DESIGNING CHANNEL ALLOCATION ALGORITHMS FOR COGNITIVE RADIO ENABLED CELLULAR NETWORKS

A thesis submitted to the Jawaharlal Nehru University
in partial fulfilment of the requirements
for the award of the degree of

DOCTOR OF PHILOSOPHY

IN

COMPUTER SCIENCE

BY

MANGALA PRASAD MISHRA

ENROLLMENT NO. O1//10/MT/012

Under the supervision of

PROF. D. P. VIDYARTHI

SCHOOL OF COMPUTER AND SYSTEMS SCIENCES

JAWAHARLAL NEHRU UNIVERSITY

NEW DELHI–110067, INDIA

JULY-2021

Dedicated to……

Almighty

जवाहरलाल नेहरू विश्वविद्यालय

SCHOOL OF COMPUTER AND SYSTEMS SCIENCES
JAWHARLAL NEHRU UNIVERSITY
NEW DELHI-110067
INDIA

DECLARTION

I hereby declare that the thesis work entitled "**Designing Channel Allocation Algorithm for Cognitive Radio Enabled Cellular Networks**" being submitted to the **School of Computer and Systems Sciences, Jawaharlal Nehru University, New Delhi-110067, India**, in partial fulfilment of the requirements for the award of the degree of **Doctor of Philosophy**, is a record of bonafide work carried out by me under the supervision of **Prof. D. P. Vidyarthi**.

The matter embodied in the thesis has not been submitted in part or full to any University or Institution for the award of any other degree or diploma.

Mangala Prasad Mishra

Enrolment No.: 01/10/MT/012

School of Computer and Systems Sciences

Jawaharlal Nehru University

New Delhi-110067, India

Email:-mpmishra@ignou.ac.in

जवाहरलाल नेहरू विश्वविद्यालय

SCHOOL OF COMPUTER AND SYSTEMS SCIENCES
JAWHARLAL NEHRU UNIVERSITY
NEW DELHI-110067
INDIA

CERTIFICATE

This is to certify that this thesis entitled "**Designing Channel Allocation Algorithm for Cognitive Radio Enabled Cellular Networks**" submitted by **Mr. Mangala Prasad Mishra** to the **School of Computer and Systems Sciences, Jawaharlal Nehru University, New Delhi-110067, India,** for the award of degree of **Doctor of Philosophy**, is a research work carried out by him under the supervision of **Prof. D. P. Vidyarthi**.

02-07-2021

Dean

Prof. T. V. Vijay Kumar

School of Computer and Systems Sciences

Jawaharlal Nehru University

New Delhi-110067, India

01/07/2021

Supervisor

Prof. D. P. Vidyarthi

School of Computer and Systems Sciences

Jawaharlal Nehru University

New Delhi-110067, India

Acknowledgement

All praises and thanks are due to The Supreme God, for his most Gracious and the Most Merciful blessing bestowed upon me and for granting the most precious patience and continuity to complete this work. Thank God for being with me always.

First of all, I would like to express my deepest and sincere gratitude to Prof. D. P. Vidyarthi School of Computer and Systems Sciences, Jawaharlal Nehru University, New Delhi, for his supervision and guidance throughout this work. His wide knowledge, positive outlook, endless unconditional support, encouragement, and personal guidance inspired me and gave me the confidence and motivation to complete this work. His deep knowledge and logical way of explaining have been of great value to me. Above all, his articulation of ideas, humility, and barrier-free access supported me in various ways during this work. It was a great privilege working with him. I am indebted to him more than I can express.

I am thankful to Prof. P. C. Saxena (Retired) School of Computer and Systems Sciences, Jawaharlal Nehru University, New Delhi, to show the seed of research and his help in developing basic understanding of research.

I would like to record my sincere thanks to my friend Dr. Sunil Kumar Singh, Assistant Professor in Mahatma Gandhi Central University, Motihari, Bihar, for his invaluable advice and support in finalizing the models, implementations, and in the analysis of the results during this work. Without his help, work of this quality would never have been possible.

I would like to record my thanks to the Dean, Prof. T. V. Vijay Kumar, faculty members and technical staff of the School of Computer and Systems Sciences, Jawaharlal Nehru University, New Delhi for providing their support and necessary facilities.

I want to record my thanks to IGNOU Authorities and Academic Coordination Division IGNOU for granting me permission to continue this work along with my service at SOCIS, IGNOU.

I am thankful to my parents for their love, selfless support and encouragement over the years. Many special thanks to my mother for always being a great source of love and motivation. Without any doubt, I can say that this dissertation is a result of their blessings.

I am grateful to my wife Seema Mishra, for her love and consistent support in every ups and down during this long journey. I am thankful to my daughter Kalpana and son Shrikant for their support, understanding and patience to make this work possible. They all are my big strength. I am indebted for stealing a lot of time of their share for this work.

Finally, I am incredibly humbled to convey my gratitude and acknowledgement to all the people who have been associated directly or indirectly with me in this academic journey and helped in the successful realization of the thesis.

Mangala Prasad Mishra

Abstract

Cognitive radio network (CRN) has grown as an alternative communication method with the evolution in the communication technology. A great deal of research, to utilize the most important resource of the mobile network i.e. bandwidth, is highly being pursued. The concept of the cognitive radio in CRN allows us to utilize the bandwidth opportunistically.

There are two critical resources in cellular network systems: the radio spectrum (bandwidth) and the energy. These two resources majorly affect the Quality of Service (QoS) and the channel capacity. Therefore, in the recent past, better bandwidth utilization in mobile communication systems has been a significant research area in the telecommunication field. As radio spectrum is limited and there is an enormous growth in the wireless communication services, including spectrum hungry multimedia applications, efficient and effective spectrum resources utilization has been continuously an exciting research area for the last two decades.

The upcoming 5G network is supposed to offer up to 1000 times the system capacity and at least 10 times the spectral efficiency over 4G network. The 5G cellular networks are expected to have a very low latency of 1ms compared to 4G cellular network latency which is up to 15ms. Also, the availability of 99.99%, the peak data rate of more than 10Gbps etc. are some other features of 5G. For the massive number of users, fulfilling the needs of a higher data rate for services and providing the increased capacity of the network is a very challenging task. To address these challenges, innovative technological capabilities with new mechanisms are required to exploit the available radio spectrum.

To address the problem of the spectrum scarcity for multimedia services and its demand of high data rates, cognitive radio (CR) has emerged as one of the core and prominent technology along with Non-Orthogonal Multiple Access (NOMA), multiple-input and multiple-output (MIMO), and relay technology for the next generation cellular systems. The opportunistic channel utilization characteristics of CR make it a suitable candidate to offer a good solution to the efficient and effective spectrum utilization in 5G cellular networks. CR works on the concept of software-defined radio (SDR) using which a significant range of radio frequency (RF) bands and air interface modes are managed. Contrast to traditional cellular networks, cognitive radio networks work intelligently and adjusts its functional parameters based on the status of the network environment and utilizes the valuable network resources more efficiently and flexibly.

The SDR provides flexible radio architecture to the CRNs, which enable CR devices to operate on different transmission power, frequency, and modulation type using their cognitive capability.

Two types of users exist in CRN; primary users (PUs) and secondary users (SUs). The licensed spectrum of the CRN belongs to PUs and they allow SUs to share their spectrum in such a way that does not affect and degrade their own performance. In CRN, SUs entirely depends on the availability of spectrum holes for their services. The availability of spectrum holes depends on the PUs activities as well as accurate detection of the free channels. The spectrum hole detection and its proper allocation for SUs services improves the QoS of the network as well as the quality of experience (QoE) of the users. Due to unpredictable nature of the availability of spectrum holes, it is usually not possible to guarantee the QoS and QoE. In CRN, SUs are equipped with cognition capabilities that may sense the available frequency in the heterogeneous wireless environment that consists of various service providers/base stations etc. However, such a heterogeneous network environment faces the challenges of fluctuating number of available channels as well as complicated mobility situation. In CRN, the need for efficient and adaptable channel utilization by SUs imposes new challenges and open research issues for designing adaptive schemes of channel allocation.

This thesis proposes few models for better channel utilization in CR enabled cellular network. The proposed models, in this thesis, are developed on fundamental assumptions that the future 5G mobile devices are expected to have cognitive capabilities and operate on dynamically varying environment. The significant contributions of the thesis are discussed in the following paragraphs.

We presented the basic concepts and principles, including different approaches of communications such as underlay, overlay, and interweave. QoS and QoE are the two crucial aspects in terms of service quality assurance and users satisfaction. These aspects have been discussed in detail, along with the related research activities reported in the literature.

A model is proposed based on a new concept in which PUs are also cognitive enabled and can opportunistically use the free spectrum of collocated base stations of other service providers. SUs are also provided access to the free spectrum of all the collocated base stations. This provides wider access of free spectrum to SU and improves the overall QoS and QoE of both primary as well as secondary services.

Next, a model is conceived to address the channel allocation problem which allocates channels based on the service requirements (in terms of bandwidth). This model takes care of fairness in channel allocation by accommodating more service requests by allocating at least some minimum amount of channels to the services so that the service may start and continue. When some channels, occupied by some services are freed, those channels are allocated to the currently running services that are falling short of channels to meet their overall channel requirements.

Thereafter, channel allocation mechanism in CRN is investigated using the concept of channel aggregation (CA) and channel fragmentation (CF). Channel aggregation (CA) is one of the key techniques which improve the communication system efficiency by aggregating the small chunk of distributed or discontinuous radio frequency. Using CA, it has been possible to combine multiple idle channels and utilize them as one bonding channel to serve the request. In this scheme, channel fragmentation (CF) has been used to accommodate more service requests. This improves the overall performance of the network in terms of throughput and utilization of system capacity. In the next model, a mechanism for dynamic aggregation based channel allocation in CRN has been developed. This applies the concept of probabilistic handover of secondary services. Also, this model attempts to minimize the call blocking and the call dropping by splitting the allocated bandwidth dynamically.

Finally, concluding remarks are drawn where the findings and contributions of the thesis have been highlighted. Future direction of research has also been set which may lead to a possible extension of the work proposed in this thesis with some other existing gaps identified in this research area.

List of Publications

Journals

[1] M. P. Mishra, S. K. Singh, and D. P. Vidyarthi, "Opportunistic Channel Allocation Model in Collocated Primary Cognitive Network," *International Journal of Mathematical, Engineering and Management Sciences*, vol. 5, no. 5, pp. 995-1012, 2020, (SCOPUS & ESCI)

[2] M.P.Mishra and P.C.Saxena, "Survey of Channel Allocation Algorithms Research for Cellular Systems," *International Journal of Networks and Communications*, vol.2, no.5, pp. 75-104, 2012, (Copernicus International)

[3] एम. पी. मिश्रा, सुनील कुमार सिंह, एवं देव प्रकाश विद्यार्थी, "कॉग्निटिव रेडियो आधारित सेलुलर संचार तंत्र में सेवा जरूरतों पर आधारित चैनल आबंटन", *Vigyan Garima Sindhu* (Accepted) (UGC CARE)

[4] S. K. Singh, M. P. Mishra, and D. P. Vidyarthi, "Requirement Based Channel Allocation in Cognitive Radio Network", *Journal of Mobile Networks and Applications* (In Revision) (SCIE)

[5] S. K. Singh, M. P. Mishra, and D. P. Vidyarthi, "A Hybrid Dynamic Aggregation and Fragmentation Model for Cognitive Channel Allocation", *IETE Journal of Research* (Communicated) (SCIE)

Conference

[1] M. P. Mishra and D. P. Vidyarthi, "Modelling Challenges of Channel Allocation in Cognitive Radio Enabled 5G Cellular Systems", *International Conference on "History of Development of Mathematics*, ICHDM-2020, Rohtak, India, 2020 (presented online)

[2] M. P. Mishra and D. P. Vidyarthi, "Spectrum Handoff in Cognitive Radio Cellular Network: A Review," *8th International Conference on System Modeling and Advancement in Research Trends (SMART)*, Moradabad, India, 2019.

[3] M. P. Mishra and P. C. Saxena, "Issues, challenges and problems in channel allocation in cellular system," *2nd International Conference on Computer and Communication Technology, (ICCCT)*, Allahabad, 2011.

Contents

List of Figures

List of Tables

Abbreviations

IoT	Internet of Things
CRN	Cognitive Radio Network
SUs	Secondary Users
QoS	Quality of Service
QoE	Quality of Experience
5G	5^{th} Generation
IMT	International Mobile Telecommunications
RA	Resource Allocation
ICT	Information and Communications Technology
PUs	Primary Users
DSA	Dynamic Spectrum Access
FCC	Federal Communications Commission
SDR	Software Defined Radio
ITU	International Telecommunications Union
ITU-R	International Telecommunications Union Recommendation
OET	Office of Engineering and Technology
FDMA	Frequency Division Multiple Access
TDMA	Time Division Multiple Access
CDMA	Code Division Multiple Access
OFDMA	Orthogonal Frequency Division Multiple Access
WRC	World Radiocommunication Conferences
UHF	Ultra High Frequency
SIR	Signal to Interference Ratio
CIR	Carrier-to-Interference Ratio
CSI	Channel State Information
SINR	Signal-to-Interference-Plus-Noise Ratio
CNR	Carrier to Noise Ratio
CNIR	Carrier to Noise Plus Interference Ratio
TDD	Time Division Duplexing
IPTV	Internet Protocol Television
CA	Channel Aggregation
CF	Channel Fragmentation
MSS	Mobile Service Station
BS	Base Station
MSC	Mobile Switching Center
SN	Secondary Network
CRT	Cognitive Radio Technologies
SNR	Signal-to-Noise Ratio
CNIR	Carrier to Noise Plus Interference Ratio
UWB	Ultra-Wideband
CCI	Co-Channel Interference
MOS	Mean Opinion Score
CBP	Call Blocking Probability
CDP	Call Dropping Probability

MU	Mobile Unit
HD	High Definition
RF	Radio Frequency
GoS	Grade of Service
PRP M/G/1	Preemptive Resume Priority (*PRP*) *M/G/1*
AI	Artificial Intelligence
DSs	Dedicated Sensors
MAC	Medium Access Control
CRP	Correct Reception Probability
VoIP	Voice over Internet Protocol
PSO	Particle Swarm Optimization
CCRN	Cooperative Cognitive Radio Network
GWO	Grey Wolf Optimization
DCR	Dynamic Channel Reservation
DSL	Dynamic Spectrum Leasing
NUM	Network Utility Maximization
CCA	Constant Channel Aggregation
VCA	Variable Channel Aggregation
ISM	Industrial Scientific, and Medical
SLM	Spectrum Lean Management
CAC	Call Admission Control
WLAN	Wireless Local Area Networks
OPUs	Opportunistic Primary Users
PRBS	Primary Radio Base Stations

Notation

CC	Channel Capacity
BW	Channel Bandwidth
S	Average Received Signal Power over the Bandwidth
N	Average Noise or Interference Power over the Bandwidth
BP	Call Blocking Probability
CDP	Call Delay Probability
λ	Average Arriving Rate of Events
μ	Mean Service Rate
C_i	Channel Id of i^{th} Channel
PR	Primary Request
SR	Secondary Request
PU	Primary User
OPU	Opportunistic Primary User
SU	Secondary User
RTS	Real-Time Service
$NRTS$	Non-Real Time Service
SBS	Secondary Base Station
SR	Secondary Request
α	Steepness Constant
β	Steepness Constant
$PSRAR$	Primary Service Request Arrival Rate
$SSRAR$	Secondary Service Request Arrival Rate
ISV	Interrupted Service Vector
QoE	Quality of Experience
AQoS	Application Quality of Service
NQoS	Network Quality of Service
NR_i	Number of Call Requests made by the Customer
CB_i	Call Rejected
$Qosp$	QoS Parameters

PIC_i	Probability of i^th Channel for being Idle
NI_i	Number of Times i^th Channel was Idle
NT_i	Number of Trials on i^th Channel
N_i	i^th Number of Non-Reserved Channel
R_i	i^th Number of Reserved Channel
D_CRN	Dynamic CRN
F_CRN	Fixed CRN
PU_1	Primary New User
PU_2	Primary Handoff User
SU_1	Secondary New User
SU_2	Secondary Handoff User
BW_{SU1}^{min}	Minimum Required Bandwidth for Type 1 Secondary User
$idleBW$	Idle Bandwidth
RRS_{size}	Remaining Required Service (in size)
TRS_{size}	Total Required Service (in size)

Chapter 1

Introduction

This chapter introduces the problem, addressed in this PhD work, and the related issues.

1.1 Thesis Motivation

With the evolution in communication technology, cognitive radio network (CRN) has grown as an alternative communication method. A great deal of research is highly being pursued in this research field. The CRN allows us to utilize the bandwidth opportunistically. In this chapter, the motivation for using CRN as a solution for utilizing channels opportunistically for the secondary users (SUs) in a cellular network is explained. Cognitive radio technology (CRT) is being established as a promising alternative for the upcoming 5^{th} Generation (5G) mobile communication. This chapter gives a background on cognitive radio based cellular network, which is efficient, effective and offers good QoS as well as QoE to its users. For effective spectrum utilization, the efficient solutions for channel allocation problem in CRN has been considered for the upcoming 5G cellular system.

This chapter presents the thesis's aim and contrition with an overview of the thesis organization.

Technological advances in the cellular system and the innovative development of handling wireless devices have resulted in the proliferation of mobile computing. The past three decades have witnessed the enormous growth in the telecommunication area. These evolutions have given the telecommunications industry the capability to provide ubiquitous information and provide efficient, reliable and cost-effective communication. Spectrum in wireless mobile systems has always been considered a very scarce resource. With rapid population increase of mobile users and incremental growth of the multimedia applications, more communication channels are required for better telecommunication services. As mobile users continue to grow exponentially with the massive bandwidth requirements of multimedia applications, there is a necessity to utilize the bandwidth efficiently. Efficient spectrum utilization is also associated with the cost-effectiveness of the mobile services.

Radio spectrum is instrumental in technological innovations in the field of wireless communication. The future 5G cellular system aims to offer the interconnection of huge number of active devices in the wireless network across the globe. In the year 2019, the expected global mobile data traffic was 29 Exabyte (EB)/month which is expected to increase to 77 Exabyte (EB)/Month by 2022 [1]. According to CISCO report, “globally, the total number of Internet users is projected to grow from 3.9 billion in 2018 to 5.3 billion by 2023” [2].

According to an estimate, presented in [3], it is anticipated that from 2020 to 2030, global International Mobile Telecommunications (IMT) traffic will have a massive growth to the tune of 10–100 times. With such increasing number of billions of wireless devices connected to the Internet, providing smooth radio spectrum access will be a big challenge in the years to come [4].

Bandwidth and energy are two essential resources for the wireless communication. These two resources majorly affect the QoS and the channel capacity. Therefore, better bandwidth utilization in mobile communication systems has been a major research area in the telecommunication domain in the recent past [4]-[14].

Resource management, mainly spectrum allocation, is an essential function of wireless communication systems. Proper spectrum allocation is one of the key requirements to utilize the available channels effectively. As the available spectrum is fixed and used by the appropriate licensing and control, it is essential to use the spectrum to the maximum extent possible to meet the ever-increasing demand of various services, including internet of things (IoT), video conferencing, gaming and other multimedia applications which often eat up more spectrums. Through regular academic and industrial research attempts are being made to develop efficient resource allocation mechanisms for better utilization of the available radio spectrum, possibility still exists with the introduction of the newer technologies. The cellular system’s users are interested in getting higher bandwidth, flexibility in service provider selection, reliability, security, QoS, QoE and, low cost of spectrum uses. Concurrently, service providers desires less complex system, low infrastructure investment and management cost, scalability, security, fault tolerance, sound business models etc. [15]. Fifth-generation (5G) cellular networks is emerging as a significant driving force for information and communications technology (ICT) applications and research due to its core objectives of reliability, very high data rate, QoS and QoE for multimedia applications with low latency and other related benefits, [13], [16].

With the growing demand for the radio spectrum, its effective utilization is one of the key concern in wireless communication systems. Cognitive radio (CR) has been considered as one of the promising technology for solving the spectrum scarcity [17]-[18]. The core idea behind CR technology (CRT) is its dynamic spectrum access capability, which can utilize the idle spectrum, called white spaces, without affecting the licensed users' rights. CRT also facilitates reuse of the available radio spectrum. However, often CR has a limiting factor of spectrum reuse because of the interference caused by the environmental factors such as noise or maybe due to other radio transmissions [17].

CR's inherent features such as flexibility, adaptability, interoperability, and integration with 5G cellular networks may provide the capability to address some of the issues, including better channel utilization. These features place CRT among the technologies and techniques that have been identified as enablers for the 5G wireless. CR provides an opportunity to use licensed spectrum by the unlicensed users opportunistically [4]-[5], [9]-[10], [19].

1.2 Cognitive Radio Network (CRN)

The concept of CR was first introduced by J. Mitola [19]-[20] to enhance the spectrum utilization by using the free spectrum of the licensed users by the unlicensed users opportunistically. The upcoming 5G cellular systems will house a good number of heterogeneous devices capable of using both the licensed frequency band and the unlicensed frequency band. Proper use of CR technology in 5G cellular systems can increase its spectrum efficiency significantly [13], [21].

