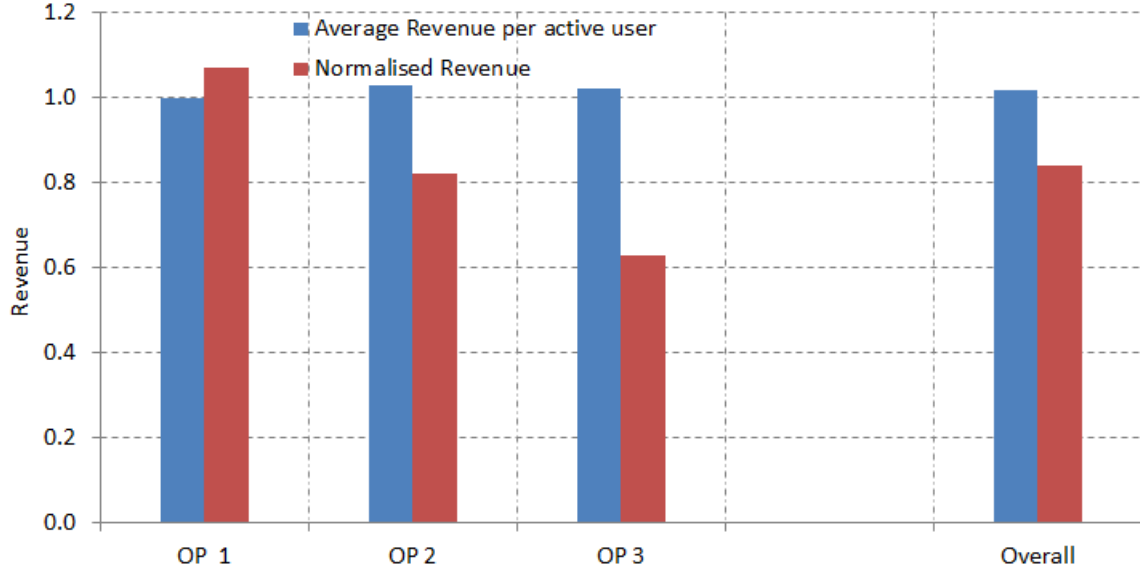


Figure 4.14: Revenue realisation at operator level in first case with total number of users=90

the three operators, but the user may not be ready to pay the highest tariff. In this situation, the user would not get connected to any of the operators. Such situation could be considered as a drawback of spectrum trading. To avoid such situation, we consider that the first group of users get connected to any one of the operators, if the signal strength is above than 10.0 dB, the second group of users get connected if the signal strength is above than 6.0 dB, and the final third group of users get connected if the signal strength is above than 0.0 dB. The result has been presented in figure 4.15.

The result shows that both the parameters i.e. average revenue per active user and normalised revenue are lower than the earlier case with exception that normalised revenue for operator 1 is higher. It shows that most of the users connected to operator 1. This case also shows that the user prefers to connect to the operator who can provide better services. If we look at overall (i.e. for all the three operators) figures, we would find that the number of active users in this condition is more than the earlier case. As far the revenue is concerned, the revenue would certainly go down as practically no user would pay the highest tariff for premium signal strength level. In our calculation, we found that almost 10-20% revenue would go down as compare to earlier case. Therefore, this case would not present true spectrum trading.

We presented two different cases for analysis of spectrum trading at

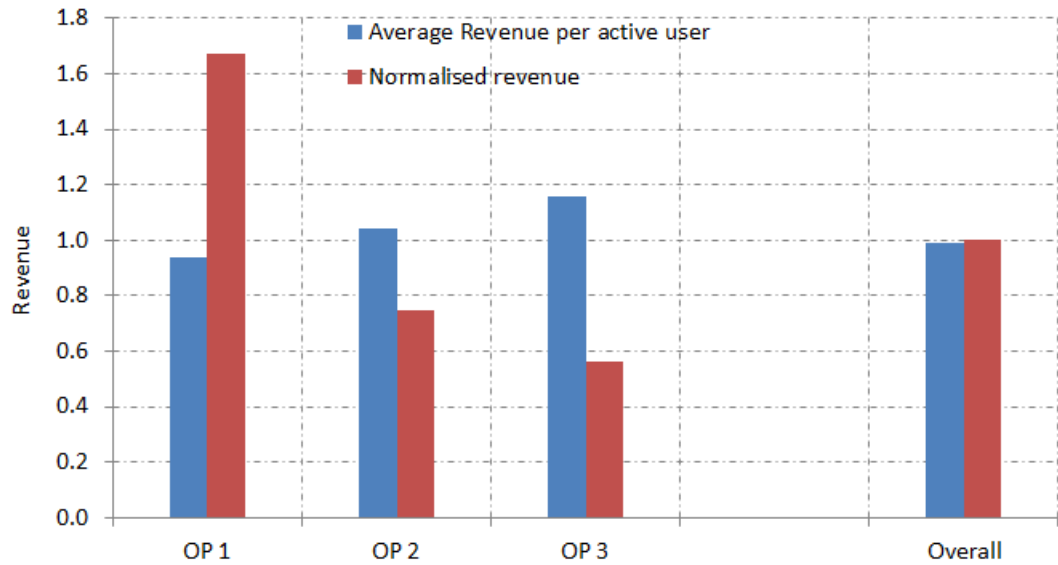


Figure 4.15: Revenue realisation at operator level in second case with total number of users=90

user level in primary network. The first one in which a differential received signal strength concept has been discussed would present a more clear picture of spectrum trading at the user level in primary network. In the second case, the user will try to connect with premium signal strength by paying second or third level cost. The second case may not be considered as a true concept of spectrum trading even with a high number of active users. The spectrum trading at user level in primary network would encourage operators to provide better service quality. Users would get multiple options at any point of time and would not be dependent on one operator for all types of services.

## 4.6 Conclusions

The chapter presented the concept of spectrum trading with a focus on the telecom sector. A methodology has also been presented for analysing spectrum trading in the telecom sector. The spectrum trading at operator level will be successful when there is a large variation in the assigned spectrum to the operators. A case study of Indian telecom sector has also been analysed. As discussed in the chapter, highly fragmented spectrum holdings, high number of operators and high level of activity offers a conducive environment for spectrum trading in telecom sector. In the second part, we presented spectrum trading at the user level and concluded that if allow

spectrum trading at the user level, the operator would force to provide better quality of services, and users would get multiple options at any point of time and would not be dependent on one operator for all types of services.

## Chapter 5

# TV White Space in India



## 5.1 Introduction

The terrestrial TV broadcasting services are operated in VHF (54 MHz to 216 MHz) and UHF (470 MHz to 806 MHz) bands. The terrestrial TV networks have been planned as multi-frequency networks (like cellular technology). In such type of planning, it is possible that some TV channels may not be used at a location to avoid interference to TV broadcasting services in the adjacent regions. These unused TV channels are known as TV white space (TVWS) with respect to that particular location. This TVWS has been opened for low power fixed and mobile devices to deliver fixed and mobile broadband and for multimedia streaming in the home provided they do not cause interference to adjacent TV channel. This has been shown in the figure 5.1, a low power device (secondary transmitter) can use channels [A1,A2,A3,B1,B2,B3,C1,C2,C3] provided they do not cause harmful interference to TV receivers within the coverage areas of A, B, C which falls under protected zone. The outer circle is known as No Talk Zone (NTZ), where neither TV signal nor low power device signal can present. This NTZ ensures that no TV receiver at the boundary of the protected zone experiences any interference from the TV band devices (TVBDs). Typical values of NTZ range from 6.0 km to 14.4 km for co-channel operation and 0.1 km to 0.74 km for adjacent channel operation.



Figure 5.1: TV white space

The major benefits of TVWS (part of the 1 GHz sub band) are excellent coverage and high penetration. Signals in TV band can cover 10 times

longer as compared to the 2.4 GHz ISM band for an equivalent transmits power and receiver bandwidth[64]. TVWS is useful due to less CAPEX and better propagation characteristics to provide wireless broadband services particularly in rural & far-flung areas that would be too expensive to serve by other means. TV white space has some strength as well as some weakness. A SWAT (Strength, Weakness, Application and Threat)analysis of TVWS is given below:

**Strength**

- *Good amounts of bandwidth, with minimum contiguous chunk of 6-8 MHz*
- *Excellent propagation characteristics provides larger coverage*
- *Higher penetration through wall and building*
- *Less capital expenditure is required for roll-out of services*
- *Less power is required to run a service in TVWS than other bands, which are at higher frequencies*
- *Can provide better mobility due to lower frequency band*
- *Promotes green energy due to cap on transmit power*
- *Improve spectrum efficiency*
- *Deliver affordable broadband service*
- *TV Broadcast infrastructure normally stable over the time*

**Weakness**

- *Not much amount of spectrum*
- *Quantity varies in spatial and temporal*
- *No guarantee of quality of services*
- *Restriction over transmit power*
- *May cause interference to primary users*
- *Experience interference from Primary users as well as other secondary users*
- *Complexity in hardware*

- *High cost of hardware*
- *Strong regulatory restrictions may make operation difficult*
- *Additional regulatory and monitoring measures required for smooth operation*

### **Applications**

- *Affordable broadband services in rural areas*
- *Hotspot Wi-Fi operation*
- *Backhaul operation*
- *Indoor broadband access*
- *M2M communications*
- *And so many others.*

### **Threats**

- *Corruption in database and its faulty updation process*
- *Greedy players, can make entire game unplayable*
- *Security issues concerning to primary users*
- *Operation based on destructive technology (Cognitive Radio) threat to primary users*
- *En-efficient regulations may jeopardize entire game*

Broadcast services are characterized by planned sites with high transmit power to cover a larger area. The broadcast infrastructure is relatively constant over the time and independent of the number of TV receivers in the coverage area. A careful planning can invite usage of low power devices in TVWS. The usage of TVWS by other devices is not a new phenomenon. There is a long history of use of TV bands by other services. One example is PMSE, which successfully working within TV band. Another example is point to point communication in the vacant TV band. Successful coexistence of Program Making and Special Event (PMSE) and other point to point communication services and increasing demand of additional spectrum for telecommunications services have forced regulators to open TVWS for non-broadcasting services. The FCC in 2007, opened TV band for the use of de-licensed cognitive radio equipped devices opportunistically under certain terms and conditions.

## 5.2 Status of TV White Space in different countries

### 5.2.1 TV White Space in the USA

The FCC was the first regulatory body which made regulations for utilization of white spaces in the TV band. The regulations were made for TVBDs while protecting the interests of licensed users. The FCC categorized the TVBDs into two classes; fixed and personal/portable devices. The personal/portable devices are further classified into Mode I and Mode II devices. These devices, except personal/portable devices operating in client mode, must have sensing and geo-location database access capability[65]. The main features are given below:

- Fixed devices may operate from a known, fixed location with maximum 4 Watts (EIRP) transmit power on any channel between 2 and 51, except channels 3, 4 and 37 and they cannot operate in adjacent working TV channels in the given location (i.e. not allowed to operate in N and N1 channel, where N is operating channel).
- Personal portable devices may operate on any unoccupied channel between 21 and 51, except channel 37 and may operate at up to 100 mW of power (20dBm) except adjacent channels (i.e. not allowed to operate in N and N1 channel). Portable devices with power limited to 40 mW (16 dBm) can operate in adjacent channel also (i.e. not allowed to operate in N channel).
- Spectrum sensing is a mandatory function that all devices must have the capability to detect TV signal and wireless microphone signals at a level of -114 dBm. A channel must be sense for 30 seconds before determining the availability. Sensing must be done periodically at every 60 seconds and if any activity is detected the channel must be vacated within 2 seconds.
- 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 depending upon distance from digital or analog TV protected contour.
- The adjacent channel emission limit for each category of device is simply the maximum power permitted in a 6 MHz bandwidth minus 72.8

dB. Out-of-band emission masks for White Space Devices along with PSD limit are given in table 5.1.

Table 5.1: Emission limit for WSD in the USA

Type of TV bands device	Power limit (6 MHz)	PSD limit (100 kHz)	Adjacent channel limit (100 kHz)
Fixed	30 dBm (1 Watt)	12.6 dBm	-42.8 dBm
Personal/portable (adj. channel)	16 dBm (40 mW)	-1.4 dBm	-56.8 dBm
Sensing only	17 dBm (50 mW)	-0.4 dBm	-55.8 dBm
All other personal/portable	20 dBm (100 mW)	2.6 dBm	-52.8 dBm

The TVBDs are required to be equipped with GPS facility with +/- 50 meters accuracy for determining their location and then contact a 'geo-location' database to know the availability of vacant channel at that location. White space devices (WSDs) are not allowed to transmit until they have successfully determined the vacant channels from the database available at that location. In the United States, the FCC has privatized the development of TV White Space databases. Presently, three database providers namely Spectrum Bridge Inc., Telcordia and Google Inc. have been approved by the FCC for providing services[33]. Their database can be accessed through the internet. Figure 5.2 shows a snapshot of the list of available channels at New York NY taken from the Telcordia TVWS database. It shows that only one channel in lower VHF is available.

### 5.2.2 TV White Space in the UK

The process for usage of interleaved spectrum (TV White Spaces) by licence-exempt devices was started by Ofcom[35], the UK regulator, in December 2007 and concluded that licence-exempt access to TVWS should be allowed as long as this would not cause harmful interference to licensed users.

Further, Ofcom in 2009 [67] stated that two mechanisms i.e. sensing and geo-location could be used by a device operating in the UHF TV band to determine which frequencies it could use. The operation parameters for sensing-based and geolocation-based WSD as proposed by Ofcom are given in table 5.2.

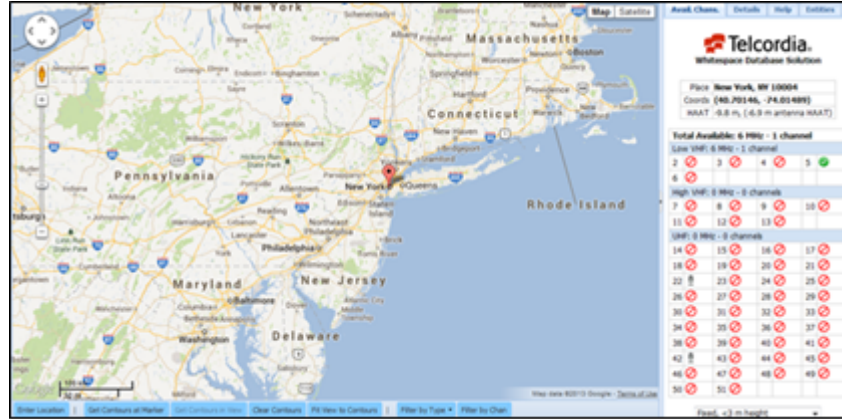


Figure 5.2: Availability of white space in New York city[66]

Ofcom has developed the following key elements of the regulatory framework regarding TVWSDs operation:

1. WSDs will be permitted to transmit in the UHF TV band provided that they do not cause undue interference to incumbent licensed users within the band, namely DTT and PMSE, or outside the band. WSDs will be exempt from the requirement for a licence under the WT Act provided that they comply with a set of requirements captured in a statutory instrument.
2. A device would be required initially to consult an Ofcom list of qualifying databases and select from this a preferred database. The device would then be required to contact this preferred database for requisite information about DTT and PMSE usage of the band and provide information about its location and technical characteristics.
3. The WSDB will respond to the WSD with a set of parameters indicated below at which the WSD can transmit without causing harmful interference to the primary users.
  - Lists of lower and upper frequency boundaries within which a master WSD will be authorised to operate.
  - A maximum permitted master WSD in-block EIRP, specified in dBm over a bandwidth of 0.1 MHz and 8 MHz, between each lower frequency boundary and its corresponding upper frequency boundary.

Table 5.2: Key parameters for WSD in the UK

<b>Key parameters for sensing Cognitive</b>	
<b>Parameter</b>	<b>Value</b>
Sensitivity assuming '0' dBi antenna	-120 dBm in 8 MHz channel (DTT) -126 dBm in 200 kHz channel (wireless microphones)
Transmit power	4 dBm (adjacent channels) to 17 dBm
Transmit-power control	Required
Bandwidth	Unlimited
Out-of-band performance	Less than -46 dBm
Time between sensing	Less than 1 second
<b>Key parameters for geolocation Cognitive</b>	
<b>Parameter</b>	<b>Value</b>
Locational accuracy	Nominally 100 metres
Transmit power	As specified by the database
Transmit-power control	Required
Bandwidth	Unlimited
Out-of-band performance	Less than -46 dBm

- Limits on the maximum total number of DTT channels that may be used at any given time, and the maximum number of contiguous DTT channels that may be used at any given time.
4. There are two categories of device: master WSDs and slave WSDs. A master WSD is required to have a communications link to access Ofcoms list of qualifying WSDBs, and a communications link to query one of the qualifying WSDBs. A slave WSD, on the other hand, does not have a direct connection to Ofcom or a WSDB; it will obtain its frequency/power parameters from a WSDB through a master WSD.
  5. A master WSD must have horizontal geo-location (latitude and longitude coordinates) capability. Horizontal geo-location capability is optional for slave WSDs.
  6. If a master WSD moves more than 50 metres in any (horizontal) direction, then it must request an update to its specific operational parameters and the generic operational parameters of the slaves in its coverage area.

7. A master WSD which wishes to transmit simultaneously over multiple DTT channels must comply with the maximum permitted in-block EIRP spectral densities in each of the DTT channels to be used; and radiate with a total in-block EIRP (measured over the total number of DTT channels to be used) which does not exceed the smallest of the maximum permitted in-block EIRPs specified over each of the DTT channels to be used.

Unlike the FCC, Ofcom has adopted a flexible approach regarding maximum EIRP. Ofcom has not fixed maximum transmit power but it left to the geolocation database. Ofcom has specified the ratio between the in-band and out-of-band emission of WSD instead of specifying absolute limits on adjacent channel emissions as done by the FCC.

Regarding geolocation database, Ofcom made provisions that there should be a master database that contain the list of channels available for cognitive devices at every location in the UK. There could be multiple copies of this master database, but with the condition that each copy database would have accurate and up-to-date version of the master database.

At present, two database providers, Spectrum Bridge Inc. and Fair-spectrum provide geolocation database service in the United Kingdom. The figures 5.3 & 5.4 shows the list of available channels in Bath and Liverpool provided by the Spectrum Bridge Inc.'s database[68]. It can be seen that the maximum permitted EIRP for WSDs is varying from 17 dBm to 41 dBm in Bath and from 6 dBm to 22 dBm in Liverpool.

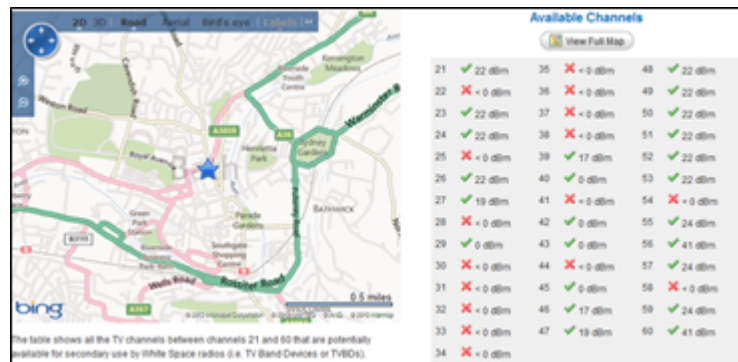


Figure 5.3: Availability of white space at Bath[68]

Figure 5.5 shows the allocation of the UHF spectrum in the United Kingdom after the completion of the digital switchover (DSO)[69]. Ofcom has divided entire spectrum from 470 MHz to 862 MHz into three parts. The first one is of the 128 MHz of spectrum (16 channels marked in green) cleared





Figure 5.4: Availability of white space at Liverpool[68]

for licensing through auction. The second one is of the 256 MHz of spectrum (32 channels marked in purple) retained for TV transmission. This spectrum is also called interleaved spectrum, which can be used on a geographical basis for TVWDs. The last one is of the 8 MHz spectrum (channel no. 38 marked in pink) is reserved for exclusive access by wireless microphones and other program making and special events (PMSE) equipment.

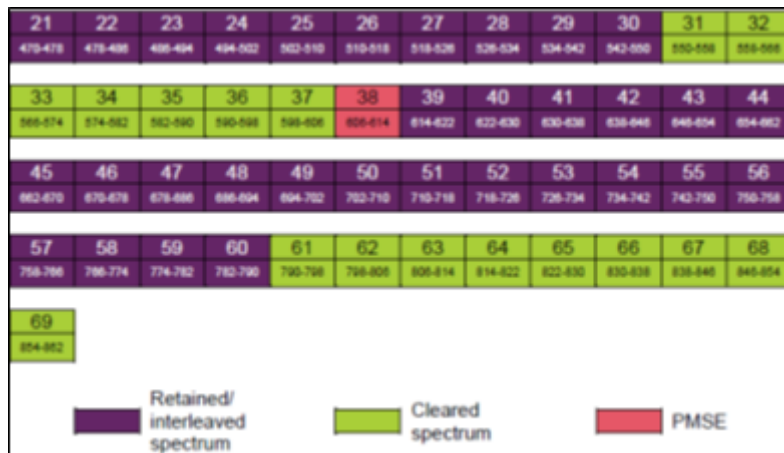


Figure 5.5: UHF spectrum in the UK after DSO [69]

### 5.2.3 TV White Space in Europe

In the EU countries, the detailed technical and regulatory framework for cognitive radio is being carried out by several working groups of CEPT (Conference European des Administrations des Poste et des Tlcommunications). Electronic Communications Committee (ECC) within CEPT in its

report no. ECC report 159 Technical and Operational Requirements for Possible Operation of Cognitive Radio Systems in the White Space of the Frequency band 470-790 MHz [70] analyzed restrictions to be imposed on secondary users to ensure protection of the incumbent radio services.

The report addressed the sensing threshold calculation method and WSD emission limit for various configurations. The detection thresholds were derived for a limited number of scenarios range from -91 to -155 dBm depending on the digital terrestrial TV (DTT) planning scenario. Different types of calculations have been presented in which a geo-location database calculate location-specific maximum permitted e.i.r.p. levels for WSDs in different geographic areas. It has been recommended that the geo-location database should provide to a WSD about the list of available frequencies and associated maximum permitted e.i.r.p. values. The report clarified that the geo-location database appears to be the most satisfactory approach considered so far in view of providing protection to PMSE services. It may be possible to reserve some channels, which are not used by DTT, only for the PMSE use. Such an approach is known as safe-harbour channels.

A quantitative analysis regarding TVWS in Europe has been done in [71]. In the paper, availability of TVWs in the frequency band 470 to 790 MHz for 11 European countries has been carried out with regard to area and population coverage. Quantification has been done considering that TVWSDs could play in no talk region of the TV transmitter. The analysis has further been extended taking into account adjacent channels. They have found that the availability of white space in Europe is notably less than in the USA and concluded that the amount of unused spectrum by TV network an average location in Europe is about 56% by area and 49% by population without taking adjacent channel into account. The same figure reduces to 25% (by area) and 18% (by population).

#### 5.2.4 TV white space in Asia

In the Asia region, Japan, Singapore and Korea have taken initiatives. Digitalization of terrestrial broadcasting has already been completed in Japan and South Korea. Digitalization in Singapore will be completed by the end of this year and in the remaining Asian countries would be completed between 2015 to 2020 time frames. In the Asia region, frequency band 698 to 806 MHz has been reserved for IMT services. Frequency band 470 to 698 MHz is available for terrestrial TV in Asia region. No qualitative analysis of TVWs has so far been undertaken in Asia. Analysis of TVWs has been done in a few Asian countries like Japan. Recently Infocomm Development Authority of Singapore (IDA)[72] has started working on the use of TVWS in Singapore.

### 5.2.5 TV White Space in Japan

The terrestrial TV broadcasting is operating in the frequency band from 470 to 710 MHz. 40 channels of 6 MHz each, a total of 240 MHz bandwidth, has been reserved for digital TV transmission. The rules for usage of TV White Spaces are still under discussion in Japan. The Ministry of Internal Affairs and Communications (MIC) has established a working group to discuss some potential use cases of TVWS in Japan. The National Institute of Information and Communications Technology (NICT) [73] has developed a white space database based on the FCC rules. Figure 5.6 shows the coverage areas of TV transmitters in Japan.



Figure 5.6: Coverage of TV transmitter in Japan[73]

An attempt, based on the FCC rulings, has been made for quantitative analysis of white spaces in Japan in [74]. As per assessment, a significant amount of white space is available in every corner of Japan. The assessment shows that more than 84% of areas in Japan have greater than 100 MHz TVWSs for 6 km separation distance. The most populated areas, like the Tokyo metropolitan area, have much more available channels than the metropolitan areas in the USA.

The National Institute of Information and Communications Technology (NICT), Japan, has developed WiFi prototype in the TV White Space (TVWS) (470 MHz - 710 MHz) based on the IEEE 802.11af draft specification. The technical specification of this prototype device is given in table 5.3

## 5.3 Spectrum Allocation in India

India is a developing country and densely populated. Doordarshan, a public service broadcaster (named Prasar Bharti [16]), is the only terrestrial

Table 5.3: Key parameters of IEEE802.11af developed by Japan

Item	Value
Frequency	470-710MHz
Channel Band	Width 6MHz
Transmission	Power 20dBm
Modulation	OFDM (802.11af compliant)
Subcarrier Modulation	BPSK
MAC	IEEE 802.11af Draft Specification (D 2.0)
Antenna Gain	0dBi

TV broadcaster. Doordarshan has one of the largest terrestrial television networks in the world and is presently operating 31 TV channels. It has a terrestrial network of 1414 transmitters installed throughout the length & breadth of the country [16] and covers almost entire country. In terrestrial mode, Doordarshan coverage is available to about 92.2% population of the country. Doordarshan broadcasts two or three TV channels all over India. India has adopted PAL B system for Analogue TV transmission in the VHF bands and PAL Gsystem for transmission in the UHF bands. More than 30 carriers have been assigned to Doordarshan. India has adopted DVB-T system for DTT in the country. At present, Doordarshan has commissioned four digital transmitters one each in Delhi, Mumbai, Kolkata & Chennai. Mobile TV service (DVB-H transmission) has been started in Delhi.

Digital switch over has not yet been completed in India. Regarding DSO, the Ministry of Information and Broadcasting, Government of India has set 31 March 2015 as the deadline for the complete shift from analog to digital systems. This deadline is for digitization of cable TV as well as terrestrial TV. However, Analog transmission will remain continue till switch over of TV sets in households into digital set. Although the date for DSO has already been announced, but switching off complete analogue transmission does not seems to be possible in next 8 to 10 years seeing the huge penetration of analogue TV sets in rural Indian households. During the transition phase, terrestrial transmission will be continued in both modes i.e. analog and digital, which may prevail next 8 to 10 years.

As per NFAP 2011 of India[20], analog and digital TV transmission is present in frequency band 47-68 MHz, 174-230 MHz and 470-806 MHz (table 5.4). These frequency bands are shared between Fixed, mobile, broadcasting and radio astronomy services.

As per available data, presently around 1000 terrestrial TV stations are operating in the frequency band 174-230 MHz and very few are operating in the frequency band 47-68 MHz. TV transmission in the frequency band 470-862 MHz is as per details given below [20, 75]:

### 5.3.1 UHF Band IV (470-582 MHz)

14 TV channels (21 to 34) with 8 MHz channel bandwidth are available. Doordarshan is operating with more than 330 analog transmitters and four digital TV transmitters in Delhi, Mumbai, Chennai and Kolkata. Mobile TV in Delhi is also working in this band. Doordarshan has also been authorized to use wireless microphone (PMSE) in this band. Besides TV broadcasting, fixed and mobile services are also present in this band. A small part of 500 KHz has been allocated to the space operation service (space-to-earth) in this band. The entire band has presently been with Doordarshan for terrestrial TV operation and some PSUs for point to point links. The usage of PSUs are almost negligible. The only active user in this band is Doordarshan. This has further been validated by field measurements as shown in figure 5.7. The measurement shows that the entire band is completely unoccupied except at one place where Doordarshan is operating digital TV transmission at Channel 29 (i.e. 534-542 MHz)(figure 5.8).

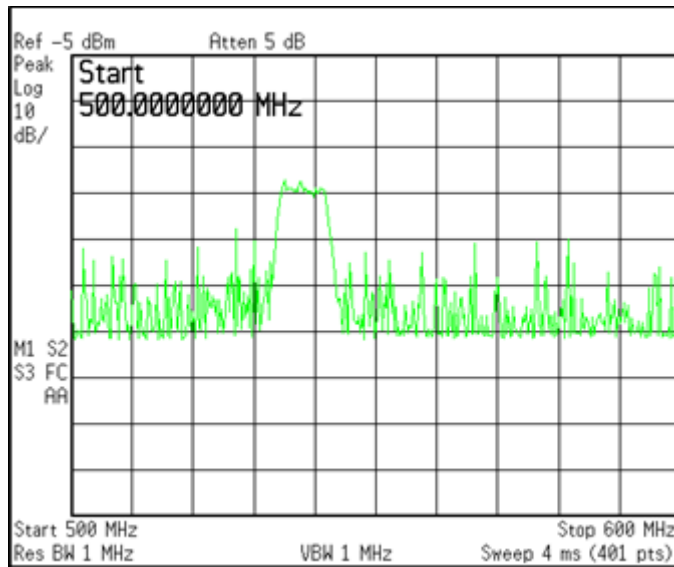


Figure 5.7: Spectrum occupancy in 500-600 MHz band

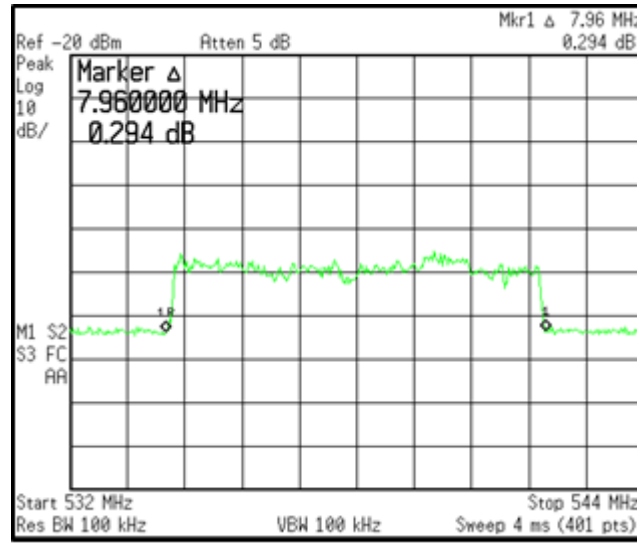


Figure 5.8: TV signal working on channel 29 (534–542 MHz)

### 5.3.2 UHF Band V (582-806 MHz)

28 TV channels (25 to 52) with 8 MHz channel bandwidth are available. Presently Doordarshan has not been assigned any channel in this band for analogue TV transmission. However, as per NFAP 2011[20], a total of 113 MHz in the frequency band 585-698 MHz has been exclusively assigned to Doordarshan for digital broadcasting services including mobile TV. The frequency band 608-614 MHz has been allocated to radio astronomy services on a primary basis. Besides radio astronomy services, other fixed and mobile users are also present in this band. As per available data, this band has been allocated to PSUs and few private companies for point to point links. Field measurements (taken in New Delhi) show that usage in this band is sparse (figure 5.9). In future entire terrestrial TV broadcasting would be restricted exclusive earmarked frequency band 585-698 MHz with reduced number of TV transmitters (3-8 channels can be accommodated in 8 MHz band in digital system).

The other part of this band 698 - 806 MHz (popularly known as 700 MHz band) has been reserved for IMT and broadband wireless access services. Frequency band 746-806 MHz has also been reserved for public protection and disaster relief (PPDR) communications.

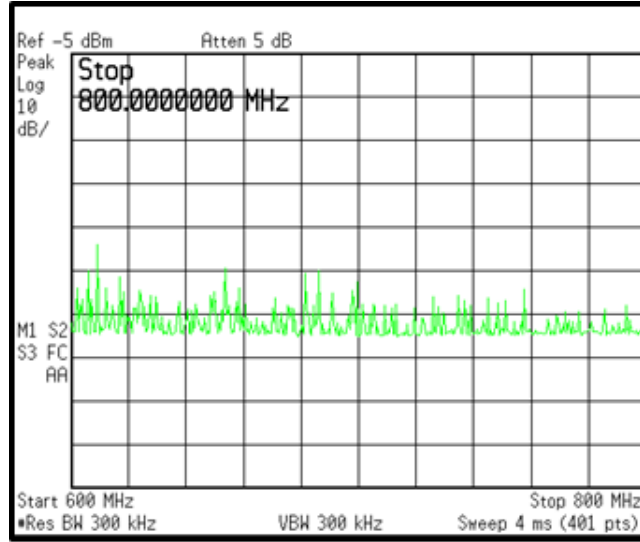


Figure 5.9: Spectrum occupancy in 600-800 MHz band

## 5.4 Assessment of TV White Space in India

The availability of TVWS at any location will depend upon the number of transmitters operating at that location. Higher the number of transmitters at any location implies lower availability of white space. Mobile devices operate with very low power can have more white space as compared to fixed devices which normally radiates high power.

The availability of white space in India at this stage is difficult to assess as DSO has not yet been completed. Presently, Doordarshan is utilising frequency band 470-582 MHz for analogue transmission. Almost all transmitters in this band are low power transmitter (LPT) except a few which are working at high power. While going through the database, it reveals that each channel has normally been used for 30-35 sites approximately scattered all over India with minimum separation of 300 K.M and each location is surrounded by 4 transmitters with different frequency (frequency reuse cluster of 5). Placement of transmitters has been planned in such way that it covers entire country population wise as well as geographically. As stated, normally each location receives 2-3 channels, out of which generally one channel operates in UHF I band. Therefore, a good amount of white space is available in 470-582 MHz.

If we apply thumb rule for calculation of white space, we could say that approximately 100-110 MHz (12-13 channels) white space would be available at each location without considering co-channel and adjacent channel. If

we take adjacent channel into account, white space at any location would reduce to 60-70 MHz (normally one site surrounded by 4 sites). When a high power device operates in vacant TV channel, energy leakage to adjacent channel may cause serious interference to adjacent occupied TV channel. TVWDs may not be permitted to operate in adjacent channel to an occupied channel. This would further reduces 40-50 MHz approximately, if we take adjacent co-channel also into account. TRAI has recommended that apart from Doordarshan, private operators may be assigned at least 1 slot of 8 MHz each for mobile TV operation in 585-806 MHz band[75]. Once it is opened, white space will further be reduced depending upon number of transmitters installed at a location. The thumb rule gives an approximate assessment of white space. The bit more precise assessment can be made through simulation modeling. A complete picture of spectrum band for terrestrial TV operation during various phases of DSO in India is shown in figure 5.10.

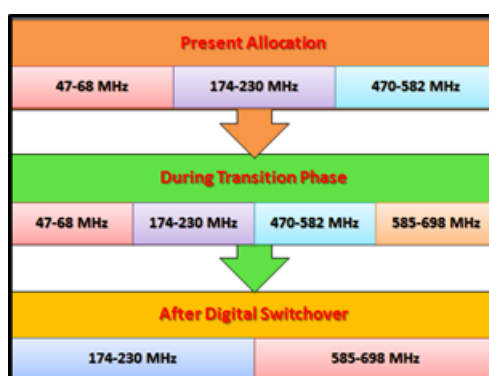


Figure 5.10: Spectrum bands for terrestrial TV operation during various phases of DSO in India

A quantitative analysis for availability of white space in India has been done in [76]. The analysis has been made for entire India except northern area. As per the assessment, 15 channels (120 MHz) white space is available in 73.66% of the area of India and almost 100 MHz white space is available in 100% of the area of the country. This has been shown in figure 5.11. This assessment has been based on the FCC rule. This is larger than many other countries like USA, UK, Japan and other EU countries.

## 5.5 Regulatory Challenges

Fragmented white space availability, geographical variations, strict restrictions on the operating parameters, lack of availability of standardized



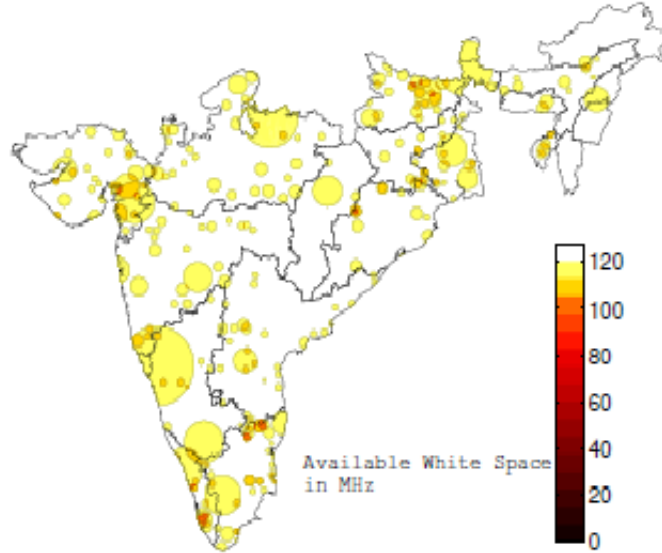


Figure 5.11: Assessment of TV white space in India[76]

technology, etc. has made regulatory affairs bit complicated[69]. The prime objective of framing strict rules for secondary users is to provide an interference free operation to primary licensed users. After several rounds consultations/discussions with stakeholder, extensive field testing, a well-defined regulatory framework has been placed in the USA and the UK. At European level, CEPTs recommendations for usage of white space are under study. Several countries like Finland, Germany, Japan, Singapore and Korea has already been taking steps for allowing testing for white space devices before making any regulatory procedures.