Cognitive radio provides the sharing of radio spectrum between licensed users, also called primary users (PU) and unlicensed users called secondary users (SU) in a non-transparent manner. This sharing of spectrum may be implemented by opportunistic sharing or negotiated sharing. Opportunistic spectrum sharing allows a cognitive user to utilize the radio spectrum when the primary or licensed spectrum is not being used by its licensed users [4], [8], [22]. CR is an intelligent communication mechanism capable of sensing and dynamically accessing the radio resources. In a cellular network, CR has the capability to increase the utilization of radio spectrum in the network by its adaptive features, i.e. opportunistic and shared radio spectrum access [4].

1.2.1 Dynamic Spectrum Access

The term dynamic spectrum access (DSA) is used in a broader context which includes activities and operations such as spectrum access, spectrum pooling, spectrum allocation, spectrum management, and its regulation activities [23]. DSA is used as an alternative policy for efficient utilization and management of spectrum [19].

Static allocation methods, which allocate the channels to its users once and sticks to it till the completion of the communication, are unable to utilize the available channels fully. This problem is overcome in DSA using CR technology (CRT). Using DSA, the same spectrum band can be utilized among multiple users by spectrum sharing [11]. Cognitive Radio (CR) has been accepted as a 5G technology for efficient spectrum utilization by the opportunistic spectrum use through DSA. CR also provides low-cost expansion for wireless systems [24]. The challenge of large bandwidth requirements of 5G cellular systems can be significantly addressed by employing the CRN [25]-[27]. CR is considered as a useful technology for communication due to its characteristics of efficient spectrum utilization, maximizing throughput, mitigating interference, facilitating interoperability, accessing secondary markets, etc. [17].

US spectrum licensing agency, Federal Communications Commission (FCC), states “A cognitive radio (CR) is a radio that can change its transmitter parameters based on its interaction with the environment in which it operates. This interaction may involve active negotiation or communication with other spectrum users and/or passive sensing and decision making within the radio. The majority of cognitive radio will probably be Software Defined Radio (SDR), but neither having software nor being field reprogrammable are the requirements of cognitive radio” [28].

1.2.2 Software Defined Radio

“CR is based on Software Defined Radio (SDR) that was proposed in order to liberate the radio networks from the previous dependencies on hardware characteristics such as frequency bands, channel coding, and bandwidth” [29]. The transceiver of a CR has the ability to operate on varying frequency bands. Therefore, CR uses SDR to dynamically adjust the transmitter operating parameters i.e. carrier frequency, modulation and transmission power [30]. In other words, by adding programmability to radio devices with the help of SDR, it becomes more flexible in operation and can use different spectrum bands with different modulations. CR mainly aims to find the best available spectrum for the secondary users (SU) that does not interfere with primary users (PU) [30]. In addition to SDR features, CR has some added features such as controlling transmission power, channel identification and, radio scene analysis [29]-[31].

The significant difference between SDR and CR is that SDR is a radio set in which most of the radio and intermediate frequency functionality is performed in digital form whereas CR works as a control entity that assists the SDR to determine the operating parameters in the specific networking situation [15].

Using cognitive capabilities, CR opportunistically uses the available bands and increases the overall spectrum utilization compared to the traditional fixed spectrum assignment approaches. In CRN, SUs transceiver can shift to different frequency bands and control the transmission power according to the availability of the spectrum holes and QoE requirements of the PUs. Hence in CR channels, types of frequency modulation, level of transmission power are dynamically adjusted using the software. This process ensures the QoE and increases the throughput of the system. The spectrum handoff in CR also varies from a traditional handoff of wireless networks where handoff occurs due to the users' mobility or poor signal quality. If a PU is using the spectrum, a cognitive user should not attempt to access the spectrum; otherwise, a cognitive user may use the free spectrum to communicate the SUs [32].

1.3 Radio Spectrum/Frequency Channel and Frequency Bands

As given in the literature, primary users are the licensed users. They have the priority in using the spectrum over the secondary users. Primary users have their own licensed channels while secondary users do not own the channels. SU totally relies on the unutilized channels of the primary users. Upon the generation of a primary user request, secondary users need to vacate the licensed channels of primary user even if it is using one. Before vacating the channel, maybe some available free channel is allocated to the secondary user using spectrum handover [33]-[34]. If no free channel is available, secondary service will be preempted and resume/repeat later when channel becomes available.

In wireless communication, different frequency bands are used by various radio transmission technologies for providing communication services. For proper operations and management, allocated frequencies are logically divided into bands. Frequency bands are the representation of logical range of frequency. The frequency bands are seen as licensed or unlicensed, depending on its usage rights assigned to them. Basically, licensing provides exclusive rights to the users for a specific range of frequency which ensures that this frequency band can be used without any interference from other wireless users. The total radio spectrum is approximately in the range of 3 kHz to 300 GHz. For managing the radio spectrum, regulatory authorities have organized them into bands with specified usage for the different services, including cellular, fixed and satellite communications. Bands are further divided into channels under the legal binding usage mandates, both nationally and via international agreements [35].

The International Telecommunications Union (ITU) manages frequency band worldwide in coordination with the governments of most of the countries. Global management of the radio frequency is one of the vital activity of ITU. The ITU's Recommendation Sector (ITU-R) manages the radio frequency spectrum. Also, ITU standards are fundamental to the operation of today's advanced wireless. The ITU-R is responsible for identifying frequency bands for almost all types of wireless communication worldwide including aviation, broadcasting, mobile communications, public protection & disaster relief, and satellite services [36].

Spectrum is categorized as a licensed and unlicensed spectrum; the FCC has allocated the spectrum for both. The Office of Engineering and Technology (OET), a unit of FCC, advices on the policy as well as technical issues related to spectrum allocation and uses. As many of the useful radio spectrum bands are already allocated; it is nontrivial to find vacant bands for new applications and for improving the existing applications. According to the FCC observation, most of the time a good portion of the allocated spectrum is underutilized; whereas an unlicensed spectrum is being exhausted by rapidly growing wireless service and applications. Also, as per the FCC report, the spectrum utilization varies geographically and temporally between 15% to 85% [28], [37].

Furthermore, as per FCC survey [28], [38] the radio spectrum usage is non-uniform where some portions are highly used and some others are underutilized. Thus the licensed spectrum, which its licensed users are not currently using, can be sensed and used by an unlicensed user for its services. The available free spectrum of licensed users is random, non-continuous and changeable [39]-[40], hence traditional frequency access mechanisms such as time division multiple access (TDMA), frequency division multiple access (FDMA), and code division multiple access(CDMA) are not suitable for CR and 5G communications as they are based on the continuous and fixed spectrum allocation [40]. In CR, the availability of spectrum is decided through spectrum sensing. Due to rapid growth in global mobile data traffic, there is an immediate need for a good mechanism design for utilizing the available spectrum to its maximum possible extent. The invention of the CR is with the objective to enhance the spectrum utilization and efficiency [4].

For 2G/3G/4G cellular communications, mainly frequency range of 700 MHz to 42 GHz is used. Also, for some transmission, 400 MHz and 70/80 GHz range is used. The frequencies are allocated by ITU Radio communication Sector (ITU-R) through World Radio communication Conferences (WRC) on both a primary and secondary basis [36], [41]. In the upcoming 5G, a large amount of spectrum will be required for providing services to high capacity broadband multimedia applications.

There are many cellular bands centered around 800/900 MHz, 1.8/1.9 GHz, 2.1 GHz, 2.3 GHz, and 2.5 GHz. These bands are suitable to serve the mobile users who are in a cells coverage area. The CRN service area is also generally the same region of the cellular network cells coverage area. The high demand of mobile broadband and breakneck data transfer speed in the range of gigabits, emerging IoT applications, smart city applications with a very large number of wireless sensors and many more such services are compelled to search for additional bands. It is expected that an additional 1000 or so MHz will be required to fulfill the demand of mobile broadband by 2020 [36].

The ITU uses the term IMT-2000 for 3G systems and IMT-Advanced for 4G systems. For upcoming 5G systems, ITU is using the term IMT-2020. Collectively all these 3G, 4G and 5G are identified as IMT. With the development in technology, IMT systems are becoming more capable of continuously enhancing user requirements and the latest technology trends [42]. To meet the massive requirements of increased data traffic with high reliability and low latency, it is compulsory to enable the transmission bandwidths for supporting very high data rates. For increasing capacity, 5G must use an extended range of frequencies to meet its massive data traffic requirements with a very high data rate. This frequency range includes higher frequency bands and also the new spectrum range below 6 GHz [42]. For 5G wireless communications, relevant frequency ranges are from below 1 GHz up to approximately 100 GHz. From the perspective of broader coverage and high data range requirements of 5G, spectrum range below 6 GHz is an important part of 5G IMT [42].

In telecommunication, bands are divided into channels and bandwidth, and subsequently, this converts into per-user data rate. As the frequency channels are unpredictable and beyond anyone's control, mapping them in more bps/Hz/km^2 (bits per second per Hertz per square kilometer) is very challenging often referred as system spectral efficiency. To handle this challenge, in addition to enormous innovations in wireless communication, almost every generation of mobile communication has exercised a new multiple access method with some improvement over the previous one. In 2G systems, FDMA and TDMA techniques have been used. The 3G systems use CDMA with LTE, WiMAX. The 4G systems are based on OFDMA (Orthogonal FDMA). Thus, it can be envisioned for 5G that it will be using a combination of the existing access methods with sufficient improvements or one or more new and improved multiple access methods [36]. In CRN, different frequency bands including Ultra High Frequency *(*UHF), cellular and fixed wireless access bands can be used for transmission. Currently, for Television (TV) broadcasting, UHF band is used. As FCC policies [43], CRN may use the TV spectrum not used by PUs for the SUs services [44].

1.3.1 Channel Capacity

For sending/receiving information, the communication channels are used as a medium (wired or wireless). In cellular communication, frequency channels are used to carry information from the base station to the user and vice-versa. The rate of transmission of information is represented using channel capacity. Using the famous Shannon–Hartley theorem, channel capacity is expressed as given in equation 1.1 [36]:

$$CC = BW \times log_2(1+\frac{S}{N}) \qquad (1.1)$$

Where, CC is channel capacity in bits per second, BW is channel bandwidth in Hertz, S is average received signal power measured in watts, and N is the average noise or interference power measured in watts.

In channel allocation, one of the basic concepts of data communication i.e. multiplexing is used. There are many techniques of multiplexing, such as frequency-division (FD), time-division (TD), or code-division (CD). In FD, frequency spectrum is divided into disjoint frequency bands with each channel being assigned to a unique frequency range, whereas in TD separate channels are achieved by dividing the signal into different time slots. In CD, the channel separation is achieved by using special coding schemes. Further, more complex techniques can be designed based on a combination of TD, FD and CD techniques. For example, with a combination of TD and FD, a hybrid technique of multiplexing have been developed, which will divide each frequency band of an FD scheme into time slots. Irrespective of the access technology (FDMA, TDMA, CDMA), the system capacity can be measured in terms of effective or equivalent bandwidth [45]-[46]. In OFDMA, the available spectrum is divided into orthogonal sub-carriers grouped into subchannels. OFDMA applies multi-access technique by allocating the users to different groups of orthogonal subchannels. In OFDMA, the system capacity can be measured in terms of effective or equivalent channels [47]. According to the Ericsson paper [48], the upcoming 5G network will incorporate LTE access, based on Orthogonal Frequency Division Multiplexing (OFDM) for providing good coverage to the mobile users.

1.4 The Channel Allocation Problem

In wireless communication, frequency bands are referred as the range of frequencies that are used for the transmission. If a frequency band has a broad range, it can transmit more data. A simple rule of thumb is "more the frequency, more the data rate" [49].

A cell is the basic geographic unit of a cellular system in which radio bandwidth is divided into channels. Only a fixed set of channels are available for the entire network. A channel or group of channels can be used to support a call or communication session. These channels are represented in terms of frequency channels, time slots, or modulation code. These channels, in a certain cell, are used for communication and further system allows the same channel to be reused in other cells provided these cells are at least the *minimum reusable distance* apart from the current cell. In figure 1.1, a reuse plan of seven channels, namely A, B, C, D, E, F and G in the cellular system, is given. Cells that can use the same channels are called *co-channel* cells.

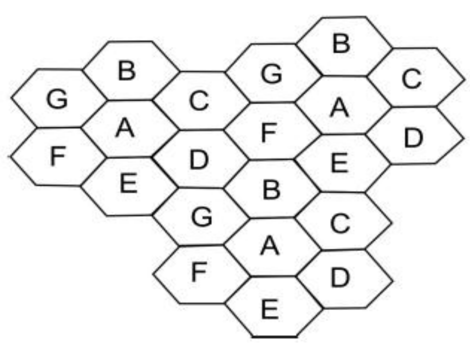

Figure 1.1: Concept of Channel Reuse in a 7 cell Cluster [50]

For better channel utilization, a simultaneous use of the channels by different cells are possible only if the distance between each pair of cells is greater or equal to the minimum reuse distance. The minimum reuse distance depends on the radius R of the cell and the minimum SIR (signal to interference ratio) also known as CIR (carrier-to-interference ratio), one of the most basic level interference caused by the proximity of other cells sharing the same channels. One of the objectives of channel allocation algorithms is to allocate channels to minimize the CIR.

During the design of a cellular system, extensive planning is required. In cellular system modeling, the important technical challenges include interference mitigation, radio resource allocation, mobility management & handoff, self-organization and learning. Some other challenges are to manage QoS and QoE, along with the fairness in offering the services. The overall environment of cellular networks is dynamic because of the landscape's geographical nature, operating frequency, and user movability/speed. The cell landscape has a significant influence on the radio characteristics and the throughput of the system.

The system design includes determining cell sites cleverly to get the clear and attractive needs for communication at present and in the near future in terms of users' load. The more the number of cells, the more the cost and complexities are involved in the system setup and operations. In real life, the size of different cells in a cellular system varies, particularly between rural and urban areas. In rural areas, few and large cells are sufficient to meet the needs as the users' density is less. The radius may be in the range of 2-4 kilometers. There is a need for smaller and more numbers of cells in denser populated areas like business centers and highly populated residential colonies, serving an area of radius down to about 500 to 1000 meters. In 5G cellular system, to meet the needs of the densely populated parts of the cities, it is better to use cells consisting of a short section of a street (micro cells) or a room or even a floor of a building (picocells).

Through spectrum analysis, prediction of channel capacity and channel state information (CSI) is performed for the channels which are to be used by the CR transmitter. CR uses a spectrum decision process to determine the data rate, the transmission mode and, the bandwidth of the transmission. Based on the spectrum, CR selects the most appropriate spectrum band for the transmission. After spectrum sensing, CR adapts the transmission parameters based on the sensed information for optimal performance using reconfigurability. CR can be programmed to transmit and receive different frequencies. It can also use different access technologies by its appropriate hardware design. CR reconfigurable parameters include operating frequency, modulation, transmission power, and communication technology.

Issues that affect the channel allocation planning and execution, in a usual scenario in cellular systems, includes:

- Whether the application is hard real-time, soft real-time or non real-time,
- Whether sufficient dedicated channels are available for system control activities,
- Whether transmitter power for the entire BS and the Mobile users are similar,
- Whether the system is scalable for high load or not,
- Whether system performance under heavy load and light load are similar, and
- Whether services offered to different users are fair or not.

The OFDMA, is widely used as a feasible technology for mobile communication systems due to its ability to allocate power, rate and frequency optimally among the subcarriers [51]. Due to its features of adaptive parameter adjustment and dynamic allocation, OFDM is widely used in wireless communication [52].

The signal to interference ratio (SIR) is a commonly used metric to characterize the quality of a communication link. In OFDMA network, co-channel interference (CCI) is a major challenge considering the aspiration of full frequency reuse. In OFDMA, co-channel interference occurs mainly when multiple users transmit on overlapping frequency bands simultaneously. Hence in the downlink of an OFDMA system, such interference is confined to inter-cell interference, as users within a given cell use orthogonal sub-carriers. One significant advantage of OFDMA is that any two MSs that belongs to two different BSs, can be assigned same subcarrier if the SINR (signal-to-interference-plus-noise ratio) of that subcarrier is higher than given threshold $SINR_{min}$ [53].

To gain more from the communication network, it is necessary to adopt an objective quality measure that addresses users' QoS perspectives and is suitable for the service providers' business perspectives. A critical QoS parameter, from the perspective of service providers, is throughput as it represents the amount of data being transferred through a channel in unit time. However, from the users' viewpoint speedy service is more important.

The bandwidth-hungry multimedia applications require more bandwidth, either in the uplink or in the downlink channel. For example, Internet access is a bias towards downlink. Hence for such applications, uplink and downlink resources need to be allocated accordingly. The OFDMA uses Time Division Duplexing (TDD) techniques for allocating varying number of channels/slots in uplink and downlink for services with biased resource requirements [54]. There are different aspects of fairness in wireless communication, including sharing channels fairly among the users, fair consumption of energy, and fairly satisfying QoS and QoE requirements of the users [55].

While serving the users request in the CRN, it is appropriate to consider the service request's nature. In the plethora of emerging services e.g. Internet Protocol Television (IPTV), mobile gaming, video conferencing, smart city, health care and IoT applications, a few classes of services are critical and important as compared to others. Therefore, it becomes obvious to give more importance to some traffic classes than others while allocating the channels. Hence, during high system load, low priority services should be blocked before high-priority services using the DSA mechanism. In 5G heterogeneous environment, managing priority by admission control becomes an exciting problem of the dynamic spectrum allocation [9].

The upcoming 5G communication systems is supposed to offer 10 to 1000 times of the system capacity and at least 10 times the spectral efficiency of 4G networks. Also, offering ultra-low latency of less than 1 millisecond, availability of 99.99%, and peak data rate of more than 10Gbps are some other requirements. These challenges are being researched by industry and academia extensively [6], [56]-[57]. Since 5G networks are comprised of heterogeneous and multimedia-rich applications, internet protocol television (IPTV), mobile gaming, video conferencing, and videos; it will have different QoS and QoE requirements. Also, categorizing applications in multiple service class with different priorities become a must [24]. To address these issues, suitable models need to be developed.

In CRN, SUs are equipped with cognition capabilities and may sense the available frequency in heterogeneous wireless environment that consists of various service providers/base stations. However, such heterogeneous network environment faces the challenge of fluctuating number of available channels and complicated mobility situations. Therefore, this environment requires some special kind of collaborative spectrum management schemes for efficient and effective channel allocation [4].

Cognitive radio-enabled cellular network not only provides services to its PUs but also serve the SUs using opportunistic spectrum access. As the CRN co-exist and operate on a spectrum of the primary network, channel allocation schemes need to be developed considering the priority of PUs services as well as QoS/QoE requirements. At the same time, efficiently utilize the resources for the SUs services.

The channel allocation scheme needs to consider the overall network performance in terms of network throughput and system capacity utilization. Channel aggregation (CA) is one of the critical techniques which improve the communication system efficiency by aggregating the small chunk of distributed or discontinuous radio frequency [58]-[59]. More data/ information can be transmitted using channel aggregation (CA) [60].

Dynamic channel allocation and permissible aggregation can be a key technology to serve with the limited resources to the users. Channel aggregation enables a user to use more than one channel to enhance its bandwidth. It is possible only when the channel aggregation is being done by considering the OFDM [61]. Channel aggregation (CA) would help to enhance the channel capacity with the aggregation from other channels. It can improve the QoS also especially when the service is running on minimum bandwidth. In general, various models have categorized the services into two categories; primary and secondary, where secondary services can be homogeneous/heterogeneous [24]. While using channel aggregation for real-time services, live voice conversation, or video calls, their QoS requirement should be satisfied as they are time-bound and have no flexibility in completing the service [62]. Channel fragmentation (CF) can also be a better idea to accommodate the number of services. In this approach, a channel can be split into more than one channel to serve the requests considering that QoS is acceptable. Simultaneously, if the channels are free, they can be assembled to allocate the higher bandwidth. Higher bandwidth will reduce the service duration if the service is a non-real-time service but in the case of real-time service, service duration will not be affected [63].

As CR system are opportunistic and primarily depends on PUs activeness in the environment, it may not provide seamless coverage [64]. The QoS and QoE of PUs are ensured at the cost of SUs services interruption or degradation. Compared to PUs, SUs are more affected due to network fluctuation and adjust their QoE expectations [4]. Though 5G mobile networks will have their licensed spectrum band, mobile devices with CR capabilities can utilize the free channels of other co-existing networks for higher data rate, especially for multimedia applications. This will improve the QoS/QoE of the system [4].

CRN aims to leverage the spectrum holes and utilize it opportunistically using DSA for efficient spectrum utilization. New models for resource allocation in CRNs should be developed addressing QoS and QoE issues with better throughput. The objectives of channel assignment mechanisms in CRNs should include assigning the spectrum holes to SUs in such a way that the following are met.

1) It leads to efficient spectrum utilization.
2) It minimizes the interference to PUs.
3) It keeps the interference minimum among SUs.
4) It provides a fair chance to the services to access the available channels.
5) High priority services are given due weightage.

If channel allocation in CRN is compared with the conventional wireless networks, there are several commonalities: interference, connectivity, stability, throughput, and fault tolerance. Always there exists a tradeoff between connectivity and interference, latency and QoE, fault tolerance and better QoS, operator profitability and network overload. Therefore, in the study of channel allocation in CRN, these tradeoffs also need consideration.

1.5 Research Contribution and the Outline of the Thesis

The contribution of this thesis is towards developing a better understanding of CRNs. This work provides new insight into utilizing CRN capabilities in efficient spectrum utilization for both PUs and SUs. Towards that, few models have been developed and studied in this research work. The organization of the thesis is as follows.