There are two types of white space devices have been allowed in TV white space, fixed and portable. The fixed devices would operate from a fixed location with high power (upto 4W) and could be used to provide commercial services such as wireless broadband Internet access. The personal/portable low power devices (upto 100 mW), such as Wi-Fi-like cards in laptop computers or wireless in-home local area networks (LANs), would operate from anywhere. The maximum transmit power and channels of operation for these two categories are different. Fixed devices and portable device (with more than 40mW power) cannot operate on the same channel (co-channel) and on the first adjacent channel. Portable devices with less than 40mW can operate anywhere except co-channel.

In the current regulatory framework, the white space device can be put

under unlicensed, quasi-licensed and licensed categories. Each category has its own advantages and disadvantages.

Worldwide regulators opened white space for low power devices on an unlicensed basis with a view that it would facilitate economical wireless broadband services to peoples particularly in rural areas, where the transaction cost would normally higher than elsewhere, promote innovation and improved spectrum utilization [65]. De-licensed devices normally operate on an open and shared access basis without any protection under strict regulatory conditions over technical parameters/equipment specifications. In de-licensed system, interference is the main issue as it would be impossible to track down the source of interference. This aspect worsens in the TV band due to its better coverage properties. Portable devices may not cause significant interference but interference due to fixed devices would be significant. Several measures have been suggested for interference mitigation in the network like white space device would be allowed to operate only after identification of vacant channel, and fixed devices must be registered with database administrator/regulator. In case of interference, these steps would make possible to identify possible sources of interference.

Another possibility is to give a quasi-license status to fixed devices and keep portable devices in de-licensed category[64]. Fixed devices would be treated as licensed devices when viewed from de-licensed portable devices and would be treated as de-licensed devices when viewed from incumbents as shown in the figure 5.12. The quasi license would provide right to use spectrum locally on non-interference/non-protection basis with restricted operating parameters so that it could not cause any interference to the operation of licensed users. No protection would be given to quasi licensor in respect of licensed users. They are authorized to get protection from unlicensed users. A certain amount of channel bandwidth may be reserved for such licensing.

There are several arguments in favour of keeping entire white space licensed as it would provide opportunity for large scale utilization of white space, assure investment, get protection from harmful interference and large amount of revenue could also be generated[64]. However, licensed spectrum provides 'Right to Use' concept, which may not be suitable for TV white space because the quantum of available white space at any location may change in future depending upon terrestrial TV standard, and no quality of services can be guaranteed with reference to terrestrial TV. TVWS is a local phenomenon meaning that quantum of spectrum and portion of frequency band vary with respect to location. If auction were held, it would be held locally, which certainly would not fetch large revenue in any way.

Due to unusual position of TV white space in terms of availability, technical constraints and licensing position, big investment is not possible in

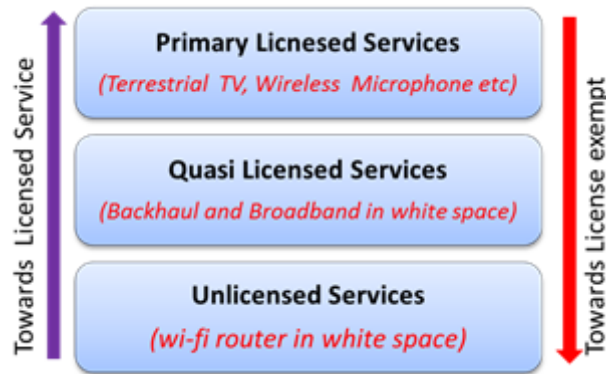


Figure 5.12: Quasi licensing status

TV white space. No such example is available where big commercial services were operating in de-licensed band. The following reasons may be attributed:

- Fragmented white space availability with geographical variations, at some places it reduces upto 6-8 MHz. No equal amount of spectrum can be allotted at every location in the entire operating area that may be a country or a state of a country.
- Low operating power with several other restrictions would limit the coverage. The wireless network with limited coverage produces limited commercial success. Coverage is operating power dependent quantity, extra BTS would be required to cover an area. Additional capex and opex would be required towards these extra BTSs, which make the services costly.
- They are allowed to access white space opportunistically. It would be difficult to maintain quality of services in the network and to manage interference in the network.
- Additional feature of spectrum sensing would be required in white space devices which make device more complex and costly.
- FDD operation may not be possible in white space, as FDD operation requires a fixed separation between base station and device transmit operating frequencies. FDD operation would further reduce the white space. Real time voice services difficult to provide, which reduce customer base.

No specific regulations for de-licensing or usage of TV band by TVWSDs is available in India. However, the National Telecom Policy 2012[77] envisage

to promote the 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), etc. The detail assessment about usage of white space in Indian scenario is given below:

### 5.5.1 Amount of White Spectrum in India

As stated, Doordarshan (Prasar Bharti) is the only terrestrial TV broadcasting channel in India. About 350 transmitters have been working across the India in UHF I band (470-582 MHz). If we assume that TV transmitters in UHF I band cover about 90% areas of the India, it can be estimated that TV transmitters are installed approximately at a distance of 100 KM across the length and breadth with different transmit power. Further, we assume that approximately 25% areas covered by two transmitters due to overlapping of adjacent channel signal and remaining 75% areas covered by one transmitter. With such assumptions, inference can be made that a good amount of white space is available at each and every locations in India. Rural areas have more white space than urban areas like any other country. The spectrum assigned for terrestrial TV in UHF band in India is less in amount, comparison with other countries like USA (336 MHz), UK (256 MHz), Japan (240 MHz) and Singapore (168 MHz). India is a single operator country whereas other countries have multi operator in broadcasting services. If we take both the points into account i.e. amount of spectrum and no. of operators, the amount of white space would be substantial in India. If we look at the status of white space in other countries, we found that limited white space is available with wide variation in quantity geographically, and that too zero at some places like New York City, USA. On the other hand, variation in the amount of white space geographically is not very high in India.

### Spectrum Price

Analog TV transmission in UHF band is limited between 470-582 MHz (a total of 112 MHz) in India. Spectrum band of 585-698 MHz (113 MHz) has been reserved for digital terrestrial TV transmission. Therefore, a total of 225 MHz spectrum in UHF band has been reserved for TV Transmission. A good amount of white space (approximately 80-100 MHz in analogue portion and an almost equal amount would be available after digital migration) is available at each and every location of India. The valuation of this white space in India is very much significant from two points, first amount of white

space at each and every location and secondly spectrum cost.

Auction has so far not been conducted for spectrum in the 700 MHz band in India. A cost analysis has been made based on recently conducted spectrum auctions for 800, 900 and 1800 MHz bands in India (November 2012/March 2013). The realized price in the 1800 MHz on pan India basis was approximately €0.26 per MHz per population for 20 years period. In addition to this amount, operators would have to pay annually spectrum usage charge at a specified rate. As per TRAI recommendations, the reserve price for 700 MHz band spectrum should be 4 times of 1800 MHz[78]. With this analogy, spectrum cost of TV band would be approximately €1.05 per MHz per population for 20 years. If we compare price realized in other countries in the digital dividend band, we find that spectrum cost in 700 MHz in India would be more than what the USA and Germany had realized.

### **Low penetration of Broadband**

India is the second largest telecom market in the world after China. The growth in telecom services in India is predominantly limited to urban areas. The majority of the rural population is still un-served even in voice telephony. The tele-density of rural areas is almost one fourth of the urban areas. If we look towards broadband connectivity, the situation is very grim. The total internet connectivity is about 198.39 million, out of which broadband connectivity is about 15.20 million and through Mobile Devices is about 176.50 million at the end of June 2013. At present about 99% of total broadband connections are being provided using wire-line which has limited geographical availability and contribution of Broadband Wireless Access (BWA) is meager 1% [79]. According to ITU-UNESCO report[80], India ranks behind over 100 countries, in terms of fixed and wireless broadband penetration. It lags behind much smaller and poorer countries. According to [81], by 2016, 814 million households worldwide will have Internet service, and over 94% will have broadband. However, Indias share in this broadband revolution is not even 1% although India is third largest in the world in terms of internet users( about 120 million) [82]. The broadband penetration in rural areas is quite low which may be a result of lack of awareness and access to affordable technologies and unaffordable broadband price.

### **Low Capex and Opex**

Capital and operational expenditure involved to run broadband services in India is low as compared to European countries. The approximate cost involved in the installation of one base station with limited power would

be €100,000 (on maximum side), if spectrum assigned free of cost or at a nominal charge. The operational cost would be around €20,000 per annum per site (on maximum side). Spectrum cost in comparison to installation cost is very much high. The spectrum cost for TV white space on pan India basis would be around €0.0525 per MHz per population per year, which is very high. A detailed cost calculation for white space spectrum is given in the table 5.5.

### Affordability

India is a vast country having an area of about 3,287,000 square kilometers. The total population of India is 1.210 billion, out of which approximately 70% population are living in villages. There are more than six lakh villages in the country[83]. India is a fast developing country with its GDP was 1841.717 billion US\$ in 2012. World Bank in its report 'Global Economic Prospects'[84], said South Asia's regional growth will be driven mainly by a projected pick up in India, whose GDP in factor cost terms is projected to grow 5.7% in the 2013 fiscal year, and then accelerate to 6.5% and 6.7% in FY2014-15 and FY2015-16, respectively. India's per capita income (nominal) is US\$ 1219 annually ranked 142nd in the world. India's per capita GDP on purchasing power parity (PPP) basis was US\$ 3,403 in 2010 and is estimated at US\$ 3,662.69 in 2011 and US\$ 3,851.31 in 2012. There is a wide disparity in rural and urban consumptions. Right now, rural per capita consumption is about half of urban consumption. However, total rural consumption has always been higher than urban areas due to the larger population. Spending in India is increasing in both pockets urban and rural as income is increasing. The demography of rural India is changing very fast. 75% of new factories in India in the last decade were in rural areas and 70% of manufacturing jobs were created in rural India [85]. Rural India contributes about half of Indias GDP which include agriculture, industry and services sector.

Broadband penetration has a direct positive impact on GDP growth as it enables efficient functioning of services across business and provides opportunities for employment. At present, the internet currently contributes about 1.6% of Indias GDP. Indias large economy, with its young and increasing urbanizing consumer base, offers strong growth potential for broadband usage. However, the growth in broadband sector has not taken place as expected due to limited availability of broadband infrastructure, costly broadband usage charges, lack of awareness and unfavorable business environment. If appropriate broadband services offer at reasonable prices, peoples are ready to take it.

### 5.5.2 Regulatory Framework

The first requirement is to prepare a digital database of active licensed users in the TV band. The basic work involved in the creation of the database is the identification of frequency bands and its extensive monitoring to know the pattern of spectrum usage by licensed users. The database should contain the following basic details of licensed users for providing interference free operation:

- Transmitter Coordinates (latitude and longitude)
- Effective Radiated Power
- Carrier frequency and occupied bandwidth
- Type of antenna and its height
- Type of polarization and antenna pattern
- Call sign/channel number (if applicable)
- Usage pattern /Duration of operation
- Details about owner

Regulating agency in the USA and the UK does not maintain the database. They have designated one or more database administrators (from the private sector) to create and operate TV bands database. In other countries, database is maintained by the regulator. Database of licensed users has been available with the regulator in India. A subset of this database for TV band (470 to 698 MHz) is required to be prepared. The copy of master database should further be extended to different regions as regional database. The regional database should be equipped with technical software for calculation of coverage and interference. This should be made available to all interested parties. The database should be dynamic in nature which contain information about licensed users and instantaneous registered secondary users. The dynamic databases must provide a list with the available channels along with the maximum transmit power for each channel at given location when requested by WSD. It must be available 99.99% of the time and should be updated periodically.

### 5.5.3 Protection Criteria for Incumbent Services

Adequate protection should be given to terrestrial TV and other incumbent operating in the band. India has adopted PAL G system for transmission in the UHF bands and DVB-T system for Digital Terrestrial Television (DTT) with 8 MHz bandwidth in both the cases. The minimum required signal strength for 8 MHz bandwidth at analog and digital TV receiver would be -80dBm and -87dBm respectively. FCC in its report[65] stated that sensing threshold would normally be taken approximately 30dB below from the minimum signal strength level. Therefore, a TVWSD with a minimum sensing level of -120dBm would be able to reliably detect the presence of a TV stations signal within the stations service area.

Wireless microphones and other programmed devices are also working in TV bands. Unlike the other countries, these are licensed device in India. The FCC and the Ofcom have reserved 1-2 TV channels exclusively for wireless microphone. No WSDs can operate in these reserved channels. The FCC and the Ofcom have made provision for sensing of wireless microphones. Therefore, a suitable provision for detection of wireless microphone may also be required along with TV signal detection.

Several licensed point to point communication system are working in the TV band. These systems need to be protected till the expiry of licenses or, if possible, may be shifted to some other bands. A comprehensive study for setting sensing threshold parameters should be undertaken taking into account all licensed devices in the TV band in the Indian environment.

Three main techniques, i.e. sensing, geo-location database and beacon have been proposed to assist the white space devices in finding unoccupied channels. Beacon is not much convincing technique due to additional overhead. It has been excluded by the regulatory authorities for detection purpose. In the spectrum sensing, device is itself capable of identifying the vacant channel by learning about the interference environment in their local geographic area without taking support of local infrastructure i.e. geo-location database. This technique is useful in remote areas, where geo-location database would difficult to access. However, spectrum sensing technique increases the complexity in TVWSDs and fails to resolve hidden node problems.

The geo-location database is widely accepted technique for detection of signal due to its simplicity and accurate determination of TV transmitter. The main problem with geo-location databases is that they can protect registered users only. The solution is dynamic database which contains information about licensed users, and WSDs during their active period. Information in the database would be dynamically change with respect to time depends



upon the number of active WSDs. At preliminary stage, the geo-location database approach appears to be best for identification of unoccupied TV channels. Once the white space device provides its location to the database, distance between white space device and licensed users can be calculated. Based on distance, adequate and reliable protection can be provided by applying standardized protection criteria and operating parameters for white space device could be fixed.

The FCC and the Ofcom both encourage dynamic database and sensing. The key difference between Ofcom and the FCCs approach is that Ofcom suggests that sensing alone could be allowed without detailed device tests whereas FCC relies on a combination of geo-location database and sensing. Therefore, a regulatory framework should be developed to enable both sensing and geo-location mechanisms and final choice may be left on the stakeholder. It would be appropriate that fixed devices and master portable devices must be equipped with both the systems whereas geo-location technique may be kept optional for slave portable devices in line with FCC and Ofcom.

The FCC has imposed a limit on EIRP (upto 4W) for WSDs. The Ofcom has adopted a flexible approach regarding maximum EIRP, may go beyond 4W subject to the level of interference at the TV receiver, which should not exceed beyond a specified limit. There are two different ways of restricting maximum EIRP. The first one is the transmitter centric in which a cap should place on maximum EIRP irrespective of distance from the NTZ and another one is the receiver centric, where EIRP is determined via maximum interference level at primary receiver i.e. how far away from the NTZ. Transmitter centric is easy to manage as it is less susceptible to interference. In receiver centric, interference is difficult to control as EIRP is not fixed but could provide better coverage. The FCC has adopted the transmitter centric approach and Ofcom has adopted the receiver centric approach for fixed and mobile devices (other than transmission in co-channel and adjacent channel). Besides limiting EIRP, out of band emission may also be specified to ensure minimum interference to the primary services in the adjoining band.

Regulatory aspects in Indian scenario would not be complex because of one operator in terrestrial TV broadcasting. Ofcom regulations i.e. receiver centric approach for fixed and mobile devices operating other than co-channel and adjacent channel and transmitter centric in co-channel and adjacent channel would be appropriate in Indian context. As regards restriction on antenna height is concerned, it should be linked with distance from the NTZ. A combination of EIRP and antenna height may be decided on the basis of distance from the NTZ. However, a maximum antenna height limit may be

applied for fixed devices for simplification in line with the FCC regulations.

TV network pattern in India shows that one carrier is repeated a minimum of 300-400 KM distance. A fixed WSD can operate with more than 4W EIRP subject to its distance from the TV transmitter. Figure 5.13 presents this concept; two transmitters are placed 300 Km apart, and operating on the same frequency. No secondary transmitter can operate in No Talk region. The coverage area for WSD could go upto 25-30 KM depending upon the transmit power and antenna height.

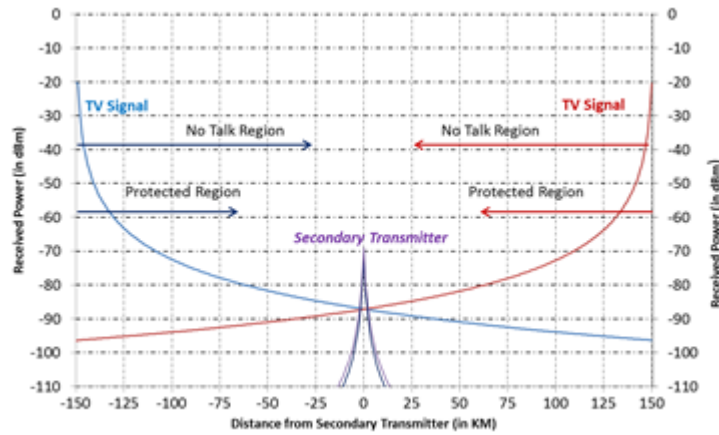


Figure 5.13: Coverage calculation for TV transmitter and WSD

In Indian scenario, regulatory framework is required to be developed considering adequate protection to primary licensed services namely broadcasting services including mobile TV, PMSE, radio astronomy services, space operation services, public protection and disaster relief communications and other fixed and mobile services operating in the same and adjacent bands. The regulatory framework should consist the following:

- Identification of frequency bands for white space
- Monitoring of spectrum usage in the identified band
- Creation of database and its periodic updation
- Framing rule for operation
  - Eligibility criteria
  - Permissible radio access technology
  - Maximum permissible transmit power

- Out of band emission limit
- Method of access of frequency database
- Antenna height limit
- Method of assignment of spectrum
- Administrative charges, if applicable
- Interference Management

## 5.6 Application for Indian Environment

As stated, growth of telecom services in India is limited to urban areas. The majority of the rural population is still un-served. Presently, approximately 275 MHz spectrum has been assigned for IMT services namely 2G (FDD), 3G (FDD) and BWA (TDD) in India. An additional amount of almost 300 MHz spectrum in different frequency bands, namely 450-470 MHz, 698-806 MHz, 2.3-2.4 GHz, 3.33.4 GHz and 3.4-3.6 GHz, has been identified for expansion of IMT services in the future. It seems to be difficult to meet the target envisage in NTP 2012 [77] that affordable broadband to all villages by 2020, with a total of approximately 600 MHz spectrum (earmarked for IMT services). Moreover, this spectrum is available for commercial use through market determined price only, which might be unaffordable by rural population. TV white space, with either no spectrum cost or on a nominal spectrum cost, can be utilized to deliver access to broadband in rural areas with less capital investment.

In Indian context, widespread access to high-speed affordable broadband would bridge the digital divide between urban and rural areas and provide efficient management of agriculture crop, better access to education which bridge the supply demand gap of high quality teachers in the countryside, improved health care through telemedicine, E-governance through which government policies can be implemented and monitored more effectively, intelligent traffic management and police security. The other sectors such as mobile banking, m-commerce, tourism, mobile-entertainment etc. would also be benefited. It also helps to fight with natural calamity like earthquake, tsunami drought and flood etc.

IEEE 802.22 standard [86] has been developed for Wireless Regional Area Network (WRAN) in the TVWS for broadband wireless access in rural areas. The IEEE 802.22 system specifies a fixed point to multi point wireless interface in which a base station manages its own cell with typical cell

radius of 33 to 100 km and 4 W EIRP. The spectrum efficiency varies from 0.76 bit/s/Hz to 3.78 bit/s/Hz, this would correspond to a total PHY data rate of 5 Mbps to 25 Mbps in a 8 MHz TV channel. PHY specification is based on orthogonal frequency division multiple access (OFDMA) for both upstream access with rate 384 kb/s and downstream access with rate 1.5 Mb/s using Inverse Fourier Transforms. The main system parameters and sensing threshold are given in table 5.6.

### Deployment Scenario

About 70% of Indias population lives in rural areas. Due to the diverse geographical terrain the size of the villages is normally small in size and, the villages tend to be bigger in plain areas. There are more than 600,000 villages; the largest numbers of villages are in the population size group of 100-2000 persons. Around 85% of these villages are in the plains, spaced 2-2.5 km apart in every direction. On the average, each village consists of a residential zone of around 0.1-0.25 sq. km, surrounded by farmland. The remaining 15% of villages are in hilly areas or desert[83]. Typically villages are located within 20-25 km within a town. These towns are connected through optical fibre network. Cellular telephony has reached all the towns and the villages surrounding them. Coverage is spotty, it does not cover the interior areas between the villages except in the more urbanized states. Broadband services are available in those villages, which are situated near the city through wireline but such villages are few. Lower affordability and inadequate infrastructure in rural areas has deterred deeper penetration of fiber/microwave links and BTS towers. TVWS can be used to provide broadband access services in the villages and backhaul network between villages.

India is fast growing developing country where the number of small townships are present or under construction in suburban areas. In most of the such townships, broadband connectivity is either not available or intermittent. Wi-Fi at 2.4 GHz is one option but highly congested and its coverage is limited. IEEE802.11af standard[87] is under development for back haul for Wi-Fi. The standard is an extension to the IEEE 802.11 base standard, also known commercially as Wi-Fi, with additional spectrum sensing capacity and can work in TVWS with a maximum data rate of 12.0 Mbps. The standard is similar to IEEE 802.22 but there is a difference in the operating range (100 m to 5 Km), total bandwidth (5, 10, 20, 40 MHz), FFT size and error correcting code. It is experienced that coverage inside big building is normally not good. The IEEE 802.11af standard based device can be placed inside the building to establish a femtocell. This femtocell would help maintaining good broadband services in the building. In addition to these, several other

applications like remote monitoring, managing the traffic system and public disaster management etc., can be established. Therefore, such applications where small capital is involved would not be risky, can be easily established and manageable in TVWS.

## 5.7 Conclusions

The chapter presented a comprehensive analysis of the allocation of radio spectrum for television broadcasting and availability of TV white space in India. The analysis concluded that sufficient TV white space is available at each and every corner of India as compared to other countries. In future more spectrum efficient TV technology will come, which further reduce the quantity of TV white space. It has also been discussed that no big investment is possible due to variable quantity of TV white space across the country and uncertainty over terrestrial TV technology. Therefore, such applications where small capital is involved would not be risky, can be easily established and manageable in TVWS.

Table 5.4: Frequency allocation for terrestrial TV in India

Frequency Band	Allocation	Remarks
47-68 MHz	FIXED MOBILE BROADCASTING	Few spots assigned for remote unit of cordless telephone  Fixed/Mobile services in the band 54-68 MHz may be considered on case-by-case basis.
174-230 MHz	FIXED MOBILE BROADCASTING	Fixed and mobile services including those of wireless telemetry seismic systems will be considered in the frequency band 174-230 MHz on a case-by-case basis.  Digital Audio Broadcasting (DAB) may be considered in the frequency band 174-230 on a case-by-case basis taking into account interference potentiality aspects.
223-230 MHz	FIXED MOBILE BROADCASTING AERONAUTICAL RADIONAVIGATION  Radiolocation	Fixed and mobile services including those of wireless telemetry seismic systems will be considered in the frequency band 174-230 MHz on a case-by-case basis.  Digital Audio Broadcasting (DAB) may be considered in the frequency band 174-230 on a case-by-case basis taking into account interference potentiality aspects.
470-585 MHz	FIXED MOBILE BROADCASTING	Fixed and mobile services will be considered in the frequency band 470-520 MHz and 520-585 MHz on case-by-case basis.
585-698 MHz	FIXED MOBILE BROADCASTING RADIO NAVIGATION RADIO ASTRONOMY	Digital Broadcasting Services including Mobile TV may be considered in the frequency band 585-698 MHz subject to coordination on case-by-case basis.

Table 5.5: Spectrum cost for white space (€/MHz/pop/year)

Spectrum cost in 1800 MHz band pan India (based on recent auction held in March 2013)	€0.26 per MHz per population (pan India for 20 years)
Approximate Spectrum cost of TV band (4 times of 1800 MHz band)	€1.05 per MHz per population for 20 years
Approximate Spectrum cost of TV band (yearly basis pan India)	€0.0525 per MHz per population per year
Approximate Spectrum cost of 112 MHz TV spectrum (Pan India)	€5.88 per population per year
Approximate Spectrum cost of TV White Space (40 MHz - Pan India)	€2.10 per MHz per population per year

Table 5.6: Technical parameters of IEEE802.22

Parameters	Specification
Frequency range	54 862 MHz
Channel bandwidth	6, 7, or 8 MHz
Data rate	5 Mbps to 25 Mbps
Spectral Efficiency	0.76 to 3.78 bit/s/Hz
Payload modulation	QPSK, 16-QAM, 64-QAM
Transmit EIRP	4W maximum for CPEs. Maximum EIRP for BSs may vary in other regulatory domains.
Multiple Access	OFDMA
FFT Size (NFFT)	2048
Cyclic Prefix Modes	1/4, 1/8, 1/16, 1/32
Duplex	TDD
<b>Key parameters for geolocation Cognitive</b>	
Digital TV	-116dBm (6 MHz channel)
Analog TV	-94dBm (at peak of sync of the NTSC picture carrier)
Microphone	-114dBm (200 KHz bandwidth)

## Chapter 6

# Dynamic Spectrum Access and Cognitive Radio



## 6.1 Introduction

The existing static approach of the spectrum management is not efficient to cater the present and future requirement of spectrum. The concept of dynamic spectrum access has emerged dramatically for improving spectrum utilization. The delicensing, allowing spectrum trading/sharing are some initiation towards dynamic spectrum access.

Dynamic spectrum access can be defined [1] as a mechanism to adjust the spectrum resource usage in a near-real-time manner in response to the changing environment and objective (e.g. available channel and type of applications), changes of radio state (e.g. transmission mode, battery status, and location), and changes in environment and external constraints (e.g. radio propagation, operational policy). In simple way, Dynamic Spectrum Access (DSA) allowing the new user (unlicensed) to access spectrum which has already been allocated to another user (licensed). The key characteristic of DSA is their ability to exploit knowledge of their electromagnetic environment to adapt their operation and access to spectrum[88]. Dynamic spectrum access is also referred to as opportunistic spectrum access, and is normally considered as part of the larger concept of cognitive radios. Dynamic spectrum access is divided into four major phases[1], namely, spectrum sensing, spectrum analysis, spectrum access and spectrum handoff.

Spectrum sensing is to identify the spectrum hole(i.e. band, location, and time) by periodically sensing the target frequency band and also determines the method of accessing it without interfering with the transmission of a licensed user. In spectrum analysis, information from spectrum sensing is analyzed to gain knowledge about the spectrum holes (e.g. interference estimation, duration of availability, and probability of collision with a licensed user) and a decision to access the spectrum (e.g. frequency, bandwidth, modulation mode, transmit power, location, and time duration) is made by optimizing the system performance given the desired objective and constraints. After a decision is made on spectrum access based on spectrum analysis, the spectrum holes are accessed by the unlicensed users is known as spectrum access. Spectrum handoff is a function related to the change of operating frequency band. When a licensed user starts accessing a radio channel which is currently being used by a licensed user, then unlicensed user immediately changes its operating frequency band. This change in operating frequency band is known as spectrum handoff. Spectrum handoff ensures that the data transmission by the unlicensed user can continue in the new spectrum band.

There are two approaches for opportunistic spectrum access[89]: spectrum underlay and spectrum overlay. In overlay spectrum access, unlicensed

user is allowed to access the spectrum, which is allocated to some licensed user when the spectrum is not used by licensed user. Access of spectrum hole/white spot is example of spectrum overlay. Spectrum overlay can be used for cognitive radio in Frequency Division Multiple Access (FDMA), Time Division Multiple Access (TDMA), or Orthogonal Frequency Division Multiplexing (OFDM) wireless systems. This approach is compatible with the existing spectrum allocation methodology, therefore, the legacy systems can continue to operate without being affected by the cognitive radio users.

In underlay spectrum access, both licensed and unlicensed user can simultaneously transmit as long as interference from unlicensed user does not degrade the quality of service (QoS) of licensed user. Spectrum underlay can be used for cognitive radio systems using Ultra-Wide Band (UWB) technology. In spectrum underlay, defining interference level and how it would be distributed between secondary users are major issue in its implementation.

Dynamic spectrum access can be deployed either centralised or distributed manner[1]. In centralized case, a central controller makes the decision on spectrum access by all unlicensed users after collecting information about the spectrum usage of the licensed users as well as information about the transmission requirements of the unlicensed users. However, information collection and exchange to and from the central controller is main issue in centralised system. In distributed dynamic spectrum access, an unlicensed user can make a decision on spectrum access independently and autonomously. Since each unlicensed user has to collect information about the ambient radio environment and make its decision locally, the cognitive radio transceiver of each unlicensed user requires greater computational resources than are required in centralized dynamic spectrum access.

### 6.1.1 Benefits of DSA

Static model of spectrum management provides efficient use of spectrum during busy hour, but inefficiently at all other times. DSA would enable spectrum to be used for other services during periods of low utilisation, increasing efficiency. This efficiency can also be extended to creating greater device convergence, allowing multiple services to coexist in the same devices, as well as in the same spectrum.

With static approach, it is very difficult to meet the demand for access to spectrum, particularly where spectrum has already been assigned to users. DSA bypass much of the delays by allowing new user to access the spectrum as SU.

Efficient use and faster access to spectrum would help encourage wireless innovation which contributes to a healthy competitive environment with

a greater choice of services for end users.

### 6.1.2 Challenges

DSA is seems conceptually very simple but its realisation is highly challenging. The biggest concern over the introduction of dynamic spectrum access systems is an increased level of interference [1]. The hidden node is one of the main source of interference. In dynamic spectrum access, device will 'listen' to determine whether any other device is using the same frequencies at that time, it may be possible that device would not be able to identify all transmissions in its area or nearby areas due to some problems like weak transmission, transmitter falls in shadow/behind tall building etc. The undetected device is known as a 'hidden node' and it creates interference to other system. Therefore, a strong regulatory system is essentially required to overcome with such problems. There are several issues such as sensing over a wide frequency band, identifying the presence of primary users and determining the nature of opportunities, coordinating the use of these opportunities with other nodes and adherence to existing regulatory policies are linked with DSA, which need to be solved before implementation.

## 6.2 Cognitive Radio

The term 'Cognitive Radio'[90], was first introduced by Joseph Mitola in an article published in 1999, he described how the flexibility in wireless services can be enhanced through cognitive radio. As per ITU definition [91], Cognitive Radio is 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. Some of the key features typically associated with CR include[92]:

- Maintains awareness of its operational and geographical environment and its internal state.
- Autonomously adjusts its operating parameters to meet requirements and goals.
- Learns from previous experiences to further improve its performance.

- Reasons on observations to adjust adaptation goals.
- Take future decision based on anticipated events.
- Collaborates with other devices to make decisions through collective observations and knowledge.

In cognitive radio, primary user(PU) is licensed user and secondary user(SU) is unlicensed user, who can exploit spectrum allocated to PU in such a way that it should not cause interference to the primary user services. Therefore, secondary users should have cognitive radio capabilities to check whether spectrum is being used by primary users and to change radio parameters to exploit the unused part of the spectrum [93].

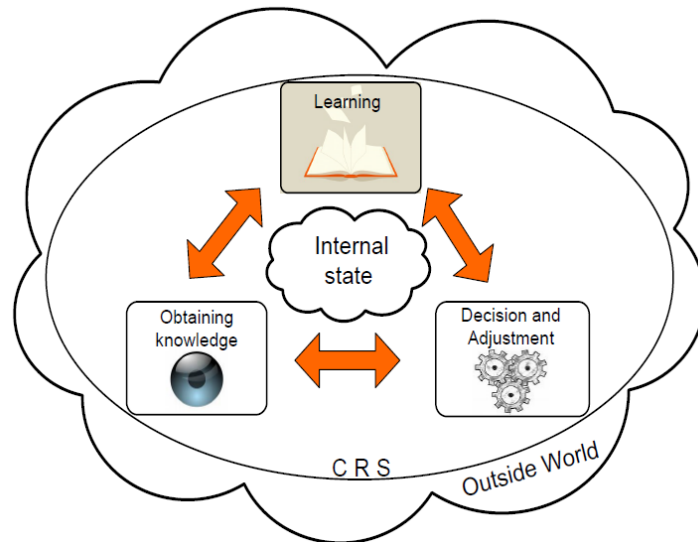


Figure 6.1: Cognitive radio system[91]

The component of cognitive radio cycle is presented in figure 6.1. Outside world includes information about established policies, other radio system, current status of spectrum usage, geo-location of PU and users' needs etc. The internal state includes traffic load distribution, interference level, coverage area, antenna orientation and transmission power levels of the cognitive radio system.

The first key feature of CR is obtaining knowledge to obtain the knowledge of operational radio environment and geographical environment, the established policies and its internal state; to monitor usage patterns and users' needs and any subsequent changes. Outside knowledge can be obtained

through spectrum sensing and database access. Database provides information about usage pattern of PU and regulatory policies etc. For example, the database could tell the cognitive device, what frequencies it can use in its current location. Obtaining knowledge is generally known as cognitive capability of the CR.

The second key feature of the CR is re-configurability i.e. decision and adjustment of operational parameters and protocols. Re-configurability of the CR is the capability to dynamically and autonomously adjust its operational parameters like operating frequency, modulation, transmit power, communication technology and protocols according to the obtained knowledge which includes past experience in order to achieve some predefined objectives. The CR analyses the obtained knowledge and dynamically & autonomously make decisions on its reconfiguration for example to get appropriate communication quality, to change the radio access technology to be used in a certain connection, to adjust the radio resources dedicated to a system and to adjust a transmission power to reduce interference.

The third key feature of CR is the capability to learn. The objective of the learning process is to improve its performance by using stored information of its past actions and their results. CR evaluates each action and constantly optimizes the parameters to further improve the performance. A key functionality of the learning process is to create and maintain knowledge basis in the changing environment.

The cognitive capability is performed in receiver whereas reconfigurability and learning from past actions are performed in transmitter based on the feedback provided by the receiver about available spectrum hole and channel conditions through cognitive capability.

Cognitive radio is a key technology for next generation heterogeneous wireless networks. Cognitive radio will provide intelligence to both the user-side and provider-side equipments to manage the air interface and network efficiently. At the user-side, a mobile device with multiple air interfaces (e.g. Wi-Fi, Wi-MAX, cellular) can observe the status of the wireless access networks and make a decision on selecting the access network[1]. At the provider-side, radio resource from multiple networks can be optimized for the given set of mobile users and their QoS requirements. Based on the mobility and traffic pattern of the users, efficient load balancing mechanisms can be implemented at the service provider's infrastructure to distribute the traffic load among multiple available networks to reduce network congestion. New wireless technologies are being developed to reuse the radio spectrum allocated to other wireless services. Cognitive radio is a solution to provide coexistence between these different technologies and wireless services. In healthcare services, medical equipment are designed to work in ISM band,

controlled transmit power and intelligent selection of RF frequency are very important phenomenon to avoid the interference with each other. Cognitive radio can also be used manage these two factors successfully. In addition to this, Military networks, public safety and emergency networks can take advantage of the cognitive radio concepts to provide reliable and flexible wireless communication.

The implementation of a cognitive radio is based on the DSA [1]. Through DSA, frequency spectrum can be shared among primary users and cognitive radio users (i.e., secondary users) in a dynamically changing radio environment. Cognitive radio and dynamic spectrum access techniques can be integrated into traditional wireless communications systems to achieve better flexibility of radio resource usage so that the system performance can be improved.