Chapter 1 is an introductory chapter that introduced the concept of the cognitive radio network, DSA, SDR, frequency channels and frequency bands. Also, in this chapter channel allocation problem in the cellular system is described, and basic issues and challenges in channel allocation have been highlighted.

Chapter 2 presents the concepts of CR channel allocation and a review of the available literature in this research area. This chapter explains CRN architecture, the concept of spectrum holes and the functions of CRN. Different approaches to channel allocation are discussed in details.

Subsequently, concepts of QoS and QoE in the context of cellular services have been explained. In CRN, mobility management is an important aspect; this chapter explains different spectrum handoff approaches used for mobility management in CRN. Generally, two approaches, namely the centralized approach and the distributed approach, are used in the cellular network to manage the channels. These approaches have been discussed in detail in this chapter. Finally, different schemes studied in the literature for channel allocation in CRN are discussed.

In chapter 3, first model is proposed in which both PUs of one network opportunistically access the channels of other collocated networks. This improves both QoS and QoE of the PUs as they are having access to frequency channels of other service providers. This proved an opportunity to effectively utilize the free channels of any service providers in the vicinity for better channel utilization using DSA. In this model, SUs service requests are also provided access to the free channels of any collocated network in the service area, but the priority to assign free channels to SUs service request is less compare to PUs service request.

In chapter 4, another model for channel allocation is proposed which considers the fairness in resource allocation. This model assumes that even when the maximum channel requirements of any service cannot be provided, it will still continue with minimum channels. At some later stage during the service, when channels are freed by some services, these channels will be allocated to the ongoing service operating with minimum number of channels. In this model, a service is only accepted if the service's minimum bandwidth requirement is fulfilled. This way more number of services are accommodated in the system which overall improves the QoS/ QoE of the system.

In chapter 5, channel allocation problem in CRN is solved using the channel aggregation and fragmentation concepts for better radio spectrum utilization and serve the maximum number of users with desired QoS/QoE. This model attempts to minimize the call block as well as call drop by splitting the allocated bandwidth dynamically. This model has been designed to increase the bandwidth utilization by allocating the available free bandwidth to the ongoing services that improves the service quality.

Finally, concluding remarks are drawn in chapter 6 besides setting the directions for future research work.

Chapter 2

The Channel Allocation Problem: Literature Review

As the channel allocation problem in cellular communication is very old, good research works have been done in this area as available in the literature. However, it has been an evolving field and technological innovation has resulted in the quality improvement in solving the channel allocation problems from both users' perspectives and the service provider's perspectives. This chapter briefs mostly the recent research work in this area, as reported in the literature.

2.1 Cognitive Radio Enabled Cellular Network

In a typical cellular system, the entire geographical area is fragmented into number of cells. A cell is seen as a basic geographic unit of the network. To represent the shape of a cell, a circle is to be considered as a natural choice; an omnidirectional antenna at the centre of the cell can be placed with a circular radiation pattern. However, in practice, while filling a large area with circles, either area overlaps or gaps in the coverage area are noticed. Hence, the hexagonal shape of a cell is most suitable. The term cellular originates from honeycomb (hexagonal) shape of the area of which a coverage region is divided theoretically [49]. Mobile users are served by a base station (BS) located at the centre of the cell which are interconnected via a wired network [65].

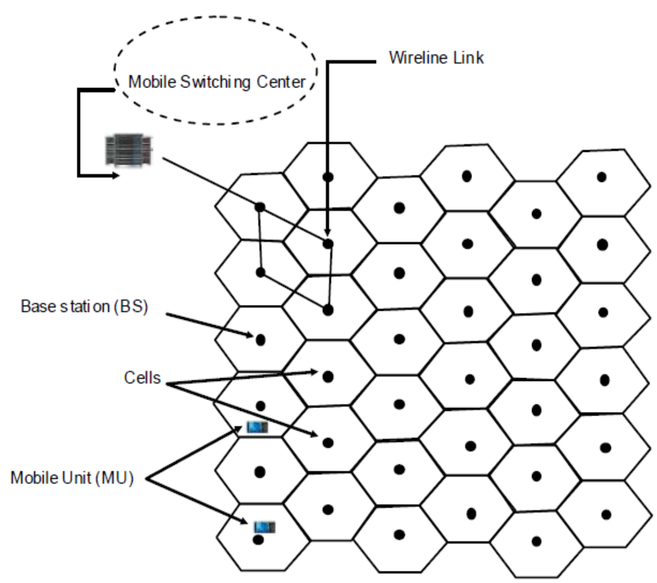

Figure 2.1: Architecture of a cellular System [50]

Each cell size may vary depending on the landscape. BSs are also known as Mobile Service Station (MSS). The wired network, connecting BSs, is known as the backbone network. Several base stations are connected to a mobile switching center (MSC) in the backbone network, as shown in figure 2.1. The MCS acts as a gateway from the cellular network to the backbone wired networks/wireless networks [50], [66].

In CR, primary users (PUs) are those who have to subscribe to a primary network. Secondary users (SUs) in CR do not have any subscribed channels and try to utilize the unused portion of the spectrum in the primary networks opportunistically. Coexistence of SU with PU is ensured with dynamic spectrum access (DSA) in CR network (CRN). Services of SUs are dependent on the free channels of the primary network [67].

5G network provides services to heterogeneous applications such as high-quality video streaming, Internet surfing, online gaming and tactile Internet, which lead to different resource requirements by different applications. It is pertinent to note that effective and efficient utilization of channels is a must for providing 5G services with QoS and QoE. CRN architecture generally comprises both primary networks and secondary networks [30]-[31], [68].

2.1.1 Cognitive Radio Network Architecture

The primary network consists of primary base stations and primary users (PUs). Primary network hold their right on the spectrum by having a license over it. PUs have their priority on the use of the spectrum of the primary network. The secondary network (SN), also known as the cognitive radio network (CRN), does not have any licensed spectrum and opportunistically uses the free spectrum of the primary network for their services. CR devices are equipped with hardware characteristics such as managing frequency bands, channel coding, and bandwidth by using software defined radio (SDR) through programming [29], which makes CR devices more flexible and adaptable to operate on different spectrum bands [4], [69].

According to FCC [28], CRT can be used for spectrum access by a third party, non-voluntarily. This means any unlicensed user can use the licensed spectrum in such a way that it does not interfere with the user that is holding the license of the spectrum [70].

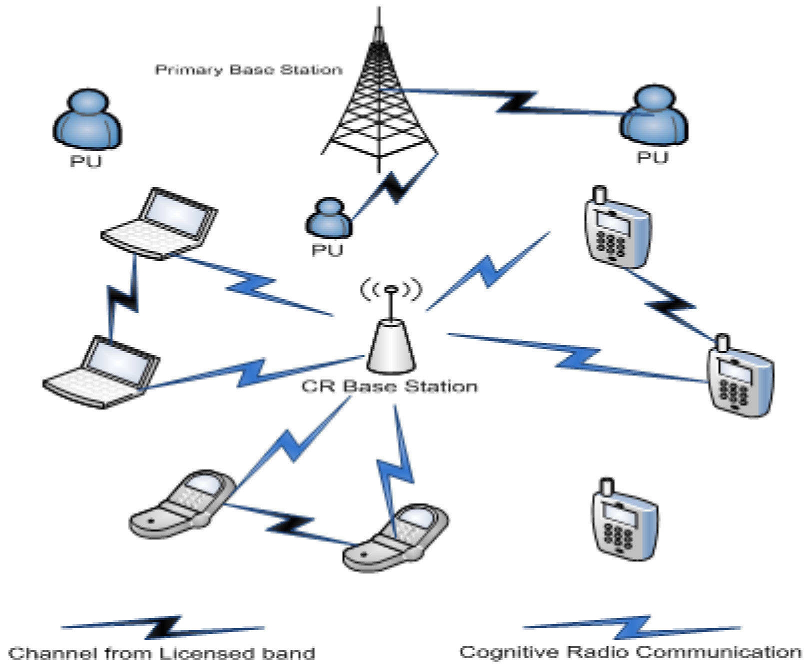

Figure 2.2: Architecture of Cognitive Radio Network [71]

CR has unique characteristics of flexibility, adaptability, and interoperability, which makes CR a capable technology for 5G cellular network spectrum management [4]. In figure 2.2, the basic architecture of CRN is shown.

2.1.2 Spectrum Hole

In CRN, the spectrum not being used by its licensed users temporarily in a specific area is known as spectrum hole (white space) as shown in figure 2.3. These spectrum holes are the basic resources for the CRN [37]. The available white space in CRN decides the network capacity. Therefore, it is essential to have accurate detection of the free spectrum (spectrum holes). The main operation of cognitive radio is based on the utilization of the spectrum holes. In CRN, one of the important jobs is to identify the spectrum holes and provide them to the SUs. The 5G devices can be enabled with cognitive capability by equipping them with the software-defined radio (SDR). Cognitive capability helps the devices to reconfigure different network protocols such as 802.16, 802.11, 802.22, etc. [4].

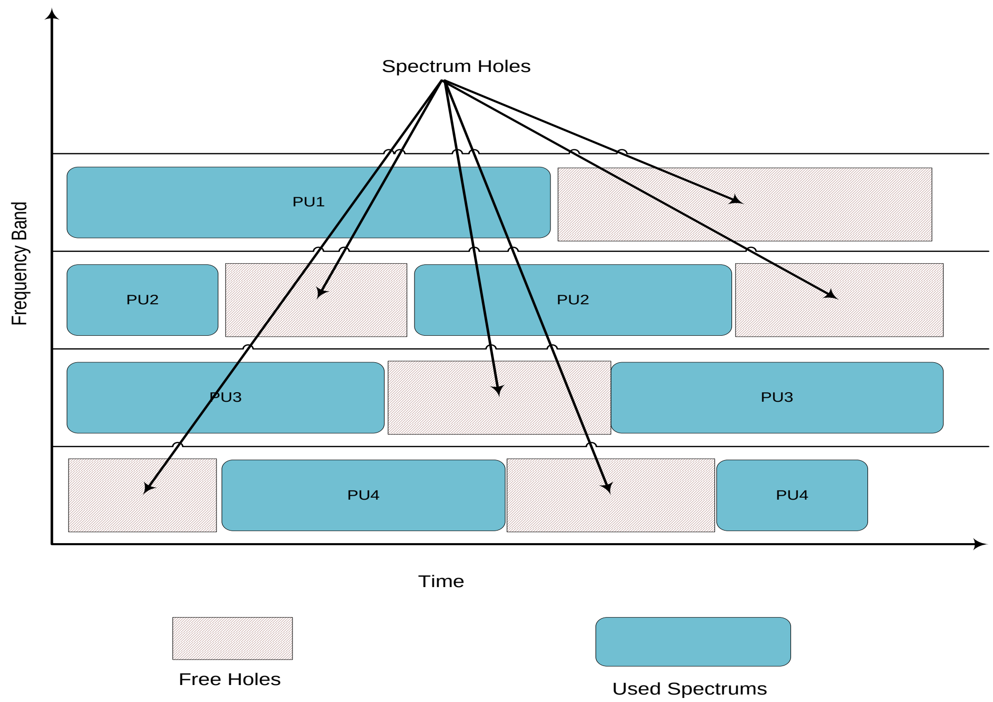

Figure 2.3: Spectrum Holes in CRN [71]

Detecting spectrum holes in CRN is very challenging as it needs to consider several factors which include fading, shadowing, and random interference etc. Detection of spectrum holes is a complex process in which the transmitter and the receiver of a SU work in coordination and try to explore common spectrum holes for the successful transmission. As in CRN, the transmission is opportunistic and entirely depends on the behavior of PU; throughput is normally difficult to guarantee.

In CRN, PUs are the users with the assigned licensed spectrum with priority uses. SUs are those users who opportunistically use the spectrum. The SU uses spectrum on a non-interfering or leasing basis, depending upon the policies agreed with PUs or regulatory authorities' guidelines. As SU uses the unused PUs spectrum, it increases the utilization of licensed spectrum. In CR, SU senses the radio environment and dynamically adapt to the communication parameters for effective communication. SUs are equipped with cognitive capability in the cognitive radio network which senses and learns from the surrounding radio environment. Using these capabilities, SUs identify the spectrum holes. Based on the available spectrum holes information, SUs select the spectrum frequencies and operating parameters dynamically using a software-defined network (SDN) [72].

Devices in cognitive radio enabled cellular network (CRN) are equipped with the capabilities of being programmed in such a way that they can transmit and receive using different frequency bands and can use different transmission access technologies [30]. The emergence of the IoT applications and 5G resource-hungry services require more spectrum than before. Therefore, to minimize the spectrum scarcity problem by achieving higher spectral utilization, CR technology can be used in 5G and IoT services [73].

In the CRN for successful connection, firstly, the best available channels are determined and then network operations are configured accordingly. In CRN, due to dynamic changes in the network environment, channel allocation requires a flexible network management system that can adapt to the network structure and utilize the available spectrum efficiently. The resource allocation schemes, developed for conventional cellular networks, are not suitable for CRNs as the transmission opportunities in CRNs are not identically available throughout the secondary user's single operation. The services of CRNs entirely depend on the activities of the primary network users [74]. Also, in CRNs, managing interference between primary users and secondary users and interference among secondary users is a big challenge.

2.2 Function of Cognitive Radio Network

In CRN, offering services are challenging because of dynamic variations in spectrum availability. Also, various QoS and QoE requirements of different services require a lot of control and management activities. CRN uses spectrum sensing, spectrum sharing, spectrum mobility, spectrum handoff, and overall spectrum management as its main functionalities. A SU uses spectrum sensing to detect whether PUs or other SUs are present in the spectrum or not. Through spectrum sensing, spectrum holes are detected by SUs, and accordingly, a decision about the transmission of data is taken. Using DSA, the selection of the best channel of various identified spectrum holes during spectrum sensing is made. Spectrum sharing is a control and management process through which available channels are shared among multiple users who compete to access the spectrum. Through spectrum mobility management, on the appearance of a PU, channels being used by SUs are switched to another channel if available. Spectrum handoff is the process of switching the channels [4], [11], [69], [75]. To manage these functionalities, a CRN spectrum management framework is needed, which can provide the following functions [4], [11], [69], [76].

2.2.1 Spectrum Sensing and Management

In 5G cellular network, devices use multiple channels for communication to improve the throughput. As in CR only idle channels can be used for communication; there is a need to perform proper spectrum sensing using a suitable mechanism to access large number of free channels. In the CR network, PUs have priority over SUs and on the appearance of a PU during the SU's transmission process, the SU must need to preempt the channel immediately for the PU.

To meet the service agreement, it is necessary for the SUs to continuously sense the spectrum band to observe PUs arrival or to find the spectrum holes. Sensing can be performed through a cooperative spectrum sensing approach by a group of SUs in collaboration or locally by a SU [40]. In the spectrum scanning technique, presented in [77], the spectrum occupancy over time and frequency is measured. This technique uses SRN (signal-to-noise ratio) estimation to improve the scanning performance. During the spectrum sensing phase, the channel detected is generally widespread over a broad frequency range. During the spectrum sensing phase, detected free channels are analyzed and channel allocation decisions are made on the basis of QoS and QoE requirements. In the spectrum sensing process, SUs regularly monitor the PUs activity. In CR, proper and precise sensing is required along with the signaling mechanisms, including transmission power control required to deal with PU activity. Irrespective of the spectrum sensing method, used for spectrum sensing, getting a perfect outcome is very difficult and there will be some sensing errors, including misdetections and false alarms. Sensing errors contribute to depressing the QoS of PUs and SUs.

In CRN, channels among the SUs are shared using the spectrum sharing process. Multiple SUs share the channels of PUs by coordinated access so that harmful interference and collision are eliminated [76]. The 24×7, broader coverage 5G heterogeneous networks can be ensured by proper spectrum sharing. Through this, a large number of users and diverse applications can be supported [78].

Many factors, including a licensed user's presence, availability of a wide range of spectrum and latency, are considered during the spectrum sharing. In cooperative spectrum sharing, a centralized location, called fusion centre, is used for data processing and to increase each CRs sensing capabilities. Data in the network is sent to the fusion centre for processing [79]. In non-cooperative sharing, all SUs behave in a selfish manner and try to maximize their gain. They do not cooperate with each other, and spectrums are sensed by the CRs independently. In this process, any CR does not obtain any data from other CRs in the vicinity. In non-cooperative sharing, all the CRs are at different position of each CR. Also, each of the CRs may have a different SRN. On the basis of the channel analyzing process, sensing techniques can be categorized into two groups: narrowband and wideband. In narrowband sensing, one frequency channel at a time is analyzed. In wideband sensing, a number of frequencies are analyzed at a time. In narrowband spectrum sensing techniques, it is in the hand of SUs to decide whether PU is present or absent for a spectrum of interest [80].

Spectrum sensing plays a major role in the performance of CRN, which helps avoid harmful obstruction like interference among the PUs and SUs and distinguish the accessible frequency band of PUs by SUs [81]. Through spectrum sensing, CRN learns about the radio environment by detecting the PU signals' presence and accordingly decides to use the PUs frequency band. Spectrum sensing helps CRN learn and adapt to the environment to make decisions on the efficient use of the radio spectrum [82].

In CRN, SUs find whether PUs are currently using signals in a specific channel or not using spectrum sensing [21]. If a channel is not in use by PU and is idle then SU receives typically noise only but if the channel is in use by PU, in that case, SU receives a signal consisting of both the PU signal and the noise. To detect the PU signal’s presence, generally, the energy detection model is used [83].

In the CR for sensing the local spectrum utilization, dedicated sensors are used or it is performed through a configured SDR receiver channel. For reliable spectrum sensing and radio resource management, localization of a PU helps in CRNs [84]. With the evolution in the cellular network, i.e. from 2G to 5G, localization methods have also evolved helping in locating the better position of the users in the system. The accuracy of the user positioning achieved in 2G system has further improved in 4G cellular system, using the assisted global navigation systems [85]. Further, in the upcoming 5G cellular systems, localization accuracy is expected to improve drastically in both outdoor as well as indoor environment that helps in providing better QoS [86].

The CRN co-exist with the primary network and uses its channel bands while managing its users’ diverse QoS requirements. It generates the requirements for proper spectrum management functions for CRN, which addresses interference avoidance challenges with primary networks. It also provides QoS in dynamic and heterogeneous communication systems with seamless communication. In CRN, spectrum management functions are required to provide proper spectrum sensing so that CR user can monitor the available spectrum bands of the primary network and detect the spectrum holes. Based on spectrum bands' availability, channels can be allocated to CR users [30], [87]. Spectrum sensing requires good knowledge of the PUs behavior for proper decision making [87].

2.3 Different Approaches of Channel Allocation

Based on the regulatory constraints and available network-side information, CRN uses three approaches, namely underlay, overlay and interweave for the communication [7], [16], [70], [88]-[89].These are as follows.

2.3.1 Overlay Approach

In this approach, the free bands of spectrum of PUs (not being used for the time being) are identified by the CR and accessed by the SUs for their services in a dynamic manner. The PUs shares the knowledge and messages of their signals with the SUs. The SUs has knowledge of the PU's codebooks and their messages and use this knowledge for interference mitigation. This approach is more practical and suitable for TV bands. In this scheme, the waiting time of SUs transmission depends on the PUs behavior. In overlay communication systems, SU and PU can communicate simultaneously on the same band using various encoding and interference mitigation schemes. In this approach, the transmission power of the SUs only depends on the device constraints.

2.3.2 Underlay Approach

In the underlay approach, both SUs and PUs transmit their signal in the same time-slots using the network's spatial and frequency channels. SUs use the location coordinate of PUs to mitigate interference with PUs during communication. In this approach, SUs are permitted to communicate simultaneously with the PUs by sharing the PUs channel with controlled and limited power. In this approach, high priority is given to the PUs and SUs are not allowed to communicate beyond a threshold limit of the interference so that it does not cause an intolerable interference on the PU [6].

The interference constraints are managed by the spread spectrum technique, by ultra-wideband (UWB) techniques, or by directional antennas. This approach is more sophisticated as the PUs allows SUs to access that spectrum currently in use by the PUs. This approach is less practical as it compromises on the QoE but it is still suitable for cellular networks and ultra-wide bands. In underlay communication, it is the SU's responsibility to determine the interference caused to PU due to their transmission and continue its transmission only if interference caused to PU is under a threshold. In this approach, SU communicates by transmitting data at very low power so that it does not have interference with the PU [7].

In CRN, PUs and SUs share the same sub-channel using the underlay approach. In this approach, strong co-channel interference (CCI) is one of the common problems in the allocation of channels. In underlay communication in CRNs, CCI may appear from three sources; from SU to PU, from PU to SU, and interference among the SUs themselves. In underlay communication, SUs are responsible for communication in such a way that interference to PUs is below a given limit. Therefore, in the underlay CR network, SUs operate with the objectives to maximize their transmission rate and keep minimum interference to the PUs. In the underlay approach, the transmitting power of SUs is limited by the device capabilities and the interference limits of the PUs.