Cognitive radio is not a radiocommunication service, but is a technology that can be implemented under any services defined in the radio regulation of ITU-R [91]. No separate radio regulation needs to be developed for cognitive radio. The key benefit for deploying cognitive radio is to improve the overall spectrum efficiency and increase flexibility. This also facilitates to enhance the economic value of spectrum. Cognitive radio system encourage the manufacturers to come up with new ideas as spectrum scarcity would not hindrance for new services. It also promotes green energy concept as high transmit power would cause interference to existing primary users.

### 6.3 Requirement for spectrum monitoring for Cognitive Radio

As stated, the reliable detection of the primary signal is the basic requirement for implementation of cognitive radio. The techniques for detection of primary signal is known as spectrum sensing. The main objective of spectrum sensing is to provide more spectrum access opportunities to CR users without interference to the primary networks[94].

Presently there are three methods[95] for spectrum sensing: match filtering, energy detection and cyclostationary feature detection. All these three techniques differ in the sensing capabilities and computational complexities. Matched filtering [96] is an optimal way for signal detection when the primary signal is known to the secondary user but the problem is that secondary user needs a dedicated demodulator for each type of primary signal, which increases overheads and make it more complicated and also it is not suitable for very low SNR environment. Energy detection [97]is used

to determine the presence of signals without prior knowledge. It simply measures the energy of received signal and compares it to predefined threshold level. This method is simplest one and has low implementation complexities. The main drawback of the energy detector is its inability to discriminate between sources of received energy (the primary signal and noise), making it susceptible to uncertainties in background noise power, especially at low SNR. Cyclostationary feature detection[98] is used to extract signal features in the background of noise. In cyclostationary detection, periodicity characteristics are used to sense the presence of primary user signal. Modulated signals are in general coupled with sine wave carriers, pulse trains, repeating spreading, hopping sequences, or cyclic prefixes which result in built-in periodicity whereas noise don't have such properties. This technique is a promising option for the spectrum sensing in cognitive radio, especially in the situation where energy detection is not sufficient effective. The disadvantage of cyclostationary detection is that it is computationally complex and requires significantly long observation time[96] and failed when periodicity of primary signal is not known. In nut shell, all the three detection methods are not very much reliable and do not provide accurate information.

Another concern with CR is the hidden node problem [96]. This situation arises when a CR is unable to detect all of the radios with which might interfere, not because of its own spectrum sensing is ineffective, but because of some radios are hidden from it. Receive-only devices (e.g. television, radio, astronomy), devices with very weak transmit signals and any devices whose transmissions are prevented from reaching the CR by the environment or terrain are examples of hidden node.

Presently, sensing technology is under development, the CR devices need to use updated database, which contains usage pattern of primary users. This database can be maintained through extensive spectrum monitoring of frequency bands. Presently spectrum monitoring is being performed for band occupancy, channel occupancy, bandwidth of a signal, transmitter power etc. Now, what should be the aim of developing database in respect of deployment of cognitive radio system. The aims are given below[95]:

- to collect data to build a statistical model for usage of the spectrum;
- to collect parameters for signal identification;
- to validate information on legitimate users;
- to investigate the usage variation of signals in different environments;
- to investigate the cases of congestion of signals;

- to collect the information for effective regulations of new bands; and
- to identifying areas for further use, sharing or reallocation.

Spectrum sensing provides an idea about the presence of signal but some other information is also require to identify the signal like signal bandwidth, power level, center frequency, type of modulation and carrier information etc. These new parameters enhance the spectrum sensing capabilities of cognitive radio systems. In our view the following should be monitored in respect of PU to create database for cognitive radio system.

1. Bandwidth/modulation
2. Transmitted power level
3. Carrier frequency
4. Radio access technology
5. Duration or duty cycle of operation
6. Geographical location
7. Outdoor or indoor operation
8. Adjacent channel interference information

Based on the above information, a centralized database should be maintained. For effective deployment of a CR system, this database should be updated regularly and the database either be made available to secondary users or may be kept in the central server. When CR equipped user desire to transmit, first it would scan the entire spectrum band and identify the white spot/spectrum hole in the band, thereafter it would exchange the information with the updated database to identify the primary signal. Based on the information, CR device would reconfigure its parameters and start transmission.

There are many challenges related to database management. The authenticity of the collection of information to the database and keeping this information consistent and up-to-date is critical for the successful use of databases. Another problem is an overhead cost involve creating, maintaining and updating of the database. The database management also includes security and privacy aspects. A protocol needs to be developed to access this database. This protocol should not be much complicated otherwise additional power and time would be required for accessing this database. This would further enhance overhead cost in CR system.



## 6.4 Energy Efficiency in Cognitive Radio Networks

Power control in SU network plays important factors in cognitive radio network. There are two main categories of power control in CR networks: a) centralized power control [99, 100], where a central manager controls the transmission power of all users within its coverage area; b) distributed power control [100, 101] where each user controls its transmission power by itself using only local information. However, since the interference temperature at the PU receiver cannot be identified by the local information, it is difficult that the QoS requirement for the PU is guaranteed in the distributed power control. In [101], the authors have proposed a fully autonomous distributed power control scheme without an additional process for CR networks where the constraint for the sum of the interference induced by all SUs in the network is replaced by a new constraint which limits the individual transmission power by making the strong assumption that the total interference constraint at the PU caused by all SUs is divided equally between SUs. As cognitive radio is in nascent stage, centralized control is easier to maintain. It has the advantage of easing the regulators control of spectrum usage, and to allow them to direct how the spectrum is used[102].

In communication system, performance can be measured in different ways. At the lowest level, bit error rate (BER) is basic criteria to measure the performance of a link. Another criteria is goodput or application level throughput which measures the amount of usable bits that received by the link[103]. These metrics provide an extremely low level and detailed view of the performance of a communications system. According to Shannon equation [104], goodput is related to bandwidth and transmitted power. In [105], a variable power and bandwidth efficient modulation strategy has been discussed. It has been shown that channel capacity can be enhanced by maximizing bandwidth efficiency, but this increases complexity of the system and overhead of the network. Another option is that if bandwidth is kept constant, goodput is dependent on transmitted power. High goodput means high transmit power though increment may not be linear. If we wish to minimize transmitted power, we have to compromise on goodput for a given bandwidth. A trade-off needs to be done depending upon the situation. With this view, we analysed a trade-off between transmit power and goodput in a centralized cognitive radio network from the aspect of energy efficiency.

We consider a spectrum-sharing model in which SUs are allowed to use the same spectrum licensed to a PU as long as the interference level at PU receiver is within a predefined level. We assume that  $N$  pairs of SU devices

(a transmitter and its corresponding receiver) distributed in an area away from PU receiver, and far away from PU transmitter so that interference due to PU transmitter at SUs receiver is negligible. The links between SUs network and between SUs & PU receiver are flat Rayleigh fading channels. In Rayleigh fading channels, the channel power gains are exponentially distributed, and have a mean value which depends on the distance between PU receiver & SUs transmitter and the distance between SUs transmitters & receivers. We further consider that channel state information between SUs receiver & transmitter and PU receiver & SUs transmitter are perfectly known to SUs through a central band manager, which mediates between primary and secondary users. We will use the following notations in the paper:  $g_{i,i}$  is channel gain between  $i^{th}$  SU transmitter and its corresponding receiver,  $g_{i,j}$  is channel gain between  $i^{th}$  SU transmitter and  $j^{th}$  SU receiver and  $g_{PU,i}$  is channel gain between  $i^{th}$  SU transmitter and PU receiver.  $P_i$  is peak transmit power from  $i^{th}$  SU and  $I_{max}$  is maximum predefined tolerable interference level at PU receiver.

A reliable implementation of a cognitive radio network depends not only on the maximum tolerable interference level at PU receiver, but also on SUs transmitted power which is determined by target SNR.

*Maximum interference level at primary receiver*

Since PU is a licensed user, its transmission should not be interfered by SUs. In particular, the total amount of interference caused by all active SUs must be lower than a predefined level denoted by  $I_{max}$ . Therefore, the QoS requirement for the primary receiver can be expressed as:

$$\sum_{i=1}^N g_{PU,i} P_i \leq I_{max} \quad (6.1)$$

where  $P_i$  is the power transmitted by the  $i^{th}$  SU transmitter and  $g_{PU,i}$  is the channel gain between primary receiver and  $i^{th}$  SU transmitter.

*Target SNIR for SUs*

Let us denote with  $\gamma_{th}$  the minimum required Signal-to-Noise plus Interference Ratio (SNIR) at the receiver for reliable communication of the  $SU_i$ . In other terms, if  $\gamma_i$  is the instantaneous received SNIR, the  $SU_i$  can communicate with the required reliability (often measured in terms of BER) if:

$$\gamma_i \geq \gamma_{th} \quad (6.2)$$

The instantaneous received SNIR of  $i^{th}$  SU receiver which is receiving the useful information from its corresponding transmitter can be written as:

$$\gamma_i = \frac{g_{i,i}(t)P_i(t)}{\sum_{j=1, j \neq i}^N g_{i,j}(t)P_j(t) + N_0B} \quad (6.3)$$

where  $N_0$  is the power spectral density of the AWGN noise and  $B$  is the received signal bandwidth. We assume that all SUs are transmitting with the same data rate.  $g_{i,i}$  is the channel gain between  $i^{th}$  transmitter and its corresponding receiver and  $g_{i,j}$  is the channel gain between  $j^{th}$  transmitter and  $i^{th}$  receiver.

Let us denote with  $P_{peak}$  the maximum transmit power for each SU.  $P_{peak}$  is fixed and depends on spectrum regulation and terminal capabilities. The power management strategies considered as full inverse power control(FIPC).

#### 6.4.1 Full inverse power control (FIPC)

This is conventional method of maintaining the desired signal strength (threshold level) at the receiver by inverting the channel power gain. In this method, SU transmits at the minimum power, needs to maintain the target SNR by inverting the channel power gain based on the channel estimates. If the total interference to the primary user is higher than the predefined threshold  $I_{max}$ , then some of SUs (with a priority given by the central band manager) are switched off. The FIPC can be described by the following:

$$P_i(t) \geq \frac{\gamma_{th}(\sum_{j=1, j \neq i}^N g_{i,j}(t)P_j(t) + N_0B)}{g_{i,i}(t)} \quad (6.4)$$

The condition given in Eq.(6.4) can be expressed as:

$$P_i \geq \gamma_{th} \left( \sum_{j=1, j \neq i}^N \frac{g_{i,j}P_j}{g_{i,i}} + \frac{N_0B}{g_{i,i}} \right) \quad (6.5)$$

Let vector  $\mathbf{P} = (P_1, P_2, \dots, P_N)^T$ , denotes the transmit powers of the users, Eq.6.5 can be rewritten with equality in the matrix form as follows

$$(\mathbf{I}-\mathbf{F})\mathbf{P}=\mathbf{U} \quad (6.6)$$

where  $\mathbf{I}$  is  $N \times N$  identity matrix and  $\mathbf{F}$  is  $N \times N$  and  $\mathbf{U}$  is  $N \times 1$  matrix. The  $\mathbf{F}$  and  $\mathbf{U}$  is given as following

$$\mathbf{F} = \begin{cases} \gamma_{th} \frac{g_{i,j}}{g_{i,i}} & i \neq j \\ 0 & j = i \end{cases} \quad (6.7)$$

$$\mathbf{U} = \gamma_{th} \frac{N_0 B}{g_{i,i}} \quad (6.8)$$

If the maximum eigenvalue of matrix  $\mathbf{F}$  is less than 1, there exist a non-negative  $\mathbf{P}$ , which satisfy the Eq. 6.5. The required threshold SNR is achievable with  $\mathbf{P}^* = (\mathbf{I} - \mathbf{F})^{-1} \mathbf{U}$  being the Pareto optimal solution and the system is feasible[101]. However, the SUs cannot increase their transmission power indefinitely, there must be an upper limit for SUs transmitted power as

$$0 \leq P_i \leq P_{max} \quad \text{for all } SUs \quad (6.9)$$

SU can make communication when their transmit power requirement satisfy Eq. (6.9).

### 6.4.2 Performance Metrics

The choice of the proper performance metric to measure the efficiency of the power management strategy in terms of average energy consumption requires some preliminary considerations. A definition of the energy efficiency is one used in [106],[107]. However, this definition is not very useful when transmission is not continuous in time. A better definition of energy efficiency for systems where transmission is not continuous can be described as average goodput over per unit average transmitted power. This can be given by the formula:

$$\eta = \frac{g_d}{P_{total}} \quad (6.10)$$

where  $P_{total}$  is the average total power transmit by SUs.

where  $P_{total}$  is average total power transmitted by SUs and  $g_d$  is average goodput produced by SUs. Goodput is number of bits successfully transmitted in one second by SUs. It can be written as follows:

$$g_d = \frac{r(t_1 + t_2 + \dots t_n)}{T} (1 - P_e) r \quad (6.11)$$

where  $r$  is data rate in bit/s;  $T$  is packet duration;  $P_e$  is Packet Error Rate (PER) and  $t_i$  is time interval in which  $i^{th}$  SU is transmitted during the time interval 'T'.

### 6.4.3 Result and Discussions

In this section, we assume that two fixed SUs are allowed to use the same spectrum licensed to a PU under spectrum-sharing model. For the simulation, we assume a packet length of 200 bits and a data rate of 100 Kbps BPSK transmission in 100 KHz bandwidth. At given transmit power, first preference will be given to both users. If it is not possible, preference will be given to the user, which transmits less power. If these two cases are not possible within given transmit power and interference constraint, both SUs will go off. We consider that both SUs are 400m apart and their proximity from PU receiver is 200m. The distance between secondary transmitter and receiver is 100m. The central band manager will provide channel state information to the SUs and also keep track of the interference level at PU receiver. When a SU enter into the network, SU will first exchange information with central band manager and after getting permission from the central band manager, SU can start their transmission.

The relationship between packet error rate (PER), probability error ( $p_e$ ), target SNR depends upon modulation/coding scheme and data rate. Assuming a binary phase-shift keying (BPSK) modulation scheme with  $N_p$  number of packets per second, the relationship among goodput and PER can be expressed as:

$$p_e = \frac{1}{2} \text{erfc}[\sqrt{SNR_{th}}] \quad (6.12)$$

$$PER = 1 - (1 - p_e)^{N_p} \quad (6.13)$$

where  $N_p = rT_c$

In cognitive radio network, two quality of service (QoS) requirement, i.e. threshold SNR in SUs network and maximum interference at PU receiver should be satisfied simultaneously. Under normal circumstances, efficiency decreases with increasing peak transmits power and after at a certain level, it becomes almost constant irrespective of increment in peak transmit power. The energy efficiency variation with peak transmit power at a different threshold SNR value is shown in figure 6.2. Energy efficiency is ratio of average goodput and peak power. This ratio is almost constant at different SNR as both variables, i.e. average goodput and peak transmit power increase simultaneously with lowering SNR.

At low peak transmit power, efficiency is high, but threshold SNR criteria is difficult to meet due to which average goodput is low. At high transmit peak power, participation of SUs becomes limited due to  $I_{max}$  criteria which

resulting almost constant efficiency. Therefore, the maximum interference level at PU receiver is a dominant constraint at high peak power.

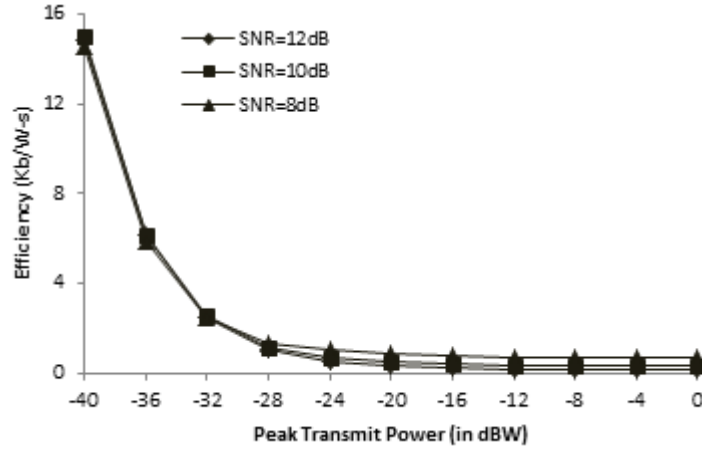


Figure 6.2: Energy efficiency Vs peak transmit power at  $I_{max}=-110\text{dBW}$

Selection of peak transmit power depends on what we need to achieve. At very high peak power, there is no significant variation in energy efficiency, and this restricts the participation of SUs. On the other hand, at low peak power, goodput is not significant even though energy efficiency is very high. Therefore, low and high peak transmit power may not be suitable in cognitive radio network.

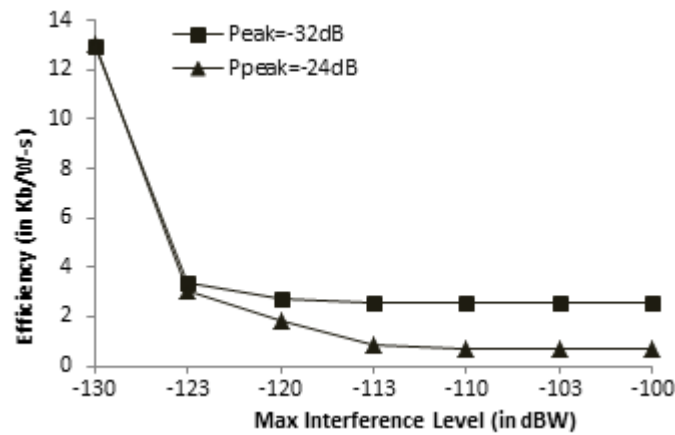


Figure 6.3: Energy efficiency Vs max interference level at different peak power and SNR=10dB

Energy efficiency at different interference level at two different peaks transmit power is shown in figure 6.3. At very high  $I_{max}$ , energy efficiency is

very high due to low peak power. As we decrease the value of  $I_{max}$ , energy efficiency decreases and attains almost a constant value. The situation will change only when we change peak transmit power.

Now we increase the number of SUs at a maximum peak power of -32dBW and 10 dB SNR. Variation in energy efficiency with respect to number of SUs at different interference level is shown in figure 6.4. It shows that energy efficiency increases with higher numbers of SUs at a given  $I_{max}$ . Energy efficiency is higher under strict interference conditions due to low peak transmit power. As we increase the number of SUs, channel occupancy increases which gives high energy efficiency and spectrum efficiency.