2.3.3 Interweave Approach

The idea of opportunistic communication is based on the utilization of spectrum holes by the SUs for their communication [31]. This idea is the original motivation for the cognitive radio [20]. In interweave systems, SUs use PUs bandwidth opportunistically and are allowed to access only those bands/spectrum which is not being used by the PUs for quite some time [7]. Hence, this scheme completely avoids interference between PUs and SUs by not allowing the transmission in a PU occupied band. In this approach, SUs search for the spectrum holes (the spectrum in either frequency or time domain), and only broadcast a signal if spectrum holes are available. In this approach, SU exploits the opportunistic feature and transmit only using the spectrum holes available in the primary network using the knowledge of the activity of the PUs. Proper spectrum sensing plays a greater role in the performance of the interweave approach. The disadvantage of this approach is that if no spectrum hole is available, SUs have to wait for a long for their services. In interweave approach, the SUs transmit power depends on device constraints and the sensing range.

2.4 QoE and QoS in CR Network

With the evolution in communication services, QoE and QoS are most often desired by the telecommunication users. These have been briefed as follows.

2.4.1 Quality of Experience (QoE)

QoE is the subjective description of the observation of the user about the working of the applications/services. QoE is application-specific and centered towards the user experiences of the service. Some examples of QoE based applications may include the experience of quality in video transmission, low latency for time-critical services such as video transmission, gamming, and augmented reality. Providing high QoE services may eat up valuable resources like spectrum, device battery, base station power etc. At the same time, delivery of services with too low QoE may increase user's dissatisfaction. Therefore, a balance between the scale of QoE and the relative cost of services are required. In 5G cellular network, QoE requirements are stringent in terms of very low latency and extremely reliable communication. Therefore, it is challenging to meet the desired level of QoE [90]-[93]. To meet the desired level of QoE, CRN uses its software-defined nature and flexibly provision the necessary resources [10], [91]. Mean opinion score (MOS), from the end-users, is obtained by applying a subjective test under the laboratory environment to measure the QoE [90].

As 5G cellular network has very stringent QoE requirement, it is challenging to provide the services with QoE's desired level. To offer better QoE, low latency and high bandwidth are among the necessary requirements. Along with the traffic optimization techniques, CRN can use its software-defined nature to flexibly provision the required resources to achieve the desired QoE [10], [91]. High spectrum handoff latency is one of the critical QoE parameters in cognitive 5G cellular networks. Specifically, spectrum handoff latency is more stringent in multimedia services as it reduces the QoE [4]. Spectrum handoff latency is shown in figure 2.4. In CRN, SUs channel sequencing has a significant impact on the handoff latency.

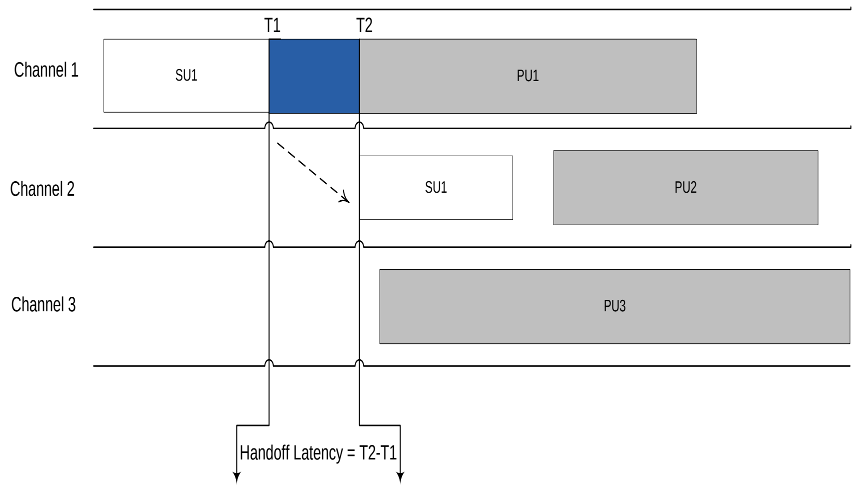

Figure 2.4: Spectrum Handoff Latency in RCN [71]

To reduce the sensing time, instead of sensing channels in a random manner, they should be sensed in the order of most probably to least probably vacant [11]. To support multimedia applications in CRN, a QoE based spectrum handoff scheme is presented in [33]. This scheme is based on the mixed preemptive and non-preemptive model. This scheme uses a resume priority queuing model to analyze the PU interruptions effects and SU spectrum access conflict situation on spectrum handoff.

2.4.2 Quality of Service (QoS)

QoS is represented using various measurement parameters such as response time, throughput, rate of transmission, blocking and dropping probabilities, access delay, transmission delay, jitter, packet loss rate etc. [10], [67], [91], [94]. QoS parameters have an overall effect on network-oriented performance and focus on the entire service experience [10], [91]. In the context of a cellular system, the quality of transmission is always related to the type of service used. Due to its varying bandwidth demand and time-critical requirements, more complexities are involved in multimedia applications than simple voice applications. The voice traffic is bustier and more sensitive to delay than the data traffic. Hence QoS requirements for voice traffic are different from data traffic. Data traffic is more delay tolerant but voice traffic is time-critical and less tolerant to delay. In terms of transmission error rate, data is highly sensitive to bit error rates, requiring it to be 10^{-6}. However, voice can be transmitted with a bit error rate of 10^{-3} [95]-[96].

The QoS parameters include a set of specific requirements that service providers should offer to their users to fetch the required services with certain level of satisfaction. To offer better QoS has always been a major concern in cellular systems. It is observed that a trade-off is involved, among the various related service parameters, in an attempt to offer better QoS. Many researchers have considered different QoS parameters, such as call blocking probability (CBP), call dropping probability (CDP), performance, flexibility, and complexity in their study. There have been attempts to provide channel allocation algorithms to improve the QoS [66], [97]-[98]. From user's point of view, call dropping is unacceptable. However, in some cases, call blocking may be tolerable up to some extent [99].

Minimizing the CDP and CBP is one of the main goals for better QoS. Most of the admission control and channel allocation schemes, proposed in the literature, have tried to minimize the CBP and/or CDP to maintain the QoS of wireless cellular networks [100]. Contrary to QoS, measurement of QoE is very specific to applications and user-centric [10], [91]. There are many challenges involved in channel allocation which directly or indirectly affect the QoS of the system. The following four conditions need to be fulfilled for a successful channel allocation.

- Channel should be available
- Carrier to noise ratio (CNR) between the mobile unit (MU) and BS is above a given predefined threshold
- Carrier to noise plus interference ratio (CNIR) is above a predefined threshold
- The minimum required channel is allocated to a multimedia service to run with the video's acceptable clarity.

In addition to these four conditions, CBP and CDP play a vital role in determining the QoS in a cellular system. *The call blocking probability (CBP) is the probability of a new initiated call being blocked while call dropping probability (CDP) is the conditional probability where handoff calls from the neighbouring cell are dropped.* The low rate in both new call and handoff call and uninterrupted communication increase the system's QoS. Model for time-critical applications for channel allocation is designed in such a way that computation at each BS/MSC should be as low as possible.

Another challenge in channel allocation is to ensure fault-tolerant and reliable communication [101]. Usually, fault tolerance and reliability would demand redundancy. Fault-tolerance and reliability may be achieved by minimizing the failure probability of the failure-prone items. Instead of keeping more reliable centralized control of the system, better reliability can be achieved by using many low-reliability components in a distributed manner [102]. Through optimal provisioning, attempts are made to offer better services to the users by maximal utilization of the capability of the selected network's resources [67]. Some of the broad measurements of QoS can be parameters such as availability of channels, accessibility, maintainability, and user satisfaction. When a user request comes, the operator is expected to assign one or more channels as per the service demand of the user within a specified time period. In the case of traditional cellular service, this time delay is a maximum of 6 seconds. [103].

The function of providing channel, as per the requirement, is termed as availability. Accessibility is referred to as users' capability by which the service provider's channels can be accessed for their service request. For example, when a 100 kHz channel is allocated to a user device for some service, the device should be capable to communicate at high modulation signal. This event is called accessibility. Maintaining established communication in a cellular system is a challenge, as a service provider has to take notice of various parameters like movement and speed of the user, handover, etc. Providing user services while managing these service parameters is known as maintainability. The user satisfaction level is a highly personalized parameter for observing the QoE and QoS. Service providers are required to deliver the services as per the user's quality of expectations to remain competitive in the market. As the services offered are also diverse, such as browsing, multimedia streaming, gaming, and uploading/downloading contents, the QoS and QoE requirements are different for different services. For example, 5G networks are expected to comprise of heterogeneous applications such as Internet gaming, high definition (HD) video streaming, tactile Internet, multimedia applications. These services have their own QoS/QoE requirements. Hence to offer better services, supporting multiple service classes is a must for 5G networks [24].

QoE relates to the user's experience of the service quality of the applications. To provide better QoE, different systems may have different amount of network resources. As QoS is a measurement from the service provider side and based on technical parameters, hence it does not directly reflect the quality of services experienced by the end-users. In measuring the QoS, QoE is more connected with the user's subjective perceptions and has more assurance about meeting the user's needs and timeliness of content delivered [104]. In CRN, QoS attempt to guarantee a minimum transmission rate, minimize latency, jitter and packet errors. In the context of multimedia transmission over CRNs, accessing QoE is still challenging and an open issue [90].

Matrices used for measuring the QoS to evaluate network performances are packet loss, delay, jitter, call dropping rate, call blocking rate [24], [105]. Though each of the candidate 5G wireless radio frequency (RF) band provides advantages of higher data rate, reliability and low latency than 2G, 3G, and 4G communications, no single band is able to fully achieve the desired level of QoE for the complete range of wireless access devices including smart phones, tablets, laptops, vehicles, health equipment, smart buildings etc. [35].

In contrast to QoS, in measuring QoE subjective matrices are used. These indicate not only the network performance but also the subjective opinion of users about the services. In recent wireless communication research, QoE has taken an important place in designing the solution models [104]. ITU has proposed many standards on subjective assessment methods for various application scenario. Mean opinion score (MOS) is the most widely used metrics for measuring the QoE [106]. MOS is used to measure the utility of the services and characterize QoE by refracting users' opinions in varying ranges from totally unacceptable to complete satisfaction on services [107]. QoE estimation models, based on the conventional QoS-QoE mapping method, are not suitable for the CRN as they ignore the parameters such as spectrum handoff delay and handoff frequency which are critical in terms of SUs' QoE performance in CR multimedia applications. It is challenging to have a simple correlation between QoS and QoE because QoE metrics not only characterize QoS but also consider users' requirements [35].

QoE attempt to address the issue of fairness in terms of user satisfaction. It is important to note that more QoS does not always make higher QoE; a detailed explanation of key determinants of wireless QoE are given by J.Mitola et al. in [35]. Better QoS always do not guarantee a high QoE score. For example, if data is delivered in 100ms for a service with delay requirement of 50ms, it may result in a low QoE score but high QoS performance [90]. The relation between QoS and QoE is more complex because QoE metrics attempt to characterize the match between user requirements and services quality [108].

QoE is used as an effective mechanism for video transmission, as it may give an actual perception of the user on the visual quality of video transmission. To measure QoE, the metrics used include the visual quality of a video transmission and network environment parameter such as packet loss rate, network delay, etc. Also, the quality of video content delivery depends on the type of content. For example, in the same network conditions, the quality of the transmission of video content having fast motion like sports, video game etc. is generally worse than that of video contents with slow motions like movies, news etc. [109]. A QoE based scheme proposed in [33], support multimedia applications that assign a priority of SUs based on their QoE requirements and achieve better performance by allocating more available resources to SUs. To study QoE for multimedia services, MOS is used to measure the end-user satisfaction [106]. A QoE-driven scheme, proposed in [106] for spectrum handoff, offer to enhance the end-user satisfaction by using MOS for spectrum handoff. The scheme proposed in [90], maximizes the SUs' expectation of MOS by adoptively using channel conditions and the traffic load of SUs'.

To sustain in the highly competitive market, 5G networks need to achieve high user QoE. All candidate 5G wireless radio technologies, including cognitive radio, offers advantages that include more extended range or higher data rate, efficient channel utilization compared to 2G, 3G, and 4G technologies, but none of the single band or air interface standard alone is able to offer ubiquitous levels of QoE for the whole range of wireless devices [35]. With strict QoE and QoS requirements in 5G services like interactive multiparty gaming, high definition (HD) content delivery, for commercial acceptance of QoE, there is the need of mapping among MOS, QoE and QoS [25].

Due to its opportunistic nature and dependency on primary network resources, CRN is prone to channel access failure compare to primary networks. Therefore in CRN, offering assurance on reliability and availability to the users is challenging [8]. The QoS metrics generally cover channel capacity, data rate, error rate, etc. However, only offering services with better QoS does not satisfy the users of heterogeneous multimedia services.

As the mobile communication environment is dynamic, some services keep on completing whereas some new service request keeps on arriving in the system. For proper services, the operator needs to manage the flow of the user's communication, handover, etc. This function is known as maintainability [103].

Considering the user, call blocking and call dropping are two most important QoS parameters. Call blocking (CB) occurs in a cellular system if upon receiving a new connection request, cell is not able to entertain it due to non-availability of the channel. Whereas call drooping (CD) occurs if an ongoing connection is dropped due to traffic congestion or due to incapability of the cell to provide enough bandwidth. Generally, call dropping occurs due to denial of some channels to an existing connection. The call dropping probability (CDP) and the call blocking probability (CBP) in any system should be minimized for better QoS. Therefore in mobile communication system, channel allocation problem is seen as an optimization problem [6], [50], [66], [97]-[98], [103].

Cellular communication systems are trunked radio systems, as each user in the system is allocated the channels on a per-call request basis. Cellular operators serve a large number of users using the trunking concept with less number of channels assigned to the operator. When a user requests for a service, and if all of the system's radio channels are busy, the new service request is blocked. In some service models of communication systems, the concept of queue is used to hold the new request until channels become available for the service. Grade of service (GoS) is used to measure the cellular systems' ability to provide access to the services in busy hours of operations. In other words, GoS measures channel congestion which is expressed in terms of probability of a call blocking or the probability of a call delay beyond a specified time. For example, if in a cellular system GoS is of 2% blocking, this means the cellular system is designed to block 2 out of 100 services of the users because of channel congestion or channel unavailability during the peak hour.

Trunked cellular systems are of two types. One in which, for call request, no queuing facility is provided is known as the "Erlang B" system. Another formula in which call request queuing facility is provided, is known as the "Erlang C" system. This is also known as Erlong B and C Formula and these were developed by A.K. Erlang [110]. Performance evaluation of call blocking probability is evaluated using the Erlang B formula, which is expressed in equation (2.1) [110].

$$BP = \frac{\frac{A^N}{N!}}{\sum_{i=0}^{N} \frac{A^i}{i!}} \qquad (2.1)$$

Where BP represents the probability of call blocking, A is total offered traffic in Erlang and N is number of trunked channels.

To measure the GoS, known as call blocking probability for that call that waited in a queue before being blocked, the "Erlang C" formula is used [110], which is expressed in equation (2.2).

$$CDP = \frac{\frac{A^N}{\left[N!\left(1-\frac{A}{N}\right)\right]}}{\sum_{i=0}^{N} \frac{A^i}{i!} + \frac{A^N}{N!\left(1-\frac{A}{N}\right)}} \qquad (2.2)$$

Where CDP represent the probability of call delay (of waiting for service), A is total offered traffic in Erlang, and N is number of trunked channels. In Erlang C formula (equation 2.2) incoming calls arrival follows Poisson distribution whereas calls service time is exponentially distributed.

While modeling cellular communication, two important factors i.e. call arrival rate and call holding time are used. These factors are unpredictable in cellular communication. The call arrivals, in classical studies of communication, is assumed to follow Poisson's distribution. This process is based on a memory less system and the system is having a large number of independent users. Poisson's process states that for non-overlapping events, if the average arriving rate of events is λ, then the probability of 's' arrivals in time t is given in equation (2.3) [8], [111]-[112].

$$P(s,t) = \frac{(\lambda t)^s}{s!} e^{-\lambda t} \quad (2.3)$$

The call holding time of the service request follows the negative exponential distribution [113]. It has the probability distribution function (pdf) as given in equation (2.4). In the negative exponential distribution, μ indicate the mean service rate and *t* indicate the time duration.

$$f(t) = \mu e^{-\mu t} \quad (2.4)$$

2.5 Mobility Management and Spectrum Handoff in CRN

Spectrum mobility management in CRN is one of the most important functionalities by which channels are managed during the service requests of PUs while SUs are using the PUs channel. The spectrum mobility process starts due to a change in the system's operational conditions, such as a SU is forced to preempt the channel currently in use due to a PU's appearance. Through spectrum mobility, SUs operations are handoff from one frequency channel to another [76]. The goal of spectrum mobility is to provide the expected QoS/QoE in the dynamically changing spectrum condition. On the arrival of a PU, services of SU are interrupted to return the channel to PU. Spectrum handoff occurs, in which SU's service is shifted from one channel to another [33]-[34].

Spectrum handoff may occur due to one of the followings: (i) arrival of a PU for the channel occupied by the SU (ii) spatial mobility of the SU (iii) degradation of link quality and SNR.

Through the spectrum handoff process, SUs are provided a suitable channel for continuing their services [11]. Multiple handoffs, in a single transmission, degrade the system performance as it leads to excess switching time, which in turn affects the system's efficiency. Spectrum handoff may cause harmful interference with PUs; thus, spectrum handoff should be performed wisely.

During the spectrum handoff process, SU pauses its ongoing transmission and return channels currently used by it to PU. It switches to some free channel if available and resume its transmission. In case no channels are available, interrupted SU is forced to terminate its session. In [7], a decision support system based on fuzzy logic is proposed. This system jointly manages with both channel selection and channel switching to improve the throughput of the system. The spectrum management process provides dynamic spectrum access to CR users. The activities of the spectrum management process are as follows [39]:

1) Determine the available portions of the spectrum,
2) Do the selection of the best available channel,
3) Do channel coordination with other users, and
4) On arrival of a licensed user, vacate the channel from a secondary user.

Spectrum management functions in CRN are done dynamically by provisioning the software using SDN features of CR. Efficient handoff handling has a good impact on QoS, which tries to ensure seamless transmission and avoids interference. In a cellular network, handoff occurs due to users' mobility from one cell to another. On the contrary, the spectrum handoff in a CRN occurs to a stable user on the arrival of PU. During its single service period, a SU may experience several spectrum handoffs [69], [114]; therefore, it is challenging to give service assurance in CRN.

As in CRN systems, SUs do not own any channel and depend on unused channels of the PUs (the owner of channels). Therefore, when a PU decides to access its licensed spectrum, SU must have to leave that channel and explore other means to access some other available channel to continue its transmission. After the arrival of PU, SU is forced for spectrum handoff. In that case, SU may have the possibility to perform one of these three actions:

1) SU suspend the transmission and leave the channel for PU and wait till PU finishes its transmission. Subsequently, after PU vacate the channel, the SU will resume its transmission again on that channel.

2) If another free channel is available, SU selects and switch to it.

3) If SU doesn't want to be in suspended mode and there is no fee channel to switch the transmission, SU has to terminate its session.

As during the spectrum handoff process, SU either transfers ongoing communication on some other free channel or keeps ongoing communication suspended, SU will not be able to provide a QoE requirement of the seamless communication [39], [111]. Spectrum mobility is managed using different spectrum handoff techniques. These techniques are non-handoff, proactive handoff, reactive handoff and hybrid handoff [33]-[34].

2.5.1 Non-Handoff

The spectrum handoff process's main activity is to find transmission opportunities for SU so that it may continue its transmission as channel switching is associated with complexities such as finding a new free channel, time of switching, etc. Sometimes, to minimize the spectrum handoff cost, SU may go in a wait state until PU's current channel is available again. Once PU makes the licensed channel free, SU resumes its transmission again on that channel [34]. This situation is known as non-handoff [39]. This strategy is not suitable for delay-sensitive applications and cannot meet the QoS requirements of many of the services [34].

5.2 Proactive Handoff

The proactive handoff approach works on the prediction of handoff occurrence. In this approach, a pre-knowledge of the PU traffic is used. This approach provides short handoff latency by keeping a target channel sequence ready before the actual handoff request is generated. To maintain the channel sequence for future use, SUs sense all channels periodically. Accurate information of channel-usage statistics is a must for a better result in this scheme [11], [115]. However, a poor prediction of PUs arrival may degrade the overall throughput and may affect the QoE adversely.

In [34], a proactive spectrum handoff mechanism is propped with the objective to minimize total cost and maximize data transmission efficiency. This scheme uses the discrete-time Markov decision process for an optimal solution.

In [4], a proactive spectrum handoff mechanism propped to optimize total cost and data transmission efficiency. This scheme uses a database and indexing in the channel allocation process to manage the spectrum handoff. This scheme addresses several issues, including different QoE requirements for different class of services, prediction of PUs, and handoff interruption management.

2.5.3 Reactive Handoff

In reactive handoff [11], [39], spectrum sensing and handoff action both are applied reactively. When handoff occurs, the target channel is selected to perform handoff. SU starts the spectrum sensing process after the handoff event occurs. Once the SU finds a free channel, its transmission is switched to that channel. SU may get an accurate target channel for handoff in the reactive handoff approach because the environment's actual requirements are used for spectrum sensing. This scheme suffers from longer handoff latency because of the delayed start of spectrum sensing. The reactive spectrum handoff performs the spectrum-sensing process with greater accuracy compared to proactive spectrum handoff. To achieve greater accuracy, reactive handoff scheme compromise for high spectrum latency. This scheme is suitable for applications which are liberal for handoff latency but requires better accuracy in spectrum sensing [11].