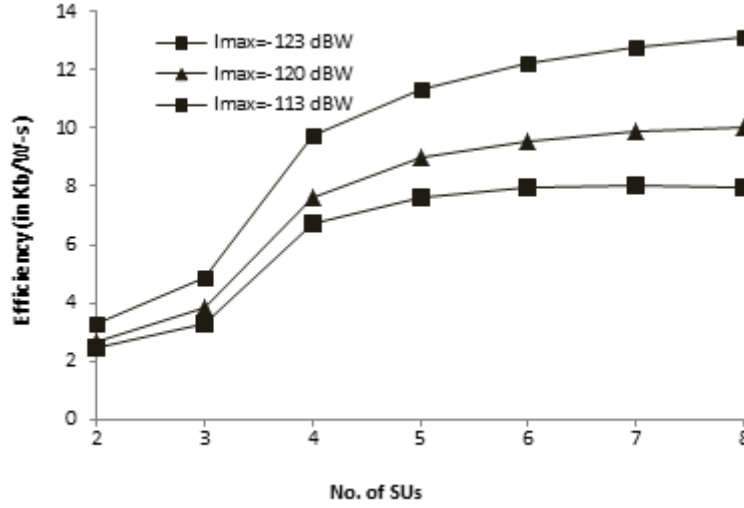


Figure 6.4: Energy efficiency Vs no. of SUs at different interference level peak transmit power=-32dBW and SNR=10dB

In the next scenario, we considered only two channels are available for SUs communications, i.e. only 2 SUs having lowest peak power can communicate at a time. Variation in energy efficiency with respect to number of SUs under unrestricted (more than 2 channels) and restricted (only two channels) channel conditions at -123dBW interference level (a bit strict condition) is shown in figure 6.5. Under strict interference conditions, energy efficiency is almost equal when number of SUs is less than 5, but when we increase no. of SUs beyond 5, energy efficiency goes on higher side in comparison to the situation, where there is no cap on the number of channels. This increment in energy efficiency under limited channel condition is more visible when interference condition is more relaxed. This can be seen in figure 6.6, where energy efficiency with respect to number of SUs at -110dBW interference

level is shown under similar condition. The difference in energy efficiency is clearly visible. It shows that channel utilization in terms of energy efficiency is higher when numbers of SUs are more than number of available channels. This also gives better spectrum utilization.

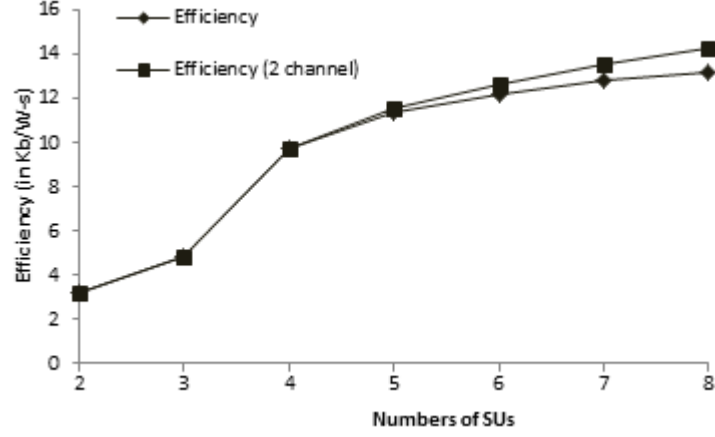


Figure 6.5: Comparison of energy efficiency in normal condition and two channel condition at  $I_{\max}=-123\text{dBW}$ , Peak transmit power= $-32\text{dBW}$  and  $\text{SNR}=10\text{dB}$

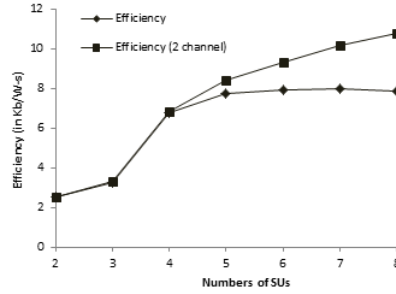


Figure 6.6: Comparison of energy efficiency in normal condition and two channel condition at  $I_{\max}=-110\text{dBW}$ , Peak transmit power= $-32\text{dBW}$  and  $\text{SNR}=10\text{dB}$

## 6.5 Deployment in Indian Secnario

An ideal CR device can work in any frequency band. Since, cognitive radio technology is in nascent stage, deployment of CR can be categorized into four different classes[108]. First category belongs to those assigned spectrum bands which are rarely utilized within a specific time and geographic



location. The second category belongs to spectrum bands allocated to predictable nature of fixed signals, such as television transmission where the spectrum appears to be fully utilized but time based opportunities are available for cognitive radio based system. The third category belongs to those spectral regions that are infrequently utilized, where the cognitive radio must be capable in detecting primary user transmissions when they occur, and also strong in ceasing transmissions immediately, or moving the transmissions to other unoccupied channel. Military and civilian government bands are examples of this class. The last category is those regions where the spectrum is relatively well-utilized, but still has some capacity available on time and location basis. In this case, the cognitive radio capabilities must be highly capable to insure that the radios do not interfere with primary spectrum users.

Presently no specific regulation has been made for use of CR technology in India. Research on cognitive radio is under progress. Therefore, deployment of CR needs to be band specific at the initial stage. The bands which have been allocated for Aeronautical services, GMDSS and safety services may not be opened for use of CR technology as CR applications may cause interference to these essential services. Use of CR devices may be permitted to those bands in which spectrum activity is low, location of base stations is known and receivers are robust against interference. Frequency bands allocated for broadcasting (FM & TV bands), Radar, amateur, radio paging, public mobile trunking etc. is the most prominent candidate for CR applications. Bands in which activity is very high e.g. GSM/CDMA band or working with very low signal strength like Satellite bands may not be suitable for cognitive radio. As per NFAP 2011[109], the following bands in India, already identified for IMT applications, can be utilised for cognitive radio application.

### **6.5.1 450-470 MHz**

This band provides good coverage and indoor penetration. As per NFAP 2011, this band has been reserved for fixed and mobile services. In this band requirement of IMT applications can be considered for coordination on a case by case basis subject to its availability. A part of this band has also been earmarked for public protection and disaster relief (PDPR) communications. Not many applications are present in this band. This band could be candidate for CR application.

### 6.5.2 TV band (700 MHz)

This band is good candidate for CR application due to excellent propagation characteristics. The band is widely used for broadcasting service. This band has been identified for IMT applications in WRC-07. Most of the countries e.g. USA, Canada, European Union have already made provisions for use of cognitive radio application in this band. As per NFAP 2011, frequency band 470-806 MHz has been earmarked for fixed, mobile and broadcasting services. The band can be divided into two parts.

The 470-698 MHz band has been primary allocated for broadcasting services on worldwide. This band has also been identified for IMT application by WRC-07. This is the most suitable band for cognitive radio application due to its good propagation properties for long-range communications, high penetration. Most of the countries e.g. USA, Canada, European Union have already made provisions for use of cognitive radio application in this band. As per NFAP 2011, this band has been earmarked for fixed, mobile and broadcasting services. This is a good candidate band for CR applications.

The second part is the frequency band 698-806 MHz has been earmarked for IMT and Broadband Wireless Access (BWA) services subject to co-ordination. A part of this band 746-806 MHz has also been reserved for public protection and disaster relief (PPDR) communications. Not much operation is reported in this band in [110]. IEEE 802.22 standard [86] for cognitive wireless regional area network (WRAN) air interface has been developed for fixed, point-to-multipoint WRAN's, which can operate on unused channels in the VHF/UHF TV bands. The use of IEEE 802.22 standard based WRAN has already been allowed in most of the countries. Equipment in the market is also available. This band is perfectly suitable for use of CR devices in India considering usage by existing services, robustness of the band in terms of penetration and sensitivity, availability of equipment etc.

The third part is beyond 806 MHz, use for PMRTS(806-824/851-869 MHz), CDMA(824-844/869-889 MHz) and GSM(890-915/935-960 MHz) services. Spectrum usage in GSM and CDMA band is relatively high whereas usage in PMRTS band is relatively low. Except PMRTS band, remaining portion of the band is difficult to utilise for CR application.

### 6.5.3 1700-2200 MHz

This band has been primarily earmarked for fixed and mobile services along with space research services. Frequency band 1710-1785/1805-1880 MHz is used for GSM mobile services. 3G services are also running in the frequency band 1920-1980/2110-2170 MHz. Deep space research operation

has also given place in the frequency bands 2110-2120 MHz (uplink) and 2290-2300 MHz (downlink). The remaining portion of this band is either lying vacant or utilised by the Government and captive users. Except 2G and 3G mobile services, usage is not very much convincing [110]. The entire band is suitable for CR technology with protection to 2G/3G services and deep space research services.

#### **6.5.4 2.3 - 2.4 GHz**

As per NFAP 2011, this band has been earmarked for fixed and mobile services for primary use. The requirement of IMT applications including BWA can also be considered in this band. This band can be utilised for CRS applications as now a day's unlicensed low power devices are working perfectly in adjacent band (2.4 GHz). However, primary services in adjacent bands allocated for Deep Space Research operations (frequency bands 2110-2120 MHz (uplink) and 2290-2300 MHz (downlink)) shall be protected from any interference due to CRS.

#### **6.5.5 De-Licensed Band**

Some of the bands have been delicensed for low power wireless technology[20] use is given below. In these bands, cognitive radio can be used in India.

1. Frequency band 2.4-2.4835 GHz: Maximum transmitter output power of 1 Watt ( 4 Watts Effective Radiated Power) with spectrum spread of 10 MHz or higher.
2. Frequency Band: 865-867 MHz: Maximum transmitter output power of 1 Watt ( 4 Watts Effective Radiated Power) and Carrier Bandwidth of 200 KHz.
3. Frequency Band: 5.150-5.350 GHz and 5.725 - 5.875 GHz: Maximum mean Effective Isotropic Radiated Power of 200mW, maximum mean Effective Isotropic Radiated Power density of 10mW/MHz in any 1 MHz bandwidth, Carrier Bandwidth: 1MHz.
4. Frequency Band: 5.825 to 5.875 GHz: Maximum transmitter output power of 1 Watt (4 Watts Effective Radiated Power) with spectrum spread of 10 MHz or higher.
5. Frequency Band: 26.957-27.283 MHz: Maximum Effective Radiated Power (ERP) of 5 Watts.

In addition to above, the following bands could also be utilised for cognitive radio applications. These bands are as good as de-licensed band. The applications in these bands are on the basis of non-interference, non-protection and non-exclusiveness.

- Frequency band 433-434 MHz with a power output of 10 mW with a channel bandwidth of 10 kHz.
- Frequency band 5725-5875 MHz: Maximum power of 100 Microwatts.
- Frequency band 5.725 to 5.825 GHz: Maximum transmitter output power of 1 Watt (4 Watts Effective Radiated Power) with spectrum spread of 10 MHz or higher.
- Frequency band 24.024.25 GHz: Maximum Effective Isotropic Radiated Power of 2Watts with spectrum spread of 50 MHz or higher.

## 6.6 Potential Applications

The cognitive radio has been permitted for the following two types of applications:

- Personal/portable devices with very small output power typically 100 mW for Wi-Fi cards etc.
- Fixed/access devices (point to multipoint) with higher transmits output power around 1W such as wireless broadband Internet access.

## 6.7 Technical and Regulatory Challenges

Implementation of cognitive radio is a challenge from technical and regulatory angles. Studies have been done for co-existence of CR technology with existing services in different bands under simulation environment but rather relying on simulation result, it would be appropriate to study impact of deployment of cognitive radio network in real environment. The experimental result would help to assess the practical difficulties in implementation of CR in real environment[111, 112].

Regulatory measures require to enhance the flexibility in accessing spectrum dynamically so that coexistence between different systems work

efficiently. Regulatory measure should not detect terms which are more technical in nature like choice of modulation, bandwidth etc. but transmit power needs to be controlled by regulator, otherwise interference between primary and secondary users would be difficult to manage. A sufficient protection should be given to primary users for maintaining QoS in their network. Therefore, regulatory constraints in respect of technical parameters should be kept to a minimum level. On the other hand, strict administrative and financial regulatory measures are required for unlicensed or lightly licensed (secondary) users like imposing heavy penalty for violating established rules.

Most of the spectrum assigned through command and control method for specific radiocommunication services with pre-defined usage. The first issue is to make allocation technology neutral. This has already been initiated in India while auctioning spectrum in the 900 MHz and 1800 MHz bands in which bidders were free to provide IMT services with any ITU approved technology. This neutrality is presently limited to IMT bands and access services only. Technical neutrality is required to be extended its coverage to other bands also. Spectrum is needed to be assigned not only on technical neutrality but also on service neutrality so that true spirit of cognitive radio system i.e. '*any radio services in any frequency band*' could be deployed

The primary holder purchases spectrum at a very high cost through open auction or administrative determined price. Primary users may not like to share its spectrum with other users. Some incentive must be given to primary users for sharing spectrum with secondary users. This would also maintain equilibrium when both the operators (primary and secondary) are providing the same services.

Devices working in unlicensed spectrum are having cognitive property to some extent. Allocation of unlicensed spectrum should be increased both nationally and internationally. Unlicensed spectrum is ideal for cognitive radio to carry out experiments in real environment, which help to make the CR system more efficient.

Therefore, a well-defined regulatory framework is required to be developed considering adequate protection to existing primary services operating in the frequency band. The regulatory framework should consist the following;

- Identification of frequency bands for CR application
- Monitoring of spectrum usage in the identified band
- Creation of database and its periodic updation
- Framing rule for operation including maximum permissible transmit power

- Permissible radio access technology
- Administrative charges, if applicable
- Interference Management

Cognitive radio has so far not entered in India but Indian administration is in the process to open the way for cognitive radio network envisaging the following steps in National Telecom Policy 2012[77] as given below:

- To make liberalised use of spectrum in any band to provide any service in any technology
- To permit spectrum pooling, sharing and later, trading to enhance optimal utilisation of spectrum
- To reform spectrum time to time to make spectrum available for introduction of new services
- To make available adequate globally harmonised spectrum for IMT services
- To identify additional frequency bands for exemption of licensing requirements for low power devices
- To consider requirement of spectrum for indigenous development of technologies/ products and their deployment
- To promote use of white spaces for deployment of Software Defined Radios (SDRs), Cognitive Radios (CRs) , etc

## 6.8 Conclusions

Cognitive radio is a key technology for the next generation. For exploiting full advantage of CR, the regulator has to allow accessing of the radio spectrum dynamically. This would help to meet the future spectrum demand as projected by the ITU. However, implementation of DSA is not an easy task. There are several issues, which need to be resolved before implementing DSA. After all, considering the technology, legal, and policy perspectives, the dynamic spectrum policy, which supports innovation, efficiency, and higher feasibility, may be the best candidate in the near future.

We have presented energy efficiency in cognitive radio networks for multiple SUs under the centralized power allocation scheme. Simulation results shows that average energy efficiency is high at low peak transmit power with low goodput. Therefore, a slightly higher peak transmit power is better because goodput and energy efficiency both are moderate, and data transfer can be done effectively. This also provides more SUs participation and better spectrum utilization. Energy efficiency and spectrum utilization can further be enhanced when numbers of SUs are more than available channels. However, there is a disadvantage that data transmission by SUs may not be continuous due to limited number of availability of channels. Therefore, delay is inevitable in SUs transmission under such a condition. This scenario is suitable for applications, like WLAN where continuous data transfer may not be required whereas the applications, like voice communication may not be suitable for such a scenario. The energy efficiency can be further increased by a tradeoff between peak power, SNR and bandwidth. A field approach to such scenario would be more interesting and could be the subject to further research work.

## Chapter 7

# Spectrum Bands for 5G Communications



## 7.1 Introduction

Advancement in mobile communication has made peoples life easy, whether it is ordering a pizza, accessing internet, searching an address in a city or connecting with others via social networking site. Essential services such as e-commerce, e-banking, e-governance, e-health etc. will continue expanding their coverage and heading towards more mobility. These expansions will lead to need for enormous wireless traffic in future. Ericsson has predicted that the wireless traffic would be increased by 1000 times in 2020 than seen in 2010. This traffic is primarily driven by increased usage of mobile multi-media services[113]. Today's wireless traffic is largely contributed by human centric applications. Machine centric traffic will contribute equally (or even more than human centric) in future as there is a forecast of approximately 50 billion connected devices by 2020[114]. The combination of human and machine centric applications will diversify the landscape of the telecom industry in terms of size, cost, energy dissipation and services. Machine centric applications require data delivery of high reliability, and on the other side human centric applications require data delivery at high speed and always connected. Therefore, the next generation of mobile communication will be moving towards to a future state of *"everything everywhere and always connected with reliability"*[115].

The mobile communications started with 1st generation in 80s for voice communication. With the time, more and more services would have converge and generations of mobile communications has also changed from 1G to 4G. The existing 4th generation mobile communications (also known as IMT-A [International Mobile Telecommunications-Advanced])[116] is all IP based network with packet switched delivery for efficiently meeting the needs of the future generation networks with high data rates of 100 Mbps (high mobility)/1Gbps (low mobility). Various networks such as the wired (PSTN - Public Switched Telephone Networks), LAN (Local Area Networks), IP based mobile network, cellular (2G/3G), WiMAX (Worldwide Interoperability for Microwave Access), nomadic, ad-hoc and sensor networks are able to communicate with the core network. The 4G network is fulfilling the present demands. However, the needs for high throughput will continue to increase in future wireless networks due to high bandwidth demanding applications such as entertainment, multimedia, Intelligent Transport Systems (ITS), telemedicine, emergency, safety/security applications and other futuristic applications. These applications will push the demand for real-time, symmetric, wireless ubiquitous connectivity to an individual with a data rate that far exceeds the capacity offered by the current 4G network [117].

A decade back, almost all of the revenue from mobile telecom services was generated by voice services and SMS. The transition to 3G/4G networks has greatly expanded the functionality of mobile services. Presently, user is spending time to access internet services and using smartphone applications. The revenue from mobile services has also increased manifolds. A number of economic studies have been undertaken to examine the impact of telecommunications on measures of economic performance, including economic growth, employment, and consumer welfare. Study conducted in [118], found that mobiles use of spectrum currently contributes 269 billion to the economies of the EU's 27 Member States and it is far more than any other use of spectrum. The study further found that the economic value of spectrum for mobile services will increase dramatically over the next 10 years, while many other applications will see far lower rates of growth or even declines in value and estimates that the economic value of spectrum used for mobile could grow to 477 billion by 2023. Study conducted in [119] found that in the UK, the economic value of spectrum use has increased by 25% in real terms since 2006 to EUR62 billion in 2011. The public mobile communications sector accounts for nearly 60% of this value and anticipated that the economic value would further increase to EUR 580 billion by 2021. The study also found that the public mobile communications sector supports a supply chain of infrastructure, equipment, applications and content providers, generating annual revenue of around EUR24 billion and supporting 75 000 jobs. In the USA, [120] estimate the introduction of broadband causes per capita income to increase by 2.7 to 3.9 percent, on average during 1996-2007. Moreover, they find that higher levels of broadband penetration result in faster growth in per capita income. In particular, a 10 percentage point increase in broadband penetration raises the growth rate of per capita income by 0.9 to 1.5 percentage points. [121] estimate that the reassignment of 300 MHz of spectrum to mobile broadband will lead to \$75 billion in new investment, 300,000 new jobs, and \$230 billion in additional GDP, within five years.