2.5.4 Hybrid Handoff

This scheme is the combination of the reactive and the proactive spectrum handoff schemes. It uses proactive spectrum sensing and reactive handoff action [4], [34]. As the SU performs spectrum sensing activity before PU arrives, fast spectrum handoff can be achieved. A hybrid spectrum handoff scheme is an attempt for a good trade-off between proactive and reactive spectrum handoff. Through the spectrum handoff process, SUs throughputs are significantly increased.

In table 2.1, a comparison of different spectrum handoff schemes is given. In CRN, where a SU may experience multiple spectrum handoff situations, there are many challenges associated with it. These challenges include high operation cost due to frequent channel switching, energy consumption, and high spectrum handoff latency on average throughput and QoE requirements. Therefore, there is a need to study the spectrum handoff strategy which considers a balance among the various trade-offs such as cost of transmission, cost of spectrum handoff, and QoE's performance constraints for transmission in CRN.

Table 2.1: Comparison of different spectrum handoff strategies

Handoff Strategy	**Classical (Stay and Wait)**	**Reactive**	**Proactive**	**Hybrid**
Main Characteristics	i. Very low interference level of PU	i. No prediction of PUs arrival required ii. Spectrum sensing is performed by SU handoff detection	i. Predict PUs arrival ii. Accurate traffic prediction required	i. Predict PUs arrival ii. Accurate traffic prediction required
Advantages	i. Low handoff cost (less energy consumption)	i. Accurate target channel section	i. Very small handoff latency ii. Minimize multiple spectrum handoff	i. Short handoff latency ii. Minimize multiple spectrum handoff
Disadvantages	i. Extremely large handoff latency ii. Reduce throughput	i. Large handoff latency	ii. False channel selection iii. Knowledge of the PUs traffic model is required	i. Knowledge of PUs traffic model is required

2.6 Centralized and Distributed Approach of Channel Allocation

In the recent past, channel allocation schemes for CRNs have been investigated extensively in the literature. It is observed that cognitive radio enabled cellular networks have been designed either using a centralized or a distributed channel sharing and control mechanism [11], [76]. In literature, proposed algorithms for resource allocation in cellular network are based on either a centralized approach or distributed approach [76]. In a centralized system, spectrum sharing is controlled by a central entity. In a distributed system, the decision of spectrum sharing and allocation is taken by each node independently [116].

Both the approaches have their advantages and disadvantages and have been applied on the basis of the problem requirement and systems priorities. The centralized approaches suffers from scalability and reliability. Distributed approaches have the potential and are both reliable and scalable. A central controller assigns the channels, in the centralized schemes. However, in distributed schemes, a channel is assigned either by the local base station of the cell or selected autonomously by the mobile user [65], [76].

2.6.1 Centralized Approach

In the centralized approach [50], [117]-[121], the channel allocation process is managed by a central entity. This entity may be a Mobile Switching Center (MSC), a base station (BS), eNodeB or a dedicated control node (server) [117], [122]. In the network, the central entity is the only one that has access to system-wide channel usage information. In this approach, particularly, each cell notifies the central entity when it acquires or releases a channel. This equips the central entity with in hand information of the available channels in each cell at any time. In centralized schemes, the central entity has full knowledge of the whole network, which helps in obtaining informed solution based on the desired performance metric (maximize spectrum efficiency, allocate channel fairly etc.) of the network. Also, in centralized schemes, user priorities are handled more efficiently. The centralized approach may suffer from single-point failure because the whole system's functioning depends only on the central entity. This approach is neither scalable nor reliable because the failure of the central entity brings down the whole system covered by it. Also, in the case of a hefty system traffic load, the central entity may become a bottleneck [117], [122].

A centralized channel allocation scheme is presented in [11] for efficient handoff handling in CRN. In this scheme, a centralized cognitive device is used for CR operations such as spectrum sensing, spectrum management. A centralized cognitive device improves the accuracy in sensing, reduces the handoff time, and minimizes energy consumption. This scheme uses a preemptive resume priority (PRP) M/G/1 queue for handling priority-based handoff requests.

2.6.2 Distributed Approach

Distributed channel allocation approach is simpler and more robust as compared to the centralized approach. The distributed approach of channel allocation [50], [76], [121], [123]-[125] is better as compared to centralized channel allocation due to its high reliability and scalability. In contrast to a centralized approach, there is no central entity to control the channel allocation process in a distributed approach. Each eNodeB/BS makes their channel allocation decision independently based on local information with limited cooperation from neighboring eNodeB/BS by exchanging only that information which is required to reach the decision on channel allocation [76], [125].

The distributed approach of channel allocation efficiently utilizes bandwidth, adoptively manages mobility, efficiently manage spectrum handoff and provides QoS guarantees [37], [70], [76], [125]. The distributed schemes are more flexible and adaptive to changes in the wireless environment than the centralized schemes. Therefore, in case of failure, the recovery is fast. This make distributed schemes a better choice for critical services. Another advantage of distributed approaches is minimum overhead in exchanging information with the neighboring cells. The disadvantage of distributed approaches includes sub-optimum channel utilization due to lack of global information of the system. Distributed approaches are not suitable for high load networks [37], [70], [97], [121]. An Artificial Intelligence (AI) based four layers distributed cellular network framework for optimal channel allocation is proposed in [13]. A comparison of centralized approach and distributed approach, based on several parameters, is given in table 2.2.

Table 2.2: Comparison between Centralized and Distributed CA Approaches

Evaluation Parameter	**Centralized Approach**	**Distributed Approach**
Network Knowledge	Global	Local
Complexity	More	Less
Reliability	Less	More
Scalability	No	Yes
Robustness	No	Yes
Use of Local Information	More	Less
Channel Utilization	Optimum	Sub-Optimum
Fairness in Channel Allocation	More	Less
Heavy Network Load	Suitable	Not suitable

2.7 Channel Allocation Schemes

It is imperative to deliberate on some popular channel allocation schemes studied in the literature.

2.7.1 Fair Channel Allocation Schemes

The channel allocation scheme, proposed for distributed cognitive radio network in [18], tries to maintain fairness among the SUs using the channel-aggregation (CA) technique and multi-channel assignment. To protect PUs from SUs interference, dedicated sensors (DSs), periodically perform spectrum sensing. In this scheme, SU uses free channels in an overlay manner. Also, to solve the fairness problem in CRN, a distributed medium access control (MAC) protocol for channel allocation is discussed in [126]. This scheme uses a combination of a greedy approach and the max-min criteria for channel allocation.

Distributed channel allocation scheme, discussed in [127], aims to fair channel allocation to the users along with maximizing the network throughput. In any cognitive radio network, an effective spectrum assignment is a challenging task. If a multi-channel selection-based spectrum assignment scheme is used, secondary users can enhance the network throughput by utilizing multiple channels. A model is given in [128], in which a fair multi-channel assignment scheme is proposed for cognitive radio networks. Through simulation, it is observed that a fair multi-channel assignment scheme results in a good trade-off between throughput and fairness of the spectrum assignment. Though the model has applied the CR concept, no cooperation with other primary networks is suggested towards further possibilities of improvement in radio spectrum utilization. Dynamic spectrum allocation for heterogeneous cognitive radio networks is given by W. Zhang et al. [129]. In this, the concept of multiple channels has been used to facilitate the secondary services with the aim to enhance the throughput of the secondary services. This model basically takes care of the appropriate channel allocation to the secondary sender-destination (S-D) [130] pair for sensing and utilization.

A fair optimal resource allocation model is given in [6], in which a correct reception probability (CRP) is introduced as a metric to measure the network utility. While allocating the resources, two constraints have been taken care of; co-channel interference and average power budget constraints. A service-oriented bandwidth borrowing model is given by J. Change et al. in [131]. In mobile multimedia wireless networks, requirement-based bandwidth borrowing is used. This model reduces the bandwidth reconfiguration overhead and controls the call admission to maintain the QoS. It infers that for the good quality of realtime services, the minimum speed for Voice Over Internet Protocol *(*VoIP*)* [132], phone calls should be between 90 kbps to 156 kbps at the other end of the VoIP speed spectrum. Although many models have been proposed for the channel allocation problem for realtime and non real-time services, it is observed that these lack the service request that has the specified bandwidth requirement. Only a few models discuss the service requirement based bandwidth borrowing in which realtime and non-real-time service requests will have specified bandwidth requirements [131].

2.7.2 Cluster Based Channel Allocation Schemes

To overcome the problem of sub-optimum channel utilization by distributed schemes, decentralized channel assignment schemes are developed [64], [133]-[134]. These schemes use cluster-based wireless networks to take advantages of both; centralized and distributed channel assignments. In a decentralized channel assignment, a cluster head performs the intra-cluster channel assignment in a centralized manner. The knowledge of the nodes of a cluster is utilized by cluster-head for the intra-cluster channel allocation. In [134], a semi-distributed hierarchical interference management scheme is proposed. This scheme is based on joint clustering and radio resource allocation for the femtocells. In [133], a QoS based, robust, clustering-based admission control scheme has been discussed for an OFDMA femtocell network. Entire subchannels of a single cluster are available to the SUs of that cluster. The SUs within a cluster can simultaneously communicate over different subchannels, avoiding mutual interference among the SUs. The numerical results show that this scheme achieves higher system capacity as compared to other schemes.

Channel allocation in CR is a non-convex problem solved by applying subchannel allocation [5] and power allocation along with k-means clustering techniques. Results presented in [5] indicate that spectrum allocation is significantly improved with a quick convergence rate in this model. It also indicates that the technique is able to ensure fairness among users.

2.7.3 AI Based Channel Allocation Schemes

To solve the resource allocation problem in CRN, heuristic/meta-heuristics e.g. genetic algorithm (GA), particle swarm optimization *(*PSO*)*, Fuzzy Logic etc. have been used extensively [7], [13], [135]-[137].

The model proposed in [13], using AI and CR technologies, divides the whole network into four tiers. BS control mechanism is made using AI technique, which optimizes the channel allocation in distributed cellular network. The result shows that after all the BS have completed the learning, channel demands of the PUs and the channels allocated by each BS are almost the same.

A Fuzzy logic-based model for efficient channel utilization is given in [7]. The proposed scheme reduces channel switching rate of the SU and makes channel selection more adaptable. Cognitive users (secondary users) opportunistically exploit the white spaces available in a licensed spectrum. Also USs immediately releases the channel on sensing the appearance of the primary users. Both channel selection and channel switching are jointly managed by the decision support system of this model to enhance the overall throughput of CRNs [7]. In this model, for better channel utilization, both underlay and interweave approaches have been used. Results show that this model performs better in transmitting data packets because of best channel selection based on susceptibility. This model assumes that if a channel is less susceptible to PU transmission, it will be available for a longer period and thus incur less channel switching.

A cognitive channel allocation model is given by Singh et al. [135], which applies genetic algorithm (GA) for channel allocation in a cellular network. The concept of GA and cognitive radio utilizes the radio spectrum better. Services are categorized into four; primary new, primary handoff, secondary new and secondary handoff. Primary services are high priority services than secondary services. The lending of single-channel, as well as multi-channel, is also applied for better radio spectrum utilization. It is observed that call block and call drop are minimized significantly in this model.

A heuristic channel allocation model using multi-lending is given in [5], where the multi-lending concept is applied over 42 cell cellular network to minimize the call block and call drop. Cognitive radio enabled the opportunistic utilization of licensed channels by the secondary users, which enhanced the radio spectrum utilization and minimized the call blocking and dropping. In the model, services are considered into two categories; real-time and non-real-time used by primary and secondary users, respectively. A CR based heuristic channel allocation model is proposed by Vidyarthi et al. [12], in which services are categorized into two; realtime and non-real-time services. Realtime services are recognized as primary services and non real-time as secondary services/cognitive services. For the effective radio spectrum utilization, cognitive radio concept is used to facilitate the secondary services. Results show that radio spectrum utilization has improved significantly with this proposed method. A revenue-based mechanism is used to accommodate the number of secondary users by applying the particle swarm optimization (PSO) in [137].

Multi-objective based resource allocation in the cellular network always has been a challenging task. A hybrid optimization-based model [138] has been proposed in a cooperative cognitive radio network (CCRN) to handle various issues. These include load balancing, PSO based energy-efficient cluster formation, multi-factor differential evolution for prioritization of traffic levels and modified gravitational search algorithm for resource allocation throughput. It is shown that hybrid CCRN (HCCRN) performs well and utilizes the radio spectrum quite well. A cognitive radio-based spectrum allocation model, given by [73], is a multi-objective optimization model that addresses the issues concerning utilization and network throughput. The model intends to maximize the spectrum utilization by concurrent transmission on the channel.

In [139], a price based channel sharing model using PSO has been proposed. This model minimizes the price incurred by the SUs. Another model, proposed by N. Ul Hasan et al. [67], uses PSO and modified GA for network selection in such a way that minimize the overall cost paid by the SUs. At the same time, it reduces the overall interference incurred to the PUs. Two scenario are used to evaluate the performance; the first is the SU data rate demands and the second is the price preferences of the SUs. Simulation results showed that the performance of the modified GA is better than the PSO. Spectrum sensing plays a very important role in proper channel allocation in CRN. In [81], the spectrum sensing process in CRN has been optimized using grey wolf optimization (GWO) and dragonfly meta-heuristic algorithms. This model uses priority weight at the fusion center, optimize the weight vector, and provide the highest value of the probability of detection. It also guarantee the maximum proportional fair reward for users.

2.7.4 Channel Reservation Based Schemes

Due to its dynamic environment that consists of mobile users, base stations, links, etc. cellular networks are vulnerable to failure [102]. There is heterogeneity of wireless networks failures which may occur due to channel failure, hardware failure, software failure or/and due to some fundamental problems in radio transmission resulting in network performance degradation [8]. To improve channel utilization and to guarantee QoS and manage failure, few recent studies have used channel reservation mechanisms in CRN [8], [24], [140].

A PU based channel reservation scheme for CRN is proposed in [140], where initially some channels are reserved for PUs. For communication, PUs cannot use unreserved channels as long as reserved channels are available; this gives a fair chance to SUs to complete their services. In model [24], both multi-level channel reservation and dynamic channel aggregation are used for admission control and QoS guarantee. This scheme reserves some specific channels for each SU in contrast to single-level channel reservation [141]. The forced termination rate in this model decreases considerably, but the blocking probability increases considerably by a small increase in CRN load.

In CRN, SUs services are affected on arrivals of the PUs services, channel failure or interference between SUs communications. To overcome the problem of error-prone channels, a model was proposed in [8], in which a dynamic channel reservation (DCR) scheme has been adopted that provides three access privilege variations. In this dynamic spectrum access model, the numbers of reserved channels are dynamically adjusted with the objectives to minimize forced termination of ongoing PU and SU services. The reserved channels are used only by those SU and PU services that face interruption due to channel failure or SU services that are forced to preempt the channels upon arrival of the new PU services. This scheme enhances the service retainability of SUs as well as the reliability of the network.

In CR-IoT network, QoS provisioning is important not only for PUs but also for SUs. In a dynamic channel reservation-based model, for admission control and channel allocation, a QoS provisioning based solution for CR-IoT network is proposed in [9]. This scheme efficiently utilizes the channels and minimizes the call blocking probability by using PU traffic patterns for channel selection. The call-blocking probability of high priority services of SUs is minimized by dynamic channel reservation. Assuming 100% spectrum sensing, PUs detection is not possible. This scheme included sensing error in the analysis of the system performance. On the basis of QoS requirements of different priority classes and their realtime traffic estimation, a dynamic number of channels are reserved for each priority class.

2.7.5 Auction Based Channel Allocation Schemes

Along with QoS and QoE, one of the major objectives of the cellular network is to provide cost-effective services to its users to retain them in this competitive market. In recent past, some work addresses the issue of pricing for channel allocation in CRN using game theory [142]-[144].

A spectrum-sharing mechanism using auction was proposed in [145], for profit maximization of the primary owner in CRN having multiple PUs and SUs. Game theory has been used as an effective tool for obtaining a competitive optimal solution for pricing related problems. A cooperative game-theoretic model has been proposed in [144], for dynamic spectrum leasing (DSL), with the objective of network utility maximization (NUM) for spectrum sharing where SUs participate in the negotiation on interference budget for channel allocation.

In [146], a revenue optimal pricing policy is proposed for spectrum access control and maximization of both the service provider's revenue and social welfare. In CRN, the channel allocation process needs to consider the speed of users for better QoS. A two-tier pricing model is proposed in [142] for heterogeneous CRN. Two types of users, high speed and low speed, are considered. Game theory has been applied to determine the spectrum price. The final decision of spectrum allocation and calculation of the payment price is made considering the result of the game for high-speed users and low-speed users. This model gets a good request success rate and achieves good spectrum utilization and user satisfaction.

To compensate an SU in CRN, a semi-cognitive radio networks paradigm is proposed in [143]. In this model, a constraint is imposed on the PUs, making PUs explore all free channels available in the network before interrupting the SUs. A game-theoretic approach is proposed to converge into a stable equilibrium state. The results indicate that interruption rates are significantly reduced and profit to the primary network is increased without affecting channel efficiency.

Another revenue-based model is given in [147] that considers the revenue aspect along with the concept of penalty on the service providers for the dropped services. Cooperation among wireless service providers helps in uninterrupted communication to the mobile users. Imposing penalty on wireless service providers compel it to offer better service. This also motivates the customers to stick to the service providers, i.e. reducing the churning of the customer. In [147]-[148], the utility of the customers are defined with the help of the modified sigmoid functions.

2.7.6 Channel Aggregation Based Schemes

In many of the existing works, static and dynamic channel aggregation along with channel fragmentation techniques have been applied [24]. Channel aggregation (CA) has been used as a tool for spectrum enhancement in cognitive radio network. Using CA, it is possible to combine multiple idle channels and utilize as one bonding channel. A distributed CA model proposed in [18], attempts to address the fairness problem in channel allocation along with improving the throughput of the system by multi-channel aggregation, which allows each SU to access multiple channels simultaneously. In some cases, narrow fragments of the spectrum bands are available and by aggregating them, radio chunks required for service requests can be created. The channel aggregation can improve effective spectrum utilization. While implementing spectrum aggregation for a service request, free segments of the spectrum from a lower frequency to a higher frequency are considered [149].

When SUs detect those spectrum wholes which are too small and discontinuous, it cannot support the requirement of high data rate as well as high-speed required for the SUs communications. In those cases, spectrum aggregation is a better solution for effective spectrum utilization [150]. A channel aggregation based multi-user cooperative relay scheme proposed in [151], aggregate those idle spectrum which can be selected for the same relay. It is observed that the throughput of the network is better when spectrum aggregation in a multi-user cooperative relay network is used compared to when the spectrum aggregation is not used. By combining dynamic relay selection and aggregation strategy, both spectrum efficiency and transmission rate have been improved.

In two approaches for channel aggregation are proposed in wideband cognitive radio networks; one is constant channel aggregation (CCA) and the other is variable channel aggregation (VCA). In VCA, channels are aggregated using probability distribution or on the basis of the number of free channels for utilization. In [153], a mechanism of channel allocation for centralized cognitive radio networks is proposed in which dynamic channel aggregation is performed based on the number of packets remaining for transmission. This mechanism highly depends on the CRN load and used discrete-time priority queuing model along with an adjustable transmission rate for minimizing forced termination rate.

In [154], a model for channel adjustment using dynamic spectrum leasing is discussed. The spectrum is leased based on the amount of ongoing traffic load and buffered PU request status. To serve the SU request, this model uses a dynamic spectrum access strategy along with channel aggregation. In [155], a model for sharing spectrum (SS) using the mechanism of channel aggregation (CA) is studied. This model allocates channels for the 5G wireless networks services, using both the licensed spectrum as well as the unlicensed spectrum, which are aggregated from the industrial, scientific, and medical (ISM) bands. The authors have developed a mechanism known as spectrum lean management (SLM) to maximize the total system throughput of the proposed system, considering both the system's internal and external constraints.

2.7.7 Few other Channel Allocation Schemes

A reasoning CR is proposed in [156], which is an advancement over the traditional CR with no interference. It can automatically determine the permissible limits for the safe transmission of secondary users' services. Cognitive radio has enabled opportunistic utilization of the licensed channels based on the primary user's behavior. A QoS provisioning for a heterogeneous services-based model is given by [9]; in which priority-based secondary users use the licensed channels opportunistically. This model aims to minimize the call blocking probability of high priority SU calls while maintaining a satisfactory level of channel utilization. Another model, given in [67], minimizes the secondary user's interference to the primary network. It also optimizes the cost paid by the secondary users.

In maintaining the QoS, the call admission control (CAC) technique plays a significant role. In CAC, bandwidth reservation and degradation schemes can be applied to achieve the desired QoS. In the model by S. Alsamhi et al. [157], to admit a new call request, an adaptive degradation scheme is proposed. The new call request will be admitted and a new channel will be created by reducing the bandwidth of the existing channels.

CR decisions can further be improved by applying AI-based machine learning techniques on input data to identify the pattern and make composed decisions. Cognitive radio is used for opportunistic utilization of the radio resources, where for centralized management of radio resources, software defined networking (SDN) [158] is used. SDN has experienced an overwhelming concern towards wired as well as wireless mobile networks [159].

In traditional wireless networks, communication begins when the required bandwidth is available. A model is given by [160], in which their proposed channel allocation technique overcomes the limitations of contiguous bandwidth allocation in the CRN. A realistic situation for multimedia communication is considered, where typically a varying number of bandwidth is needed for the users' services. This technique is based on the utilization of many non-contiguous channels whose bandwidth is smaller than the required bandwidth but collectively is equal to or more than the required bandwidth. This study shows that the heuristic-based model outperforms other existing first-fit and best-fit allocation techniques under all traffic situations. It is demonstrated that their proposed technique can accommodate around 96% of the traffic load and also is able to allocate the channels in less than 4.5 seconds. Cognitive radio plays a vital role in utilizing the unlicensed and non-contiguous radio spectrum.

An underlay channel allocation algorithm is proposed in [25], in which both PUs and SUs are capable of communicating under different modulation schemes, power levels etc. SUs transmit within the permissible limit of interference level, defined by the PUs. Different users of the network transmit on different slices of the frequency band using OFDMA. Through results analysis, it is observed that in case of increased PUs interference limit, the total data rate is increased to a maximum possible value and increases the system's overall capacity. This happens because it permits the SUs to transmit at a higher rate. In a practical scenario, different multimedia services require a different number of channels. In a channel allocation model proposed in [129], each SU is allocated more than one channel if available at that instant. PUs channels are characterized using channel idle probability and channel capacity. SUs are depicted using its geographical location, received SNR and the energy detection threshold. This algorithm is less complex and its performance is close-to-optimal solution, as demonstrated through experimental results.

Unpredictable behavior of PUs makes CRN management more challenging. Considering the dynamic nature of channel availability for SUs due to interference constraints and PUs reclaim of multiple channels simultaneously, in [161] a fault-tolerant model based on k-channel-connectivity has been proposed. The theoretical analysis and simulation results demonstrate that this model is fault-tolerant, provides a connectivity guarantee, and is energy efficient.

This chapter gives a good insight into the channel allocation problem in cellular systems, in general, with an emphasis on opportunistic channel utilization in cognitive radio enabled cellular systems and discussed many related research works reported in the literature in the channel allocation research area.

Though there have been consistent effort to develop mechanisms to address various issues and challenges in channel allocation in CRN, still due to a very large number of emerging services, e.g. internet protocol television (IPTV), mobile gaming, video conferencing, smart city, health care and videos conferencing etc. in which majority of the services are of multimedia nature and resource-demanding, it requires more attention. At the same time, to address the upcoming 5G services, including IoT applications, we need to consider fairness in service providing by prioritizing a few classes of services that are more critical and important than other services. Also, future cellular network systems are expected to work in sync with other network base stations to collaboratively exploit the available frequency resources to the maximum extent possible using the DSA mechanism. To manage 5G heterogeneous environment, it is necessary to have proper priority-based admission control with dynamic spectrum allocation to serve both PUs and SUs services. Both the heterogeneous environment of networks and multimedia-rich service demand generates different QoS/QoE requirements. A cognitive radio-enabled cellular network not only provides services to its PUs but also serve the SUs using opportunistic spectrum access. As the CRN co-exist and operate on a spectrum of the primary network, channel allocation schemes need to be developed considering the priority of PUs services and their QoS/QoE requirements. At the same time, efficient utilization of the resources for SUs services is necessary.

2.8 Research Gaps Identified

While considering the existing research work and the points mentioned above, some gaps have been identified, which are listed as follows.

1. Mechanisms need to be developed which facilitate utilizing the free channels available opportunistically, not only by SUs in the CRN but also by PUs belonging to another service provider in the vicinity. This will increase the collaborative utilization of free channels available at any base station (BS).
2. Fairness in providing service is a major challenge. There is a need to develop mechanisms by which fairness in channel allocation may be ensured and the running services get a fair chance to utilize the available channels. Also, more service requests may be accepted by some adjustment and compromise in the services' QoS/QoE requirements.
3. The mechanism to enhance the overall network performance in terms of network throughput and system capacity utilization needs to be developed using the concept of aggregating small chunks of free channels to fulfill the requirements of service requests and ensure the priority of PUs in the entire service process.

4. In the upcoming 5G CRN, it is expected that one user may run more than one service at a time that too using the free channels of different service providers. To address such a scenario, models need to be developed in which QoE of the users is ensured and the overall throughput of the network increases.
5. Mobility management of SUs is an important aspect to address both QoS and QoE assurance to the SUs in the CRN. Mobility management becomes complex in the environment where a CRN is having access to free channels of several service providers for SUs services. To have mobility management mechanisms where SUs are in motion is a significant problem of the study in CRN.

This thesis has proposed and studied some models to address some of the research gaps as mentioned above and presented them in the upcoming chapters.

Chapter 3

Opportunistic Channel Allocation in Collocated Primary Cognitive Network

In order to facilitate primary/secondary users in a cellular network, meeting the growing demand for radio spectrum has become a challenge. In the past, many channel allocation models have been proposed that applies cognition, for better radio spectrum utilization. The proposed model, in this chapter, is based on our work published in [162]. Three types of users have been considered: primary users (PUs), opportunistic primary users (OPUs), and secondary users (SUs). They use radio resources in collocated primary base stations. The opportunistic primary users and the secondary users may request for handover as and when required. The model aims to enhance the radio spectrum utilization by making opportunistic use of radio resources by OPUs. This also enables the cognitive radio base stations to dynamically collect the free channel information. The CR base stations maintain the information on centralized free channels at the collocated primary base stations to opportunistically facilitate SUs. The proposed channel allocation model maintains the QoE of the users besides the QoS. The performance analysis, of the proposed model, is done by simulation.

3.1 The Problem

Most of the proposed models in the literature have applied diverse cognitive approaches for channel allocation. Many of these consider two categories of services; real-time and non-real time with differing priorities [136]-[137]. Further, primary and secondary services are considered as follows; primary services are real-time in nature while secondary services are non-real time services. Few other models, such as GA based [135] and the pricing based [147], also categorized the services into real-time and non-real time services.

In general, primary and secondary requests reaches to the service providers which utilize the channels opportunistically using the Cognitive Radio (CR) concept. Although CR has increased the utilization of radio spectrum to some extent, the possibility still exists for its better utilization, and therefore, this issue is still relevant for the researchers.

The proposed model considers two categories of services; real-time and non-real time. Real-time services are delay-sensitive while non-real time services are delay tolerant. This model also considers three kinds of users; primary users (PUs), opportunistic primary users (OPUs), and secondary users (SUs). As mentioned earlier, Primary users are the licensed/privileged users, whereas secondary users are the one who uses the radio resources opportunistically. The third category of users, considered as OPUs, uses the radio spectrum of other primary networks opportunistically. In case of interruption by the primary users of the same network, it may be shifted to their own primary network by performing the handover.

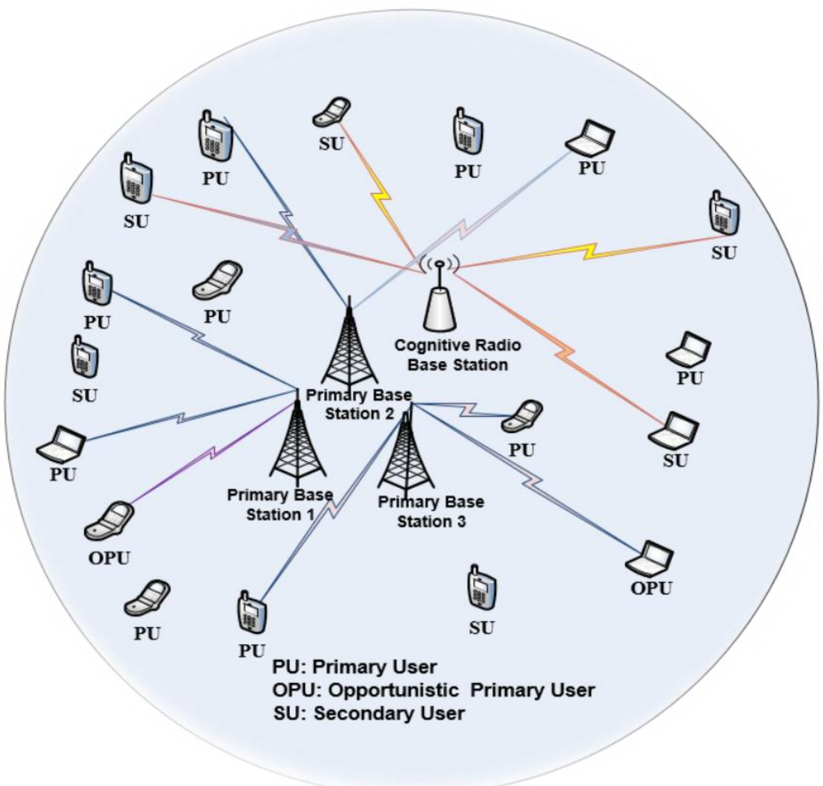

Figure 3.1: Primary and Cognitive communications in Collocated PBS

Figure 3.1 depicts three collocated primary radio base stations (PRBS) of different primary networks serving their primary user's requests. CR base station (secondary base station) is equipped with the sensing ability to collect the free channel information from all the primary radio base stations. These free channels are being used by SUs and OPUs opportunistically. Opportunistic primary users (OPUs) are those primary users who are using the channels opportunistically in other primary networks.

The proposed model aims to increase the utilization of the radio spectrum by allocating the channels for the service requirement. The model applies the opportunistic utilization of radio resources by other primary users as opportunistic primary users.

3.2 The Proposed Model

In the proposed model, it is considered that the primary user has the requirement of channels for both delay-sensitive and delay-tolerant services, while secondary users have only non-real time (delay-tolerant) services. On falling short of a channel, the primary users can explore other primary networks (owned by some other service providers) to complete their services. When a primary user is running its services in other networks, it will be categorized as the opportunistic primary user.

Let there are N number of primary networks with their base stations to handle primary requests. For secondary requests, there will be a specialized secondary base station that can locate the free channels of each primary network. The secondary base station allocates the channels to the secondary users for opportunistic utilization. Each channel has its specified capacity and is allocated to the primary/ secondary users considering their bandwidth requirements for their services.

3.2.1 Service Vector

As shown in table 3.1, the service vector maintains the running status of various PUs, OPUs, and SUs status in terms of real-time and non-real time services.

Table 3.1: Service Vector

Channel id	C_1	C_2	C_3	C_4	C_5	C_6	C_7
Channel Bandwidth (kbps)	219	237	217	223	225	140	212
Service Time (s)/Size (Kb)	169 kb	1523 kb	2	1	3	836 kb	900 kb
Service Category	NRTS	NRTS	RTS	RTS	RTS	NRTS	NRTS
User Category	PU	PU	PU	PU	OPU	OPU	SU

Table 3.1 shows the running status of channels for C_i $(i = 1 \dots 7)$. The second row, in the table, depicts the bandwidths of the channels, the third row represents the size/time required by the primary and the secondary services e.g C_2 requires 1523 Kb size to upload or download while C_3

requires 2-time units to complete the service. The third row in the table shows that C_5 and C_6 has the service time and service size (kb) respectively depicting real and non-real time services respectively. The fourth row represents the service category types, i.e. real-time or non-real time service. The last row of the table indicates the user's category; a primary user, an opportunistic primary user, or a secondary user. OPU is the user of other service providers. For example, C_5 and C_6 are running OPU services, real-time and non-real time, respectively.

3.2.3 Spectrum Handover

Spectrum handover is the process of switching from one channel to another as per the requirement. In this model, the opportunistic primary user (OPU) will participate in the handover process. It is because OPUs will be using the channels of other primary networks. It is also possible that OPUs will be interrupted to release the channels for the primary users that belong to that particular network. For this, OPUs will be migrated back to their own network. In case the channels are not available in their own network and the nature of the service is non-real time, OPU status will be stored in the interrupted service vector and will be resumed on the availability of the channels. Otherwise, if OPU is using a real-time service, it will simply be dropped.

Whenever a primary network falls short of channels to facilitate its licensed users, it will interrupt the low priority serving SUs first. Subsequently, on the non-availability of channels occupied by SUs, PU will interrupt the OPUs as stated above. This mechanism will increase the radio spectrum utilization and minimize the drop/block rate of the primary services.

3.2.4 Update Channel Status

Channel status information will be updated whenever a channel becomes free or occupied. The service status of both real-time and non-real time services will be updated as given in equation 3.1.

$$Service_{time/size} = \begin{Bmatrix} Service\ time - time, & if\ RTS \\ Service\ Size_{upload/download} - time \times BW & Otherwise\ for\ NRTS \end{Bmatrix} \quad (3.1)$$

If the service is real-time, it is delay-sensitive and will require some time to complete, as reflected in table 3.1. If the service is non-real time, it will be in terms of size (upload/download). After the completion of the service, the channel will be released and will be pooled to the free channel list of the respective primary network.

3.2.5 The Flow Chart

A self-explanatory flow chart, of the proposed model, appears in figure 3.2.

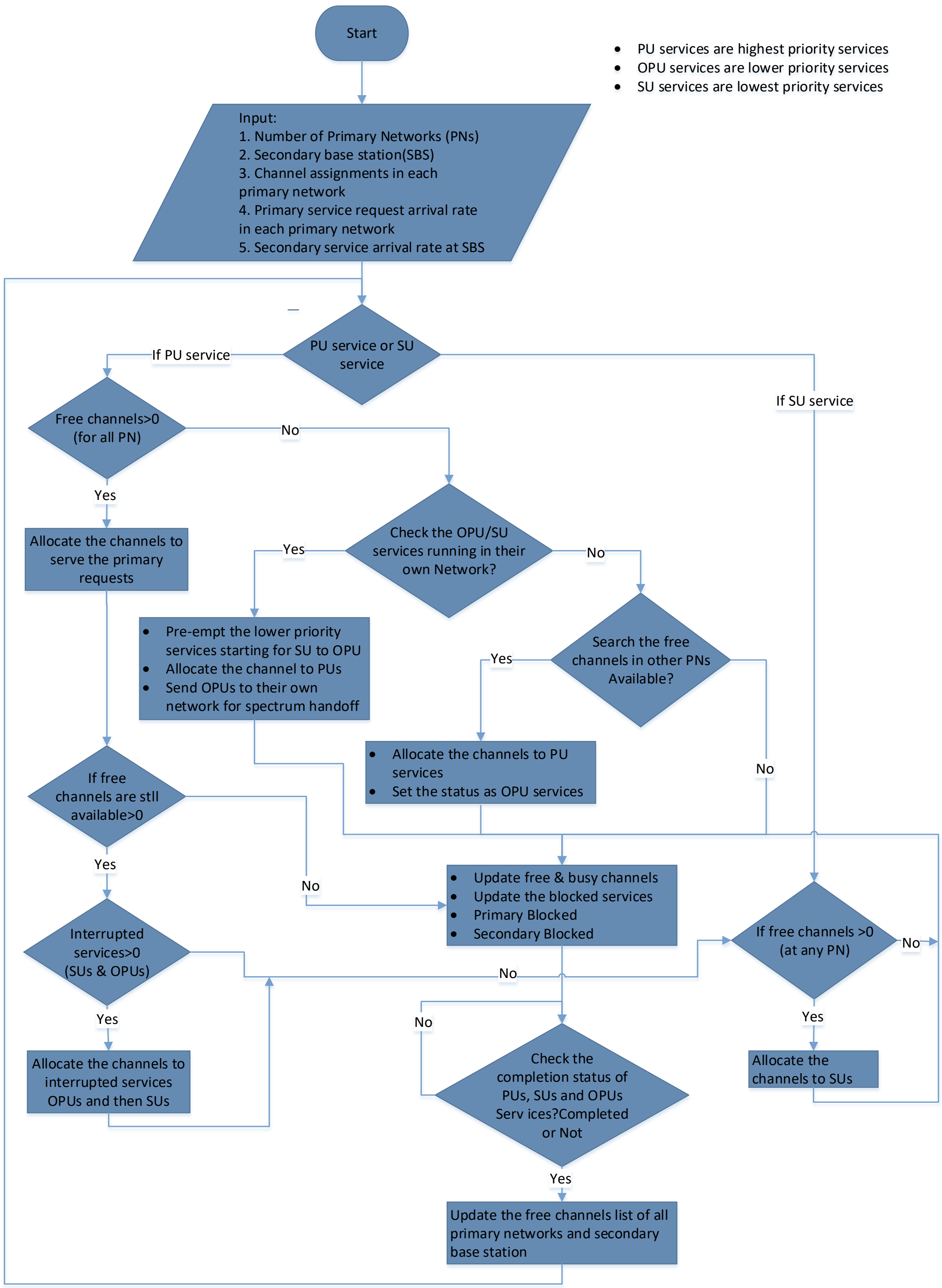

Figure 3.2: The Flow Chart of the Proposed Model

3.2.6 The Algorithm

The algorithm, of the proposed model, is as follows.

Algorithm 3.1: Cognitive Channel Allocation

Input: *Number of Primary Networks, SBS, Channel Assignment in each primary network, PSRAR in the primary network, SSRAR at SBS.*

⊳ PSRAR is the primary service request arrival rate and SSRAR is secondary service request arrival rate.

Output: *Primary blocked services, Secondary blocked services, Opportunistic dropped services*

1. *Set the channels bandwidth*
2. *Set the value of TET* ⊳ *TET: Total execution time of the experiment.*
3. $time \leftarrow 0$
4. *while* $time \leq TET$ *do*
5. *Classify the Primary and Secondary services*
6. ***For*** *each primary network*
7. ***If*** $free\_channels > 0$
8. *Then allocate channels to primary users services*
9. ***elseif*** *check the running status of OPUs and SUs*
10. ***If*** *SUs or OPUs are running then*

    preempt the lower priority services from SUs to OPUs

    Send OPUs to their own network and SUs to interrupted services
    allocate the channels to PUs
11. ***else*** *search the channels in other pirmary netowrk, if available*
    then allocate the channel to PUs
    Set the service status as OPUs
12. ***end***
13. ***else*** *go to step number* 17
14. ***end***
15. ***If*** $free_{channels} > 0$ ⊳ *In any primary network*
    Then resume the interrupted services if any otherwise serve the

$secondary\ services$

16. $Endif\ \&\ endfor$
17. $update\ the\ free\ and\ busy\ channels$
18. $update\ the\ primary\ and\ secondary\ blocked$
19. $check\ the\ running\ status\ of\ services\ \boldsymbol{if\ completed}\ then$

    $Release\ the\ channels$

    $Update\ the\ free\ channel\ list$
20. $time \leftarrow time + 1$
21. $\boldsymbol{end\ while}\ loop$

In the above algorithm, steps 1 to 3 are the initialization steps. The duration of the total execution time is being set in step 2. The timer is initialized to zero to begin.

Step 5 classifies the requests to primary and secondary. Steps 6-8 allocate the channels to the primary requests in each primary network.

In steps 9-14, if free channels are not available, SUs and OPUs are suspended to facilitate the PUs. Suspended SUs information will be stored in the Interrupted Service Vector to resume later, after the availability of the channels. Suspended OPUs will be shifted to their own primary network.

Steps 15-16 serve the interrupted services and allocate the channels to SUs as per the availability of the channels. Free channel and busy channel information will be updated in step 17, while step 18 stores the status of primary and secondary blocked services.

After checking the status of channels to free or occupied, in step 19, the free channel list will be updated. The algorithm will iterate until a termination criteria is satisfied.

3.3 The Performance Analysis

In this section, the performance of the proposed model has been analyzed through simulation. The parameters used for the performance evaluation have been discussed. In order to conduct the experiments, few assumptions have also been laid down.

3.3.1 Performance Evaluation Criteria

The following metrics have been used to evaluate the performance of the proposed opportunistic channel allocation model.

Service request arrival, in the cellular network, is random and follows the Poisson distribution model with some specified mean arrival rate. In the model, primary and secondary requests have been assumed to follow the Poisson distribution [112]. $P_n(t)$ denotes the probability of n number of request arrivals in time duration t as indicated in equation 3.2 and λ is the mean arrival rate.

$$P_n(t) = \frac{(\lambda\, t)^n}{n!}\, e^{-\lambda t} \qquad (3.2)$$

The call holding time of the service request follows the negative exponential distribution [113]. **[**It has the probability distribution function (pdf) as given in equation 3.3. In the exponential distribution, μ indicate the mean service rate.

$$f(t) = \mu e^{-\mu t} \qquad (3.3)$$

In the model, we have assumed that 60% of the primary services will be real-time services, and 40% will be non-real time services.

3.4 Simulation Results

This section demonstrates the outcome of the experimentation done to evaluate the performance of the proposed channel allocation model. It is done in MATLAB. The study is performed on varying number of primary networks for minimizing the number of blocked primary as well as secondary services. Cells of the network have three types of requests PUs, OPUs, and SUs. The data used in the experiments, conforms to that of [147].

3.4.1 On Varying Number of Primary Request

This experiment is carried out to observe the performance of the primary requests on varying request arrival rates. The input parameters of the experiment are as follows: the number of channels per network is 10, mean arrival rate of each primary requests is 5, secondary request arrival rate on the cognitive base station is also 5, the service time of real-time services are in the range of 3 to 5 time units and non-real time services are in the range of (100kb to 2000kb). The experiment is carried out for a 500-time unit and the results of the last 10 iterations are taken, i.e. after the system is stabilized.