The increasing use of smartphones over existing 3G and 4G network, extensive usage of Wi-Fi network and the growth of device to device (D2D) and machine to machine (M2M) communications are predicted to drive the economic value of mobile use. The high economic value of mobile services emphasise the importance of 24/7 connectivity at high speed in consumers lives and underlines the importance of ubiquitous connectivity conceptualised under 5G network. The growth of 5G network would drive substantial economic benefits, by serving as a platform for new innovation in many areas of public and commercial importance and benefits will likely lead to increased investment, faster economic growth, and new jobs. The vision of a 5G wireless communication system is one of universally deployable converging technolo-

gies that will enable wireless services and applications at a data rate of more than one terabit per second (Tbit/s), with coverage extending from a city, to a country, to the continents and to the world, that will enable user-centric mega-communications[12].

Radio spectrum is a prime factor in driving the growth of mobile services. The success of 5G network is based on the unconstrained availability of spectrum. About 1200 MHz of spectrum in the frequency bands below 5GHz has been identified for IMT services during World Administrative Radio Conference (WARC)-92, World Radiocommunication Conference (WRC) -2000 and WRC-2007. These frequency bands are 450-470 MHz, 698-960 MHz, 1710-2025 MHz, 2110-2200 MHz, 2300-2400 MHz, 2500-2690 MHz, and 3400-3600 MHz[49]. The identified spectrum is non-contiguous and scattered in different frequency bands from 450 MHz to 3.4 GHz. However, the actual allocation is ranging between the frequency band 700 MHz to 2.6 GHz. The spectrum available for cellular mobile services does not exceed a total of 780 MHz, and an operator has approximately 200 MHz spectrum across all IMT bands for providing telecom services with different access technologies from GSM to LTE [17]. However, 1200 MHz non-contiguous spectrum would not hold the pressure of high mobile data growth, demand for convergence of different varieties of services and speed. Therefore, more spectrum bands would needs to be explored during next session of WRC.

## 7.2 Concept of 5G Network

The 4G network offers convergence of heterogeneous wireless network of different access technologies and wireless networks and has the ability to connect anywhere and anytime. The future network will be the extension of the existing 4G network. The 5G wireless network will have capabilities for supporting high capacity and massive connectivity for an increasingly diverse set of services, application and users, and flexible and efficient use of all available contiguous/non-contiguous, licensed/unlicensed spectrum. Convergence of technologies, ultra-high capacity, universal coverage, minimum energy usage and cost-efficiency are key characteristics of the 5G wireless system concept. At the core of 5G applications are M2M communications enabled by technological breakthroughs in a plethora of scientific areas, wireless and wired communications, artificial intelligence, Internet, robotics and space[12].

Currently, operators are providing services using multiple RATs (2G, 3G, WiMAX, LTE, WLAN, Bluetooth and other emerging access technologies, etc.). For example, operators rely on unlicensed Wi-Fi network to of-

flood traffic demand at hot-spots. Devices are equipped with multiple RATs like cellular, Wi-Fi and Bluetooth to connect the peripheral devices and internet. The 5G network should have the capability to integrate multiple radio access technologies seamlessly and to choose suitable one among them, and to switch over between various access technologies, combine different streams coming from different technologies during a session to meet capacity demands[11].

The constant decrease in cell size enhances the cell capacity, spectral efficiency by exploiting spatial reuse and brings the communication services closer to the user [122]. The small cell with low transmit power provides flexibility in managing high data traffic hot spots. The future 5G network will have a relatively large number of small cell sites with different cell size from macro to femto and with low transmit power to meet the high traffic demand. The low-powered small cell sites will use to enhance the capacity whereas macro cells will use to enhance the coverage. The 5G networks offer multiple options in respect of transmit power, coverage, capacity, spectrum usage and choice of RATs, and move towards cost reduction, green energy and better resource utilisation.

The network would also create a dynamic environment to cover D2D and M2M communications so that such communication takes place directly between user equipment or between machines (in the context of Internet of Thing) without use of base stations or core network[122]l efficiency, cellular coverage and reduce end-to-end latency and power consumption.

Therefore, the 5G network would be an integrated wireline/wireless network, where the wireless part comprises a dense network of small cells with capacity enhanced through high-order spatial multiplexing (MIMO), cell data rates of the order of 10 Gbps and round-trip latency of 1 ms. With these attributes, the combined network will support everything from simple M2M devices to immersive virtual reality streaming, with monitoring and control of literally billions of sensors and multiple simultaneous streaming services, and will support the massive data collection and distribution needs of the Internet of Things (IOT)[115]. There are three main aspects to realizing 5G communication systems (figure 7.1)[12].

**Enabling 5G intelligent core:** Intelligent core will be soul of the 5G network. M2M and IoT are key for realizing the intelligent core which provides seamless ubiquitous networking and connectivity in 5G network.

**Enabling ubiquitous connectivity:** Ubiquitous connectivity will be for coverage under high mobility and data rates, and to moving application from device to device without any content interruption. Use of millimetre wave links, high-order spatial multiplexing (MIMO) antenna, virtualization, small cell deployments and novel spectrum usage methods, are some of the

key for ubiquitous connectivity.

**Enabling Ubiquitous networking:** The ubiquitous networking will provide the same quality of services to end users regardless of how many access networks and spectrum bands are integrated for connectivity purposes.

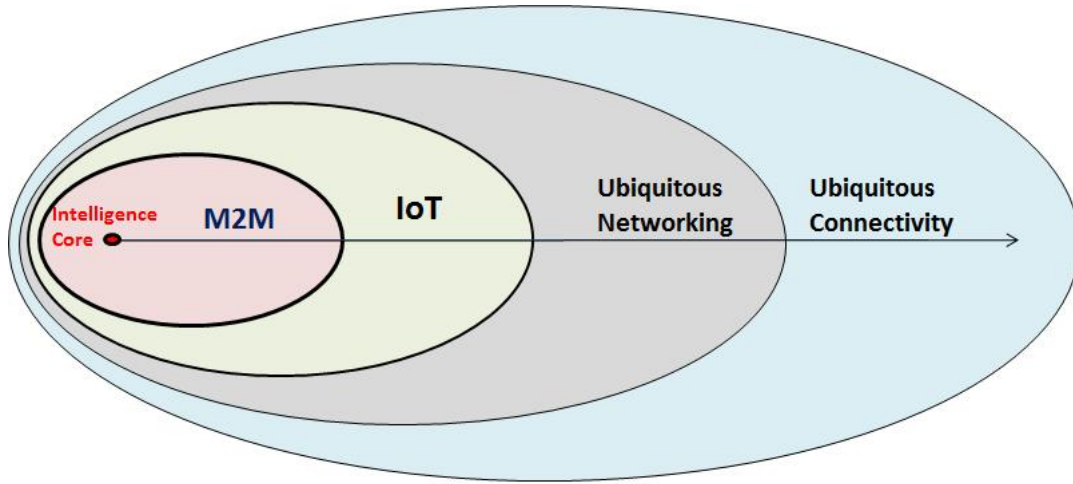


Figure 7.1: Concept of 5G network [12]

The 5G network is conceptualized as a multi-layers heterogeneous network. Primary layer will be a macro layer which responsible for ubiquitous connectivity. Secondary layers, embedded in the primary layer, will be a combination of small cells (micro, pico and femto) to provide additional capacity to end users. This additional capacity will be in the form of extra spectrum on the same carrier, different access technology or additional stream on different carrier. The network will be controlled by an intelligent unit WISDOM[[123, 12, 11, 124]]. The function of multilayer network is conceived as initially, a user will be connected to the primary layer. When data requirements go beyond the primary layer network capacity after providing the additional spectrum (if available) and change in radio access technology available within the primary layer, the user will also get connected to the nearest secondary layer through the WISDOM network. This has been depicted in the figure 7.2, where three users A, B and C have been shown. The requirements of the user A and B is beyond the capacity of primary layer, they have also been connected to secondary layers whereas the user C requirement is within the capacity of primary layer.

With the above mentioned features, a slight modification in 4G networks could make it best candidate for 5G network. Based on this assumption, the concept of 5G has been introduced as integration of 4G with WIS-

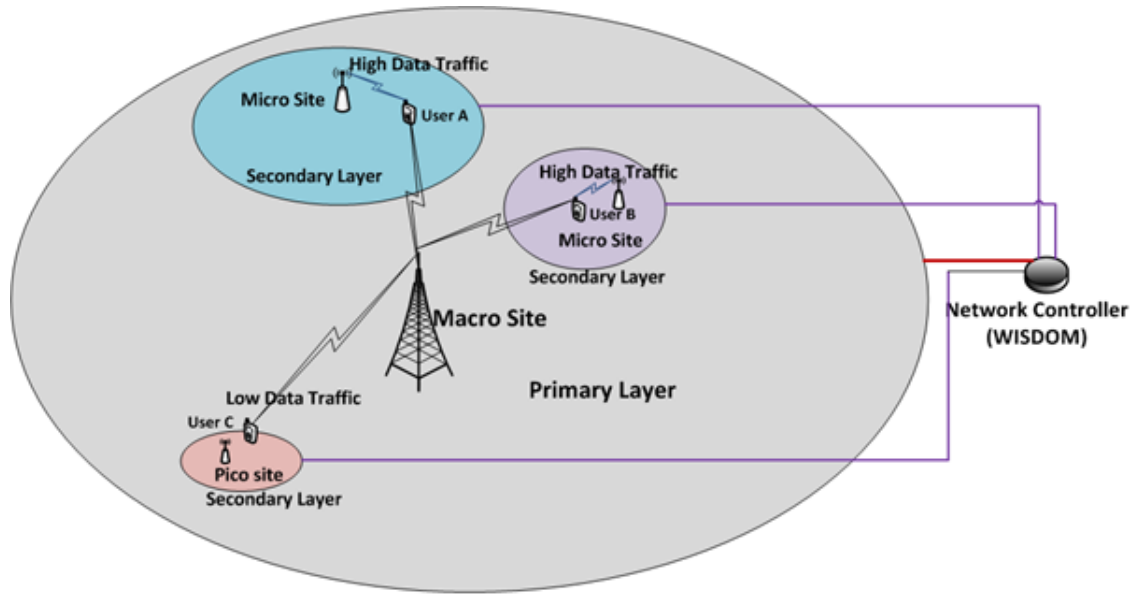


Figure 7.2: 5G Network consist of primary and secondary layer

DOM as given below [12],[11]:

$$4G\&WISDOM \implies 5G \quad (7.1)$$

The Wireless Innovative System for Dynamic Operating Mega Communications (WISDOM) is a communication system for ubiquitous trustworthy human-centric connectivity via an arbitrary infrastructure support. The WISDOM, as shown in figure 7.3, principle brings unlimited wireless world interconnection, convergence, and cooperation (geographically including cities, countries, continents, and finally, the whole world), together with a large variety of multimedia services at very high data rates, and becomes the main 5G definition point. The three founding pillars of WISDOM are[11]:

- An information theoretic performance/capacity estimation of different types of networking paradigms
- Design of protocols based on end-to-end, cross-layer and cross-network-domain performance optimization
- Cognitive radio network based self-organising networks for management of possible usage scenarios and to minimize the spectrum and energy requirements.

WISDOM aims to design and develop technologies, system that could globally integrate, interconnect and communicate into a flexible and dynamic system for the human-centric and machine centric communications in 2020 and beyond [123]. The operational domain of WISDOM concept require a well-defined network protocols, architecture for heterogeneous network, integration between different kinds of terrestrial and satellite network to provide applications in every walks of human life and to provide upto 1Tbps link rate at short distance or as system aggregate operating in burst mode and at least 250 Mbps to the end user for real time applications with coverage extending from a city, to a country, the continent and the world (figure 7.4). The WISDOM concept will lead wireless communications beyond the currently emerging technologies and towards the realization of that new paradigm, based on the combination of five independent elements, Communication, Connectivity, Convergence, Content and Cooperation [11].

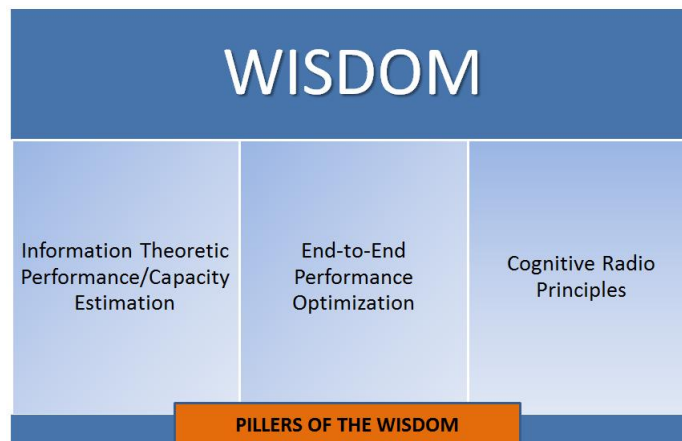


Figure 7.3: WISDOM principle [11]

The cognitive radio (CR) [18], [112] is the driving force in the WISDOM for intelligence quotient. The cognitive radio is 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. The main objective of CR is to provide reliable communication whenever and wherever needed. CR network is a self-organizing network, which change the network parameters in accordance with user preference. In indoor environment, it will connect with some Wi-Fi enabled femto cell for high speed data requirements and in outdoor environment, it will connect with some macro or micro cells for

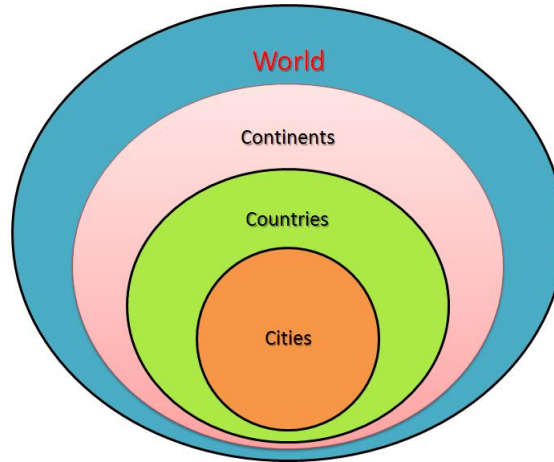


Figure 7.4: Global connectivity through WISDOM

uninterrupted connectivity. Whenever, user moves from indoor to outdoor and vice-versa, CR change its operating parameters instantly to meet the users requirements. Like 5G network, CR has the ability to work with heterogeneous networks, different RATs and spectrum bands to meet the end user demands. The CR technology in WISDOM facilitates decisions related to cell configuration, traffic distribution to the cell, suitable radio access technology along with spectrum band, bandwidth and transmit power to the transceiver to manage end users requirements[124].

### 7.3 Spectrum for 5G services

The network capacity depends on the number of base stations, radio access technology and frequency bandwidth. The 5G network will have several short range cell base stations for capacity boosting, which works alongside macro cells. The spectrum requirements for macro cell and short range cells are different. Macro cells will be for ubiquitous connectivity, and small cells will be for capacity booster[122]. Low frequency waves are suitable for macro cells due to its wide coverage and better penetration, and high frequency waves are suitable for booster cells due to large data carrying capacity. Therefore, spectrum requirements for the 5G networks could be divided into two different categories, low and high frequency waves.



### 7.3.1 Candidate Frequency Bands for 5G services

#### (a) Lower Spectrum Bands: 400 MHz to 6 GHz bands

As stated above, approximately 1200 MHz of spectrum has been identified for IMT-A services in the different frequency bands below 5GHz[116]. These frequency bands are suitable for macro cell sites due to better propagation and penetration properties. If we look at the frequency allocation table, almost 50% of the total spectrum between 300 MHz to 6 GHz has been earmarked for mobile services as primary services. It means that this 50% of the total spectrum can be utilized for mobile services alone or in sharing with other primary services. The frequency bands below 6 GHz have already been allocated to legacy services long back. Therefore, no vacant spectrum is available below 6 GHz at present. The two options are available to enhance the spectrum availability for 5G communications; spectrum re-farming and spectrum sharing.

The spectrum re-farming is basically allowing existing license holders to utilise the allocated spectrum for some other purpose or migration of license holders from the existing band to some other band and reuse of the current band for other radio services. For example, re-farming of 900 MHz or 1800 MHz band, which was earlier allotted for 2G GSM services, is now being replaced by 3G or 4G network. Another example is vacation of spectrum in the 700 MHz band by broadcasting services due to digital switch over. Re-farming is a cumbersome process involves lots of persuasion to existing operators for migration and invites additional expenditure in migration.

Spectrum sharing is another option, where two or more than two operators share the same spectrum in frequency, time and geographic dimensions for providing same or different services. For example, there are several services, which use spectrum for a certain period of time or at certain locations. Such spectrum could be considered vacant, during the period or at the locations, where existing licensed operator is not using and the same could be utilised by mobile operators to provide IMT services. This type of sharing is known as static spectrum sharing. Another possibility is the dynamic spectrum access (DSA)[10] that allows to access spectrum in opportunistic manners. CR is the basic tool for exploiting DSA. The CR enabled system sense the vacant spectrum and operates from the vacant spot, and retreat occupied spectrum on arrival of the primary user. A big chunk of already identified 1200 MHz spectrum has not yet been freed for IMT services worldwide. If we allow DSA, the spectrum crunch for the 5G network in lower bands would get resolved without doing large scale spectrum re-farming.

**(b) Millimeters-Waves**

The spectrum bands identified under the IMT umbrella do not have the capacity to carry such enormous data which required for 5G services. Therefore, mm-waves could be the candidate bands for 5G mobile communications especially for second layer network due to high data carrying capacity. The mm-waves have the following advantages[125]:

1. Not much operation at mm-waves so more spectrum is available at these frequencies.
2. Very large blocks of contiguous spectrum to support future applications.
3. Due to high attenuation in free space, frequency reuse is possible at shorter distance
4. Spatial resolution is better at mm-waves hardware with CMOS technology
5. Advancement in semiconductor technology allow low cost
6. Small size of antenna at mm-waves facilitates easy integration on chip and installation at suitable locations.
7. Small wave-length makes possible use of large antenna arrays for adaptive beam forming

Millimeter waves allow larger bandwidth and offer high data transfer and low latency rate that are suitable for high speed reliable internet services. The small wavelength facilitates small size antenna and other part of radio hardware, which reduces costs and also easy to install. The transmitters antenna would be like a lamppost, which could be installed on building, street lamppost, etc.

The traditional uses of the mm-waves include radio navigation, space research, radio astronomy, earth exploration satellite, radar, military weapons and other applications. The backbone/backhaul networks (point to point network) for existing telecom network to connect base station to main switching centre (MSC), Local Multipoint Distribution System (LMDS), indoor WLAN, high capacity dense networks are also present in the mm-waves. The typical microwave backhaul bands are at 6.0 GHz, 11.0 GHz, 18.0 GHz, 23.0 GHz, and 38.0 GHz frequency bands.

The light use of mm-waves could be attributed to high attenuation and low penetration. At such high frequency, waves are more prone to rain and

other atmospheric attenuation. The wavelength is in the order of millimeters, and rain drops are also of the same size. Rains absorb high frequency waves and make it difficult for propagation. However, the experimental results show that in heavy rain condition, attenuation is 1.4 dB and 1.6 dB for 200 meters distance at 28 GHz and 38 GHz respectively [17]. A proper link design with slight high transmit power may take care of rain attenuation.

Wavelength at such high frequencies is in the range of millimetres. Any slight change in the position would affect the signal strength at the receiving end, due to which mm-waves are deeply affected by scattering, reflection and refraction. The r.m.s. delay spread for mm-wave is of the order of few nano seconds, and it is high for non-line of sight (NLOS) links than line of sight (LOS) links[17]. Similarly, path loss exponent for NLOS links is higher than LOS links. Due to higher path loss and r.m.s delay spread, it is assumed that mm-waves are not suitable for non-line of sight (NLOS) links. However, these difficulties could be managed by using carrier aggregation, high order MIMO, steerable antenna, beamforming techniques. Propagation feasibility studies for mm waves have been carried out at research institutes, and concluded that propagation is feasible upto 200 meters of distance [17, 109, 125, 126] in both the conditions i.e. line of sight (LOS) and non-line of sight (NLOS) with transmit power of the order of 40-50dBm in a difficult urban environment. The cell size in dense urban areas normally varies between 100 meters to 300 meters. Therefore, mobile cellular is possible at mm-waves.

The Radiocommunication Sector of International Telecom Union (ITU) is responsible for management of radio spectrum at international level. As per ITU-R frequency allocation plan [127], the frequency band 10-40 GHz has been earmarked for satellite based services in all the three regions along with Fixed and mobile services. Local Multipoint Distribution System (LMDS), WLAN, Satellite services and High capacity dense network etc. are main services present in mm-waves. The allocation against these services has been shown in figure 5. Several point to point fixed microwaves links are also working in this band. These links are basically for backbone/backhaul network for GSM and other services. A good amount of vacant spectrum is available at mm-waves which could be utilised for 5G communications services. 5G services may transmit high power approximately 40-50 dBW. Therefore, coexistence study needs to be carried out with existing LMDS and satellite services, which working in neighbouring spectrum bands. The analysis of the allocations made in mm-waves is given in figure 7.5.

#### **(i) Frequency Band 10-20 GHz**

As per ITU frequency allocation plan [127], the entire band has been earmarked for satellite based services in all the three regions along with

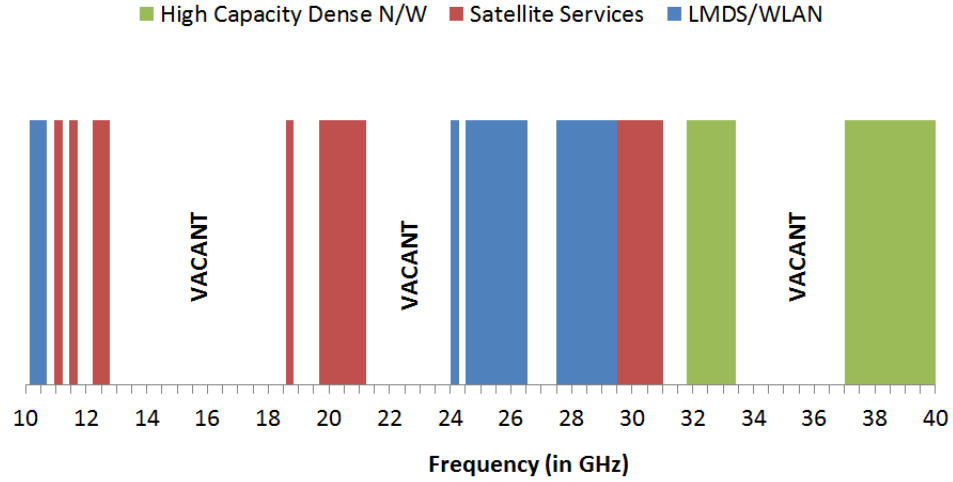


Figure 7.5: Spectrum allocation in mm-waves to various services

Fixed and mobile services. Approximately 4.5 GHz of spectrum, which is common in all the three regions, has been earmarked for mobile services as primary services along with other primary services. Almost 80% of spectrum has also been allocated for mobile services. Several point to point fixed microwave links are also working in this band. These networks are basically for backbone/backhaul services for other network like GSM services. Local Multipoint Distribution System (LMDS) has also been present in this band. The LMDS is considered as a Broadband Wireless Access (BWA) services. LMDS is a fixed wireless, point-to-multipoint technology for utilization in the last mile. Initially, the bands identified for LMDS can be utilized for 5G services on experimental basis. Therefore, a common allocation of spectrum for 5G services could be made easily.

### (ii) Frequency Band 20-30 GHz

As per ITU allocation[127], this band has also been earmarked for satellite services in all the three regions alongwith Fixed and Mobile services. About 65% part of this has also been earmarked for mobile services common to all regions. This band is highly popular for LMDS services worldwide. In the United States, LMDS services are operating from 28-30 GHz frequency band to deliver broadband services in point to point and point to multipoint system to residential and commercial users [126].

### (iii) Frequency Band 30-60 GHz

Beyond 30 GHz and upto 60 GHz spectrum could also be utilised for 5G network. There are several applications like Zigbee, WiGig WLAN (IEEE802.11AD), WirelessHD and UWB are successfully working in unlicensed spectrum at 60 GHz frequency band[26]. As per ITU allocation[127], the allocations between 30 to 60 GHz are common for all the three regions. The band is mainly utilised for space research and indoor wireless equipment. An allocation of 12.0 GHz spectrum between 30-40 GHz has been assigned in all the three regions for high capacity dense network. Such high frequency would be good for pico and femto cells. This band could also be utilised for backhaul services using high directional antenna.

### 7.3.2 ITU Initiatives for 5G Network

After successful implementation of the IMT-Advanced standards, ITU-R is looking beyond IMT-A[116]. The pre-standardisation activities regarding 5G network started by the working party 5D of ITU-R Study Group 5[128], which is studying the following two documents in the context of 5G network. These two documents will establish the standard for 5G network.

**(a) IMT.VISION document**[128]: "Framework and overall objectives of the future development of IMT for 2020 and beyond"

The document is being prepared with the objective of defining the framework and overall objectives of IMT for 2020 and beyond to drive the future developments for IMT. It will be based on the global market, technology and spectrum trends, including user demand for mobile broadband communication services, new service applications and the needs of developing countries. The study is scheduled to be completed by July 2015 and the final draft will be discussed and approved during WRC 2015.

**(b) IMT.FUTURE TECHNOLOGY TRENDS Document**[128]:

The document is being prepared with the objective to provide a view of future IMT technology aspects 2015-2020 and beyond and to provide information on trends of future IMT technology aspects. The study will cover future technologies on the aspects of efficient usage of frequency, energy efficiency, wider coverage, and ease deployment and network coverage etc. The study will be completed by October 2014.

**(c) WRC 15 Agenda Item No. 1.1**[50]:

ITU has also set an agenda item for WRC-15 to identify additional spectrum for IMT services. The agenda item 1.1 of WRC 15 states that "to consider additional spectrum allocations to the mobile service on a pri-

mary basis and identification of additional frequency bands for International Mobile Telecommunications (IMT) and related regulatory provisions, to facilitate the development of terrestrial mobile broadband applications, in accordance with Resolution 233 [COM6/8] (WRC 12)”;

ITU-R has constituted the Joint Task Group JTG 4-5-6-7 for execution of for the WRC-15 Agenda Items 1.1. The JTG 4-5-6-7 is responsible for the development of draft CPM text under WRC 15 Agenda items 1.1 based on the results of studies on the spectrum requirements for the mobile service, including suitable frequency ranges, and other specific requirements as well as results of studies from any concerned Working Parties on technical and operational characteristics, spectrum requirements and performance objectives or protection requirements of other services. The frequency bands under consideration are: 470-698 MHz, 1300-1400 MHz, 1427-1 527 MHz, 1695-1700 MHz, 2025-2110 MHz, 2200-2290 MHz, 2700-3100 MHz, 3400-4200 MHz, 4400-5 000 MHz, 5350-5 470 MHz and 5725-6425 MHz. Some of them will be finalised during WRC-15 and thereafter will be earmarked for IMT-A services.

### 7.3.3 Timeline for implementation of 5G

A road map for the development of the 5G network as shown in figure 7.6 comprises research activities, identification of additional spectrum bands, standardisation activities relating to market, services, and technology aspects before commencement of commercialisation of the 5G network. The process started from WRC-12 with identification of radio access technologies LTE-advanced and WiMAX (802.16m) for 4G network. Agenda for making available additional spectrum for 5G network has been set for WRC-15. 5G standard is expected to be discussed in WRC-15. Thereafter, standardisation activities will be started and to be taken up during WRC-18/19. Finally, the 5G network will be available for commercial utilisation in 2020 time frame[129].



Figure 7.6: : Timeline for implementation of 5G

## 7.4 Conclusions

In this chapter we discussed frequency bands for 5G mobile communications services. Lower band is suitable for the primary layer due to better propagation characteristics. Exclusive spectrum below 6 GHz is not available. The availability can be increased through spectrum sharing as primary and secondary user concept. The Millimetres waves are most suitable candidate bands for secondary layer of 5G network. Analysis of candidate bands shows that sufficient spectrum is available, which could be allocated for the 5G services. However, extensive co-existence study with existing usage is required to be carried out for making provision for the 5G communications services.

## Chapter 8

# Conclusions and Outlook



## 8.1 Reflections

Radio spectrum is a natural scarce but renewable resource. Unlike other natural resources, radio frequency spectrum is not consumed upon its usage. Radio spectrum is not very easy to manage due to its physical characteristics. So far we are able to exploit only upto 50 GHz (on maximum side). Within this range, 41 radiocommunication services have been accommodated. Telecommunications has played a very significant role to make radio spectrum valuable and to acquire omnipresence status. There are the examples that administrator earned a lot of revenue by auctioning a small chunk of radio spectrum for telecom services.

The mobile telecom service was started for voice delivery in 80s. With the passage of time, services get converged and revenue from mobile telecom services has also increased manyfold than that was in 80's. Convergence of services require additional spectrum. Now, we are looking towards 5th generation of mobile communications, which envisages to provide applications with a speed upto 1Tbps link rate. To realise 5th generation concept, we need additional spectrum. ITU has presently identified approximately 1200 MHz spectrum for telecom services, which is the highest amount of spectrum allocated to any radiocommunication services. However, this identified spectrum is not sufficient to cater the 5G concept, even it is unable to meet the demands of existing telecom services. Considering the gravity of situation, radiocommunication sector of ITU has constituted a separate joint task group JTG 4-5-6-7 to study the spectrum requirements for the mobile service including suitable additional frequency ranges and other specific requirements. The study result will be presented in WRC 2015. Finally, WRC 2015 will decide additional spectrum bands for telecom services. The irony is that the already identified spectrum band has been occupied by the incumbents. However, it is difficult to make available these spectrum bands for telecom services as vacating involves a huge expenditure in shifting of users from the identified bands. Therefore, identifying additional spectrum bands for telecom services may not yield any substantial result. There is a ray of light that spectrum occupancy studies show that spectrum utilisation by the existing users is not significant. Vacant spectrum chunks are available on time and location basis in the already occupied spectrum bands, even in the bands assigned for telecom services. This vacant spectrum can be utilised for further expansion and offloading of spectrum crunch for telecom services.

## 8.2 Concluding Remarks

Considering the above facts, some measures for efficient management of spectrum especially for telecom sector has been discussed in the thesis. A brief revisit of what each main chapter was all about is provided here.

Chapter 2 provided a depth analysis of radio spectrum management at different levels i.e. international, regional and national level. ITU is the international organisation which is responsible for radio spectrum management at international level. A brief functioning of ITU has also been presented in this chapter.

Chapter 3 provided an overview of existing command and control method of spectrum management and justified that the existing method of assignment of spectrum for commercial services is inefficient. With existing method, it is possible that spectrum remains lying vacant at a location and time. To manage this inefficiency, the chapter presented a new concept of assignment of spectrum for commercial services. Allocation of spectrum at a location and time basis would provide additional revenue to regulator and also ensures high spectrum utilization.

Chapter 4 presented a method for analysis of spectrum trading in the telecom sector and indicated a relation between ARPU, acquired spectrum and subscriber base for survival of the business. The chapter also discussed spectrum trading at the user level and concluded that if spectrum trading allow at the user level, the operator would force to provide better quality of services and also scope of earning would increase.

Chapter 5 presented an analysis about availability of TV white space in India and concluded that sufficient TV white space is available at each and every corner of India as compared to other countries. This white could be utilised for providing affordable broadband services in villages and other remote areas of the country, which still untouched with telecom revolution.

Chapter 6 discussed about dynamic spectrum access and cognitive radio. Cognitive radio is the one of the tools for exploiting white space and concluded that CR technology based services are more energy and spectrum efficient. We can infer that spectrum crunch may not be possible for CR technology based mobile telecom services as it can use any spectrum bands. CR technology also promotes green energy due to restriction on transmit power.

Chapter 7 provided the concept of 5G network. The 5G network is extension of existing 4G network with WISDOM. Spectrum requirements for 5G network has also been discussed in this chapter and concluded that lower band spectrum is suitable for the primary layer and the millimetres waves

are most suitable candidate bands for secondary layer of 5G network.

### 8.3 Future Directions

The thesis gives an idea about the spectrum crunch for telecom services, which will certainly increase in future. Therefore, new measures need to be envisaged at the earliest to overcome the spectrum crunch. A new method for assignment of spectrum for commercial services using two parameters, time and location, has been discussed in the thesis. The proposed methodology can further be improved by adding more parameters which would help to improve spectrum utilisation. Radio spectrum for telecom services is available through auction and other market based method. The spectrum auction cannot be conducted at the behest of each and every operators. Therefore, it is difficult for an operator to get spectrum as per his business requirements. The spectrum trading is one of the options, which could provide additional spectrum to the operators whenever they want. We analysed spectrum trading in telecom sector using parameters ARPU, subscriber base and spectrum holding. Some more parameters could also be added to make spectrum trading analysis more effective. Spectrum trading at user level is a new idea. It would force operators to provide better quality of services to users. We discussed trading at primary level. The trading at user level can further be enhanced by incorporating additional parameters in the analysis.

The availability of white space in India is relatively high. Cognitive radio is the best tool to exploit white space. The broadband revolution has not yet taken place in India. This white space needs to be exploited for broadband revolution to provide affordable broadband services in rural and far flung areas. Finally, without introducing 5G network, it is very difficult to achieve broadband with 1Tbps. With the 5G network concept, distance between big cities, small cities and villages virtually would not exist. A person sitting in a remote village can avail same facility that a person has while sitting in a big city with the 5G network. As stated, spectrum is the main resource for telecom services. The spectrum requirements for 5G network has been categorised into two parts, lower spectrum band and higher spectrum band. Access of lower spectrum can be possible with CR technology and adequate vacant spectrum is available in the higher spectrum band. There are several services which are already present in the bands. Therefore, a coexistence study would needs to be carried out for efficient use of spectrum.

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# List of Publications

1. K. Sridhara, A.Chandra and P. S. M. Tripathi. "Spectrum Challenges and Solutions by Cognitive Radio: An Overview." *Wireless Pers Commun* (2008) 45:281-291 DOI 10.1007/s11277-008-9465-6 Springer Science + Business Media, LLC. 2008
2. P.S.M. Tripathi and Ramjee Prasad. "Spectrum Trading in India and 5G." *Journal of ICT Standardisation* (Special issue on GISFI Standardisation activities). River Publisher. September 2013
3. P.S.M. Tripathi, Ashok Chandra and Ramjee Prasad. "Deployment of Cognitive Radio in India." Springer *International Journal on Wireless Personal Communications*-Accepted and under publication
4. P.S.M. Tripathi and Ramjee Prasad. "Frequency Bands for 5G Communications" under submission- IEEE Communication Magazine September 2014
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6. P. S. M. Tripathi, Ambuj Kumar, A. Chandra and K. Sridhara. "Dynamic Spectrum Access and Cognitive Radio". *Wireless Communication, Vehicular Technology, Information Theory and Aerospace & Electronic Systems Technology (Wireless VITAE), 2011 2nd International Conference*, pp.1-5, Feb. 28 2011-March 3 2011 doi: 10.1109/WIRELESSVITAE.2011.5940911
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8. P.S.M. Tripathi, Ashok Chandra and Ramjee Prasad. "TV White Space in India." Presented at *Wireless Personal Multimedia Communications Symposium (WPMC'13)*, Princeton, USA, IEEE Xplore, 2013
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### **Book Chapter**

1. K. Sridhara, P. K. Garg, A. Chandra and P. S. M. Tripathi. "Radio Frequency Spectrum and Regulation" in book *Future Trends and Challenges for ICT Standardization*. River Publisher, Denmark; ISBN 978-87-92329-38-7
2. K. Sridhara, P. S. M. Tripathi, Ambuj Kumar, A. Chandra and Ramjee Prasad. "Multi-users Participation in Bidding Process in a Congested Cellular Network" in book *Globalization of Mobile and Wireless Communications: Today and in 2020*. Signal and Communication Technology Series, Springer, 1st Edition, 2011, XXI, ISBN: 978-94-007-0106-9



# Mapping of Published Papers with Chapters

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