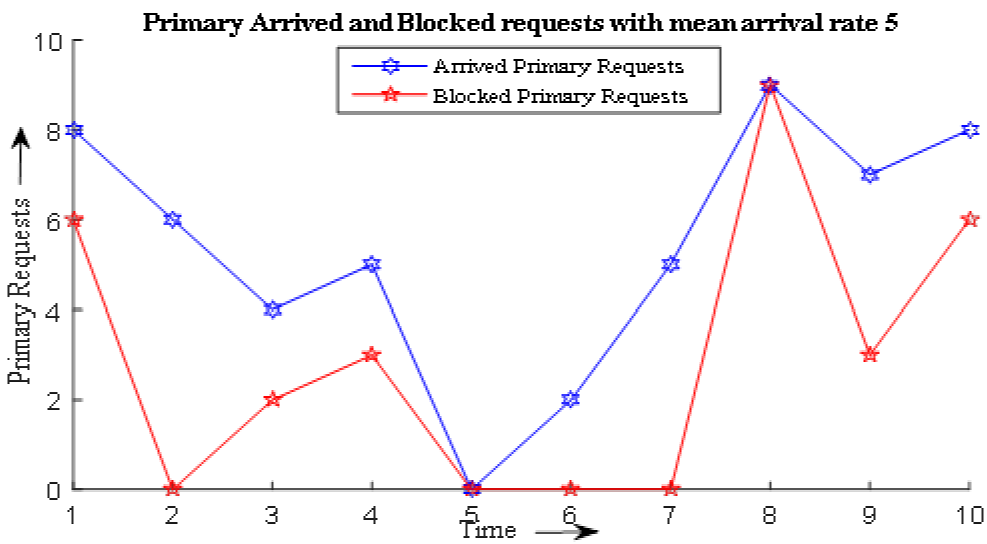

Figure 3.3: Primary Arrived and Blocked requests ($\lambda = 5$)

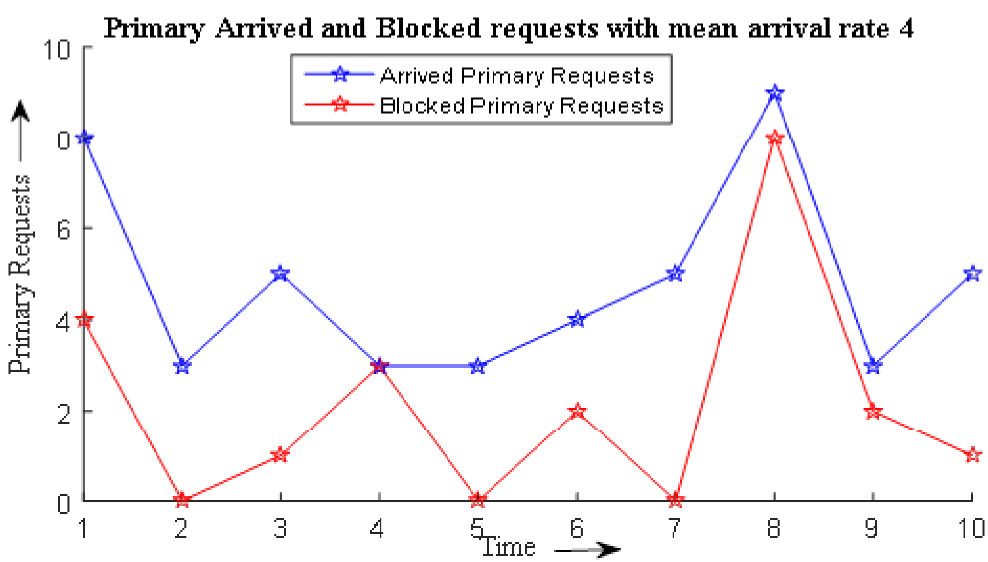

Figure 3.4 :Primary Arrived and Blocked requests ($\lambda = 4$)

Figure 3.3 shows that requests are being served even on the high mean arrival rate of 5. When the mean arrival rate decreases to 4, blocked requests are reduced significantly, as shown in Figure 3.4.

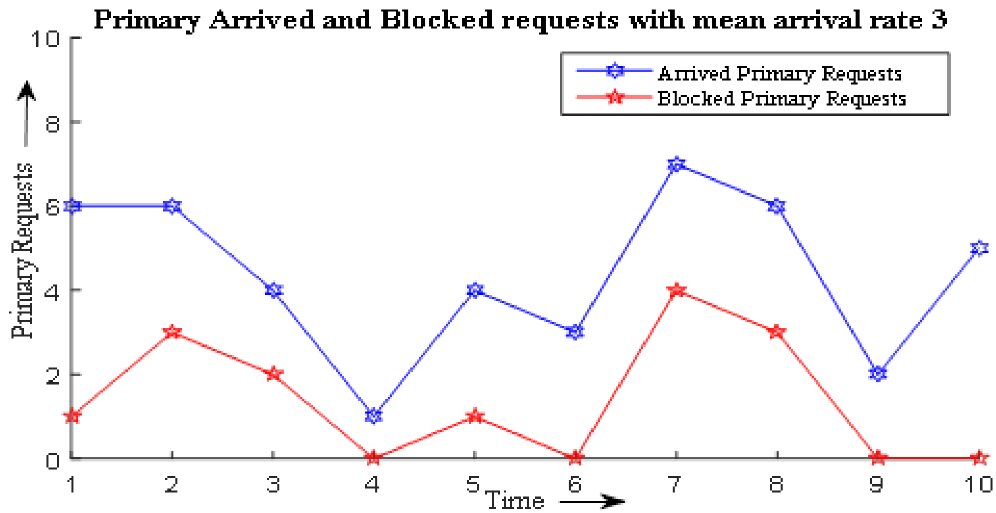

Figure 3.5 : Primary Arrived and Blocked requests ($\lambda = 3$)

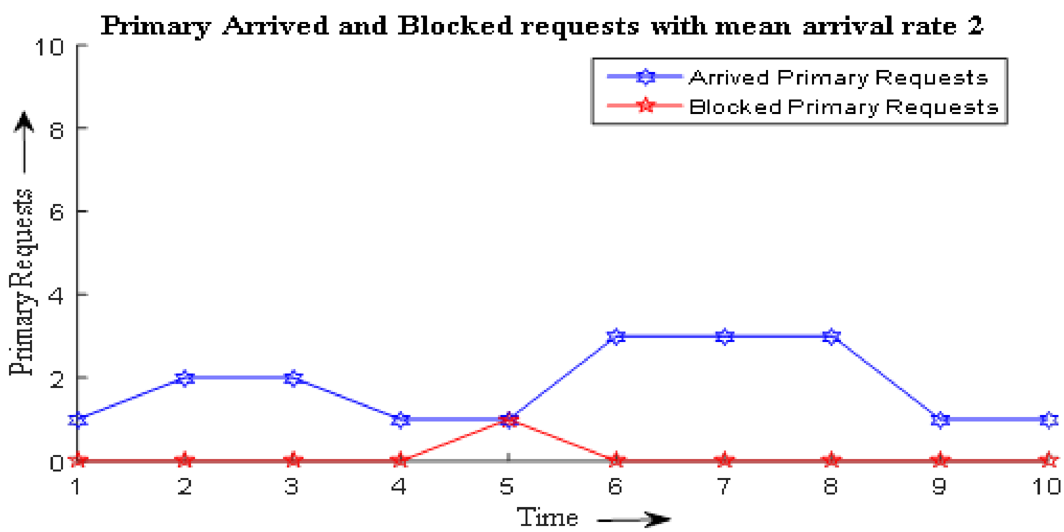

Figure 3.6 : Primary Arrived and Blocked requests ($\lambda = 2$)

Figures 3.5 and 3.6 show the results of further decreasing mean arrival rates (3 and 2) respectively. The observation from figure 3.5 shows the improvement in serving the requests. Figure 3.6 shows that blocked requests are almost nil.

The overall observations, from figures 3.3 to 3.6, reflect that when the mean arrival rate diminishes, then the number of blocked requests is also reduced. After decreasing the mean arrival rate to a certain level, almost all the requests are being served, and blocked requests are negligible.

3.4.2 On Varying Number of Channels with Fixed Arrival Rate

This experiment is carried out to test the average secondary blocked requests. The input parameters for the experiment are as follows: The number of primary networks is 5, primary requests mean arrival rate in each network is 3, the mean arrival rate of secondary request is 5. The experiment is carried for 5000 iterations on a varying number of channels as 10, 15, 20, 25. The output is shown as average blocked secondary requests.

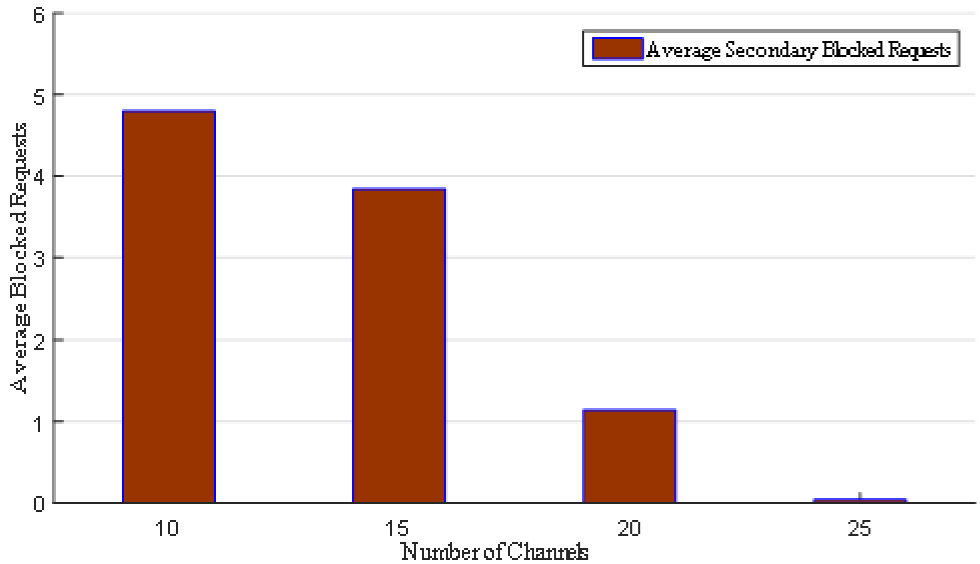

Figure 3.7 : Average Secondary blocked requests on varying number of channels

Figure 3.7 confirms that secondary requests are also getting served, though opportunistically, very well. It is further observed that on increasing the number of channels in the network, average blocked secondary requests are being reduced. When the number of channels is 25, almost all the secondary requests are being served.

3.4.3 On Varying Number of Primary Networks with Fixed Arrival Rate

This section performs another set of experiments to observe the effect on secondary services on a varying number of primary networks. The input parameters are as follows: 10 channels are assigned to each network, the mean arrival rate on each primary network is 2, and secondary requests mean arrival rate is 5. The number of primary networks is varied from 2, 4, 6, 8, 10. The average result of 5000 iterations is taken.

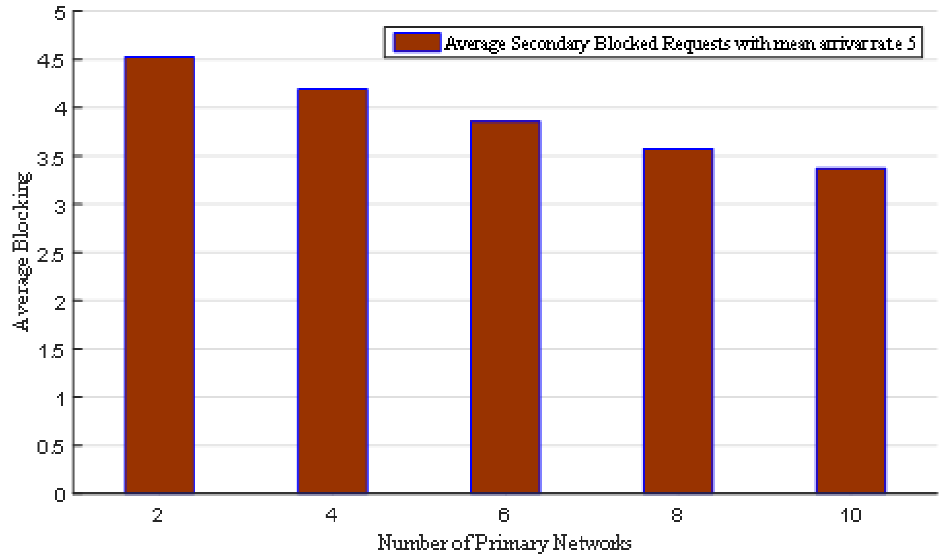

Figure 3.8 : Average Secondary blocked requests on varying number of primary networks

Figure 3.8 shows that on varying number of primary networks, average secondary blocked requests are reduced even with the limited number of channels in the network. When the number of primary networks is 10, average blocked requests are quite low.

3.4.4 A Comparative Study on Varying Number of Primary Networks

A comparative study has been performed to observe the primary average blocked with and without using OPUs on varying numbers of Primary Networks (PNs). The experiment is carried out to observe the role of opportunistic primary users on average blocked requests. The input parameters for the experiments are as follows. The number of channels per network is 10, the primary service mean-arrival rate is 5 in each network and the secondary service mean arrival rate is also 5. These parameters remain fixed for all sets of experiments. Average blocking of primary requests has been observed on varying number of primary networks (PNs); with and without using the opportunistic primary users.

Figure 3.9 reflects that without using the concept of the opportunistic primary user, average blocked requests are high. On increasing the number of primary networks (PNs) and enabling the opportunistic primary users to use the services opportunistically, average blocked requests are decreased. When the number of PNs is 8, the average blocked requests are significantly low.

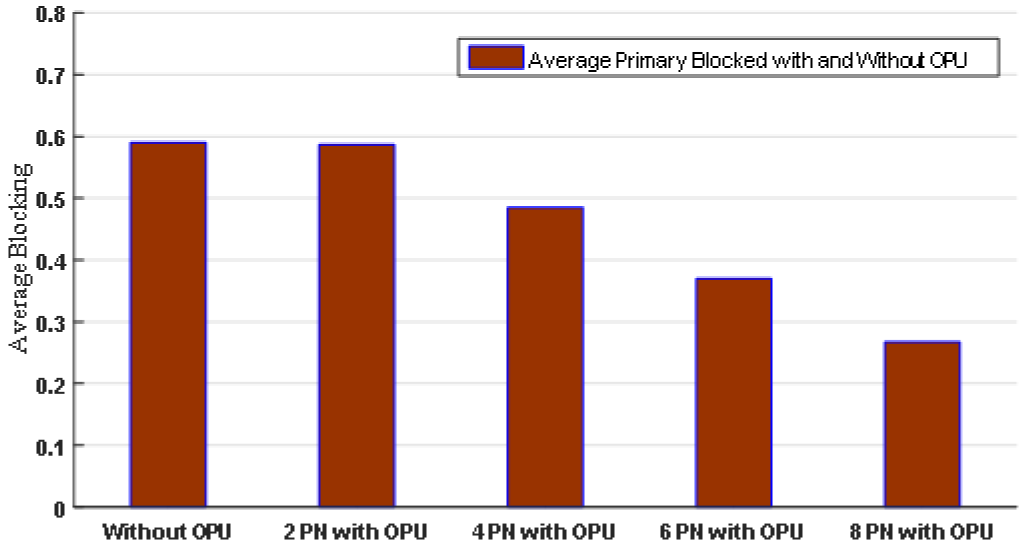

Figure 3.9 : Average Primary Blocked With and Without OPUs

3.4.5 A Comparative Study on Varying Number of Channels

A comparative study has been performed to observe the primary average blocked with and without using OPUs on varying number of channels. A set of experiments is performed on varying the number of channels to 10, 15, and 20 to observe the impact of opportunistic primary users. Other input parameters in the experiment are as follows. The number of primary networks is 5, the primary services mean arrival rate is 5 for each network, and mean request arrival rate on the cognitive base station is also 5. The result, shown in figure 3.10, is the average of 5000 iterations.

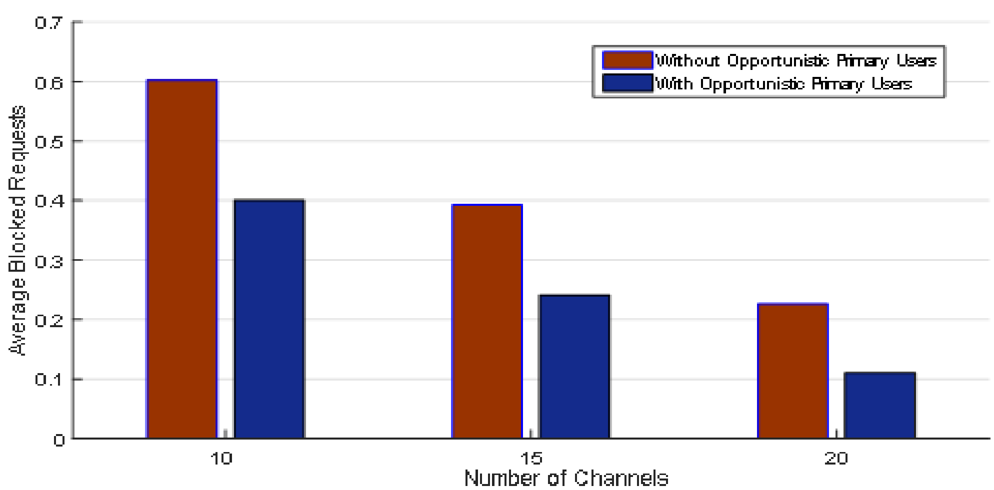

Figure 3.10 : Average blocked requests on varying number of channels

Figure 3.10 shows that when primary requests utilize the channels of other primary networks opportunistically, average blocked requests are quite low in comparison to without using the OPU concept. When the number of channels is increased to 20, the average blocked requests of primary services are minimized quite significantly. Figures 3.9-3.10 show that the opportunistic primary users concept increases the utilization of the radio spectrum and also minimizes the primary blocked requests effectively.

3.5 Concluding Remarks

In this chapter, a model is proposed with a new concept of OPU, besides the other existing types of mobile network users and observes its effect on channel utilization. This model applies CR's concept to facilitate both the PUs and SUs services in the collocated primary network's vicinity. The radio spectrum utilization has been enhanced by the opportunistic access of radio resources by OPUs and by enabling the CR base stations to collect information on free channels dynamically. It has been observed, through simulation, that the requirement based channel allocation increases the channel utilization by allocating it opportunistically.

The model has been evaluated by carrying out many experiments which depict that when primary users of a primary network share other collocated primary networks channels for their services as an opportunistic primary user (OPU), the primary users' service requests are effectively addressed. It has been observed that when the number of channels is increased to a certain level, the average secondary blocked requests are negligible. The secondary services' performance is also studied on varying numbers of primary networks, and it has been observed that they perform very well. Model is also tested with and without opportunistic primary users (OPU), and it is observed that the performance of the model is quite encouraging when it uses the opportunistic primary users to utilize the radio spectrum opportunistically. The overall study about the proposed model suggests that it can be implemented for future communication networks for the channel allocation problem for better QoS and QoE.

Chapter 4

Requirement Based Channel Allocation in CRN

Radio spectrum is a scarce resource and its utilization has always been a key concern in a cellular network. Various techniques have been applied in the past to enhance the utilization of the radio spectrum. With the growth in technology, QoS and QoE are often desired by the spectrum users. This is taken care of by allocating the channels based on the minimum bandwidth requirement. Cognitive radio deals with the opportunistic usage of the radio spectrum by the secondary users. In this work, a bandwidth requirement-based channel allocation is proposed in the CRN, which considers the minimum bandwidth requirement for allocating the channels. Two types of services are considered in the model; primary and secondary. Primary services are high-priority services that are facilitated by performing the spectrum handover with the secondary services. The performance study of the model depicts its effectiveness in terms of primary and secondary services.

The problem addressed in this chapter proposes a novel approach of channel allocation in a cognitive radio network based on the users' bandwidth requirement. The objective of the work is as follows:

- To enhance the radio spectrum utilization by using the CR.
- To allocate the channels as per the bandwidth requirement.
- To minimize the call blocking/dropping for both primary and secondary services.
- To improve the throughput of the system by allocating the appropriate number of channels as per the minimum bandwidth requirement.

4.1 The Problem

The problem addressed, in this work, is channel allocation in the cognitive radio network with fair requirement-based bandwidth management. It is evident from the chapter on the related work that many existing models do not address the issue of the service request with specified bandwidth requirements. Many a times, services run by compromising their minimum bandwidth requirements. Thus hampers the quality of service and quality of experience. This model addresses this issue and channel allocation is done considering the minimum bandwidth requirement. This helps to improve the desired quality parameters.

Service request arrival, in a cellular system, is purely random and follows the Poisson's distribution [8], [112]. In this work also, the arrival pattern of the primary and the secondary requests in a cellular system has been considered to follow the Poisson distribution [111]. Let $P_n(t)$ denotes the probability of arrival of n number of requests in the time duration t as indicated in equation 4.1 and λ is the mean arrival rate.

$$P_n(t) = \frac{(\lambda\, t)^n}{n!}\, e^{-\lambda t} \qquad (4.1)$$

In the proposed model, a practical scenario of the spectrum allocation is considered in which the requests arrive with the specific requirements. All the primary and secondary services arrive with their minimum and maximum bandwidth requirements and the channels will be allocated to the services satisfying the minimum bandwidth requirement of the request. This model aims to improve the quality parameters and enhance the utilization of the radio spectrum.

Quality of Experience (QoE) is a very subjective metric with respect to the specific quality of service parameters from users' point of view. It can also be defined as the degree of the delight of a customer. If customer satisfaction is high then QoE will be high. However, If customer satisfaction is low, it will make the degree of annoyance high [92]-[93]. Subjective QoE measurement quantifies it in terms of mean opinion score (MOS) [92], which is measured using a point scale. Quality of Service (QoS) measures is very objective. In the proposed model, availability of the channels, quality of call (without interruption), Call block, Call drop, and waiting time for the services are considered as the QoS parameters. The QoE can be measured in terms of Application's Quality of Service (*AQoS*) and Network Quality of Service (*NQoS*). Thus, Quality of Experience [93] can be defined as shown in equation 4.2. Where $NQoS$ basically covers the reliable delivery aspects of multimedia data over wireless medium and $AQoS$ is concerned about End-User QoS [163].

$$QoE = f\,(AQoS, NQoS) \qquad (4.2)$$

In the proposed model, the utility of the customer depends on the call block/call drop and other QoS parameters such as availability of channels and waiting time of the secondary services.

Mathematically, utility of the customer can be defined with the help of the modified sigmoid function [147]-[148] as shown in equation 4.3.

$$Utilization_i = \frac{1}{1+e^{-\alpha\times(NR_i-CB_i)-\beta\times Qosp}} \qquad (4.3)$$

Where, NR_i, CB_i and $Qosp$ is the number of call requests made by the customer, call rejected and QoS parameters respectively and α and β determine the steepness of the curve. Physically, these constants influence the utilization of the radio spectrum. In equation 4.3, α is associated with call block and call drop while β is associatd with other QoS parameters. $\alpha \geq 1$ and $0 \leq \beta \leq 1$, because in mobile communication system, call blocking and dropping are crucial factors and cannot be compromised. We can compromise other quality of service parameters, sometimes.

4.2 The Proposed Model

In the proposed model, two types of services are considered; real-time and non-real-time. Real-time services are time-constrained and is often used by the primary users. Non-real time services are delay tolerant and is used by the secondary users/cognitive users. Primary services will have high priority than secondary services. The model also considers that service providers cooperate with each other to enhance the utilization of the radio spectrum. By the cooperation in the network, it is possible to serve the secondary services of the other service providers as per the availability of the channels.

Before the proposed model is described, some preliminaries are given as follows.

4.2.1 Channels

The channels will have some specified capacity (bandwidth) to serve the real time and non-real time services as indicated in table 4.1. Channels will be allocated by considering the bandwidth requirements of the services.

Table 4.1: Channels with specified bandwidth

Channel_Id	C_1	C_2	C_3	C_4	C_5	C_6
Channel_Bandwidth	40 kbps	60 kbps	30 kbps	70 kbps	75 kbps	65kbps

4.2.2 Primary/Secondary Service Request

Primary and secondary service requests arrive with the specified minimum and maximum bandwidth requirements as indicated in table 4.2.

Table 4.2: Primary/Secondary Service Requests

Request Id	PR_1	PR_2	PR_3	PR_4	PR_5	PR_6	SR_1	SR_2	SR_3
Minimum Bandwidth Requirement (Kbps)	54	71	77	76	57	65	38	37	29
Maximum Bandwidth Requirement (Kbps)	95	94	90	94	98	91	100	99	98
Required Service Time (Sec.) / Size (KB)	2	3	1	2	3	2	975	1206	1203

As indicated in the last row of the table 4.2, primary requests is attributed with service time whereas secondary requests are attributed with size.

4.2.3 Service Vector

Channels are allocated to primary and secondary services as per the minimum bandwidth requirements to ensure the QoS. Table 4.3 shows the channel allocation to primary and secondary services where primary services are high priority services.

Table 4.3: Service Vector Status Matrix

Channel Id	C_1	C_2	C_3	C_4	C_5	C_6
Channel Bandwidth (Kbps)	40	60	30	70	75	65
Minimum Bandwidth Requirement (Kbps)	38	54	29	57	65	64
Maximum Bandwidth Requirement (Kbps)	100	95	98	98	91	100
Service time (sec)/ Size (KB)	975	2	1203	3	2	3
Remaining Service time (sec) / Size (KB)	895	0	1143	1	0	1
Service type (Primary/ Secondary)	SR_1	PR_1	SR_3	PR_5	PR_6	PR_7

Table 4.3 shows the status of channels C_i $(i = 1 \dots 6)$ in which C_1 and C_3 are allocated to the secondary services whereas remaining channels (C_2, C_4, C_5, C_6) are allocated to the primary services. Each channel satisfies the minimum requirements of the services running on it. For example, channel C_2 is allocated to PR_1 (Primary request) which requires minimum 54kbps bandwidth and channel bandwidth is 60kbps. The 5th row in table 4.3 shows the required service time for primary services and required size to uplink/downlink for secondary services. 6th row shows the required service time/size to complete the services. Zero (0) value in the field indicates that service has been completed and channel is free now to be allocated to any other request.

4.2.4 Spectrum Handover

Spectrum handover is the process of switching from one channel to another without interrupting the ongoing services. In the model, on the arrival of a primary request, if no free channel is available then for facilitating the primary services, secondary services will be moved to some other channel of some other service providers. Secondary services will be terminated only when spectrum handover is not possible.

4.2.5 Interrupted Services

In the proposed model, non-real time services i.e. secondary services can be interrupted to facilitate a real-time service. Interrupted service vector stores the information of interrupted secondary services. Secondary services will be interrupted to facilitate the primary request if a free channel to serve the primary service is not available. Once the channel becomes available, interrupted service (secondary service) may resume from the point where from it was interrupted i.e. it will complete its service using a preemptive-resume approach. Interrupted service vector contains the interrupted service-id, minimum bandwidth requirement, maximum bandwidth requirement, and remaining size for upload/download. Table 4.4 contains the information of the interrupted services.

Table 4.4: Interrupted Services

Interrupted Service-id	1	2	3	4	5	6	7
Minimum Bandwidth Requirement	80	78	80	80	78	59	65
Maximum Bandwidth Requirement	100	90	97	96	91	99	99
Remaining Service time/ Size (KB)	894	1518	876	899	421	1060	1213

4.2.6 Channel Update

In the proposed model, the channel update is required to update the free and busy channel information. After completing the running service, the channel immediately will be returned to a free channel pool. The remaining size of data for upload/download (to send or receive a file), required by the secondary services, will be calculated with the help of the equation 4.4. The equation 4.5 is used to update the service time for the primary services where service time indicates the time required for the real-time service to complete.

$$Remaining\ Service\ (Size) = \ Service\ Size - (Channel\ bandwidth\ \times\ time) \quad (4.4)$$

$$Remaining\ Service\ time = Service\ Time - time \quad (4.5)$$

4.2.7 The Flowchart

The flowchart, to explain the working of the model, is given in figure 4.1 which illustrates the channel allocation to primary and secondary users. It also shows the interruption of secondary services when no channel is available to facilitate the primary services.

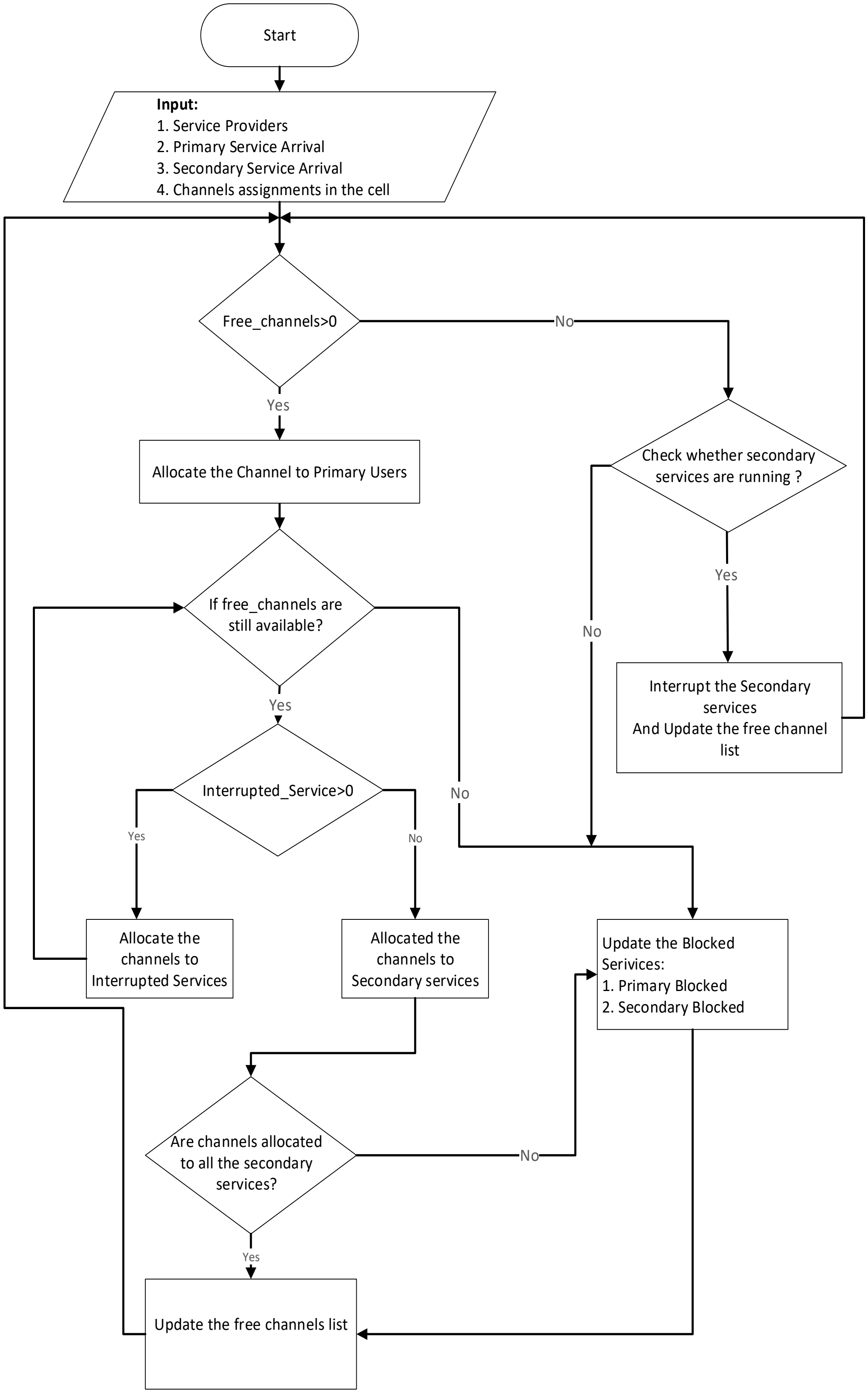

Figure 4.1: The flowchart of the proposed model

4.2.8 The Algorithm

The algorithm of the proposed model is as follows.

Algorithm 4.1: Channel Allocation based on Bandwidth Requirement

Input: *SP, PSRAR, SSRAR, Channels*

Output: Blocked Primary service, Blocked Secondary service

1. *Set the bandwidth of the channels and T*

   $\triangleright$ T $indicates\ the\ total\ execution\ time\ of\ the\ experiment$
2. *Set min and max bandwidth requirement of primary and secondary services*
3. *time=0;*
4. *while time* $\leq$ *T do*
5. *Repeat steps 6 to 8 till all primary requests are served* ***AND*** *until step 6 returns true.*
6. ***If*** *(available_channels>0* ***AND*** *min bandwidth requirement of primary request is satisfied) then*
7. *{Assign the channel to the requested primary service*
8. *Update the information in the service vector}*
9. ***Else if*** *(active secondary_services>0* ***AND*** *respective channel satisfying the min bandwidth requirement)* ***Then***
10. *Interrupt the secondary service // Algorithm 4.3*
11. *Store the interrupted secondary service information in ISV*

    $\triangleright$ $interrupted\ service\ vector$ Mention in Table 4.4 for sample
12. *Assign the vacated channel to the primary request*
13. *Repeat steps 9 to 12 till either all the primary request is served* ***OR*** *there is no active secondary service.*
14. ***End If***
15. ***If*** *(Available_channel>0)* ***Then***
16. *//Interrupted services will resume their execution before new secondary services*
17. *Resume the secondary interrupted service*
18. ***End If*** *// if free channel is still available then allocate the channel to secondary services*

19. ***If*** *(available_channels>0* ***AND*** *min bandwidth requirement of secondary request is satisfied)* ***Then***
20. *Assign the channel to requested secondary services*
21. *Update the information in Service Vector.*
22. *Repeat steps 19 to 21 till the condition is satisfied.*
23. ***End***
24. *Update the channel status()* ⊳ *Alogorithm 4.2*
25. *time=time+1;*

Algorithm 4.2: Update the Channel Status Information

Input: *Service Vector*

Output: *free_channel, Busy_channel*

1. *Update the remaining service time of primary requests* ⊳ $equation$ 4.5
2. *Update the remaining service size of secondary requests* ⊳ $equation$ 4.4
3. ***For*** *all busy channels* ***Do***
4. ***If*** *((remaining service time ≤ 0) OR (remaining service size))*
5. *Return the channel into free_channel list*
6. *Update the free and busy channel information*
7. ***End If***
8. ***End For***

Algorithm 4.3: Spectrum Handover

⊳ *Spectrum handover will be performed with secondary services only as per the availability of channels*

1. ***For each*** *service provider search the free channel*
2. ***If*** *(free_channel bandwidth $\geq$ min bandwidth requirement of secondary services)*
3. *Perform the handover of the secondary service.*
4. ***End If***
5. ***End For***

In Algorithm 4.1, steps 1 to 3 are the initialization of the parameters. Steps 4 to 24 are the iterative steps for channel allocation for primary and secondary services in which channels allocated to primary services are high priority and is covered from steps 5 to 8.

Steps 9 to 12 cover the spectrum handover and channel allocation to secondary services. Spectrum handover is required when a few primary services are not served. After serving the primary, secondary services will be served as per the availability of the channels.

In Algorithm 4.2, aim is to update the status of free and busy channels information. Free channel list will be updated to further facilitate the primary and secondary services.

In Algorithm 4.3, objective is to handle the spectrum handover of the secondary services. Steps 2-3 is used to locate the free channels from other service providers. If free channels are available and satisfy the minimum bandwidth requirement of the secondary service, then spectrum handover will be performed.

4.3 The Performance Study

For the performance study of the model, simulation is done in MATLAB. More than one service providers are considered in a cell of the cellular network. The cell of a network receives two types of requests; primary and secondary. Spectrum handover is done for the unserved primary service. For this, secondary services are interrupted and allocated some other channels possibly from some other nearby service providers as per the availability of the channels. Numbers of experiment have been performed by varying the parameters.

4.3.1 Primary and Secondary Services Analysis on Varying Arrival Rate

In this set of experiment, the observation is taken on the number of primary and secondary requests served. The input parameters, for the experiment, are as follows. The number of channels in each cell is considered to be 10. While allocating the channels to primary and secondary services, the minimum bandwidth requirement of the service is considered. Execution is done up to 100-time units and results are taken of the last 10 time units after the system is stabilized. This ensures the real behavior of the system. Bandwidth is in the range of 90 to 156 kbps. The request arrival rate of primary and secondary services is considered to be the same for analyzing the system performance when the same traffic capacity is being generated by both kinds of services. However, it can be different also.

- **Experiment 1**

In this experiment, the observation is taken on the number of primary requests served. The mean arrival rate for both Primary and Secondary requests are 5. Figure 4.2 exhibits that primary services are being served significantly better even with the high arrival rate of the request.

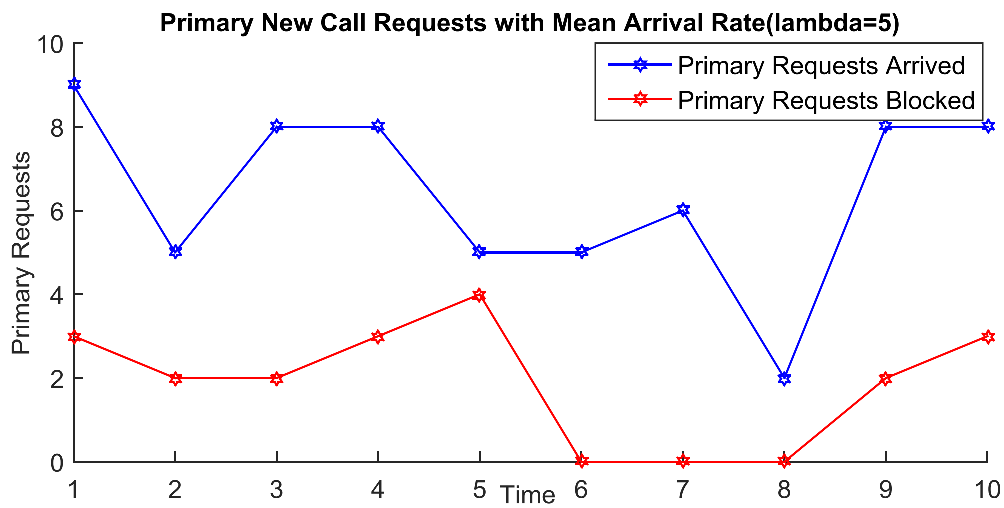

Figure 4.2: Arrived and served primary requests with arrival rate 5

- **Experiment 2**

This experiment is carried out by decreasing the mean arrival rate for primary and secondary requests to 4. Other parameters remain unchanged. Figure 4.3 shows that almost all primary service requests are served. Thus, on decreased arrival rate, blocked requests are negligible.

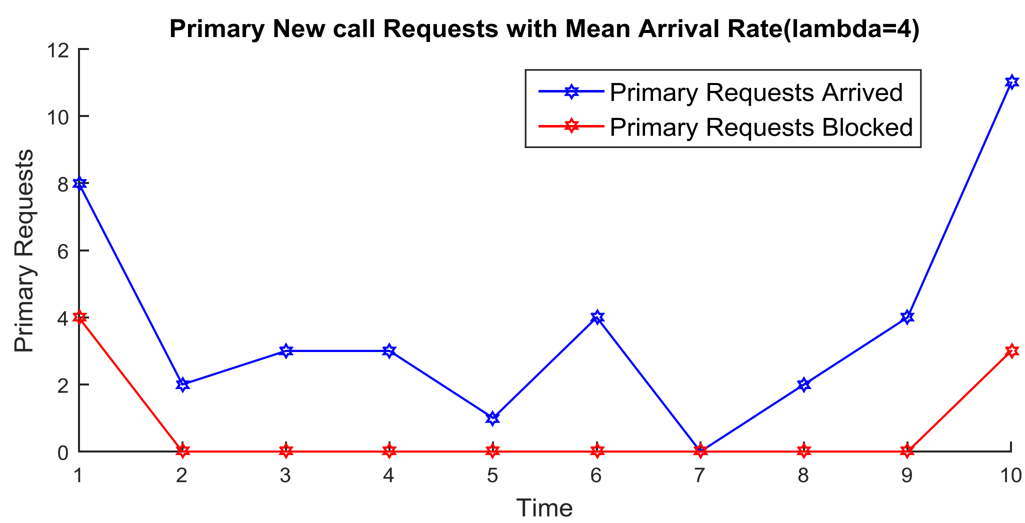

Figure 4.3: Arrived and served primary requests with arrival rate 4

- **Experiment 3**

Further, mean arrival rate of primary and secondary requests are decreased to 3. Figure 4.4 shows that all the arrived requests are served now.

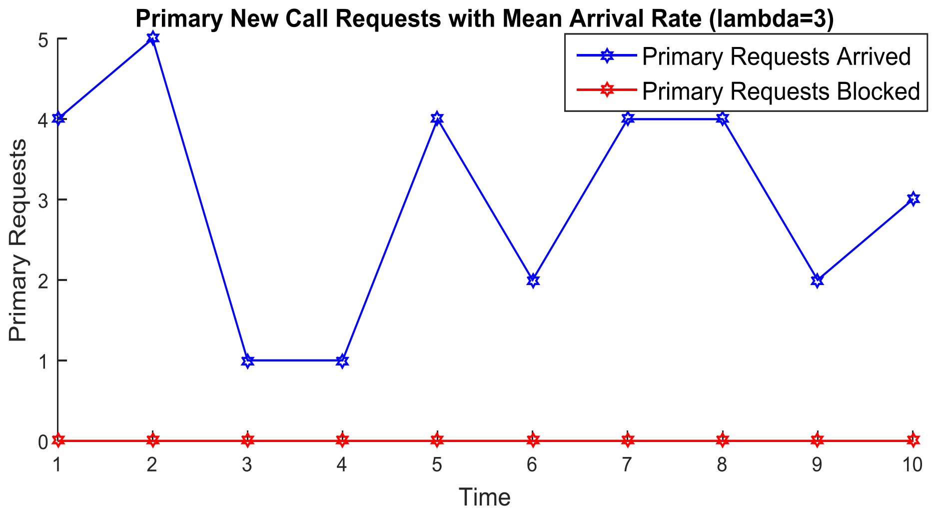

Figure 4.4: Arrived and served primary requests with arrival rate 3

Same set of experiments are carried out to observe how the secondary requests are being served.

- **Experiment 4**

This experiment is carried out to observe the arrival and service pattern of the secondary services. Notable is that when the mean arrival rate of secondary service is 5, only few secondary services are served as shown in figure 4.5.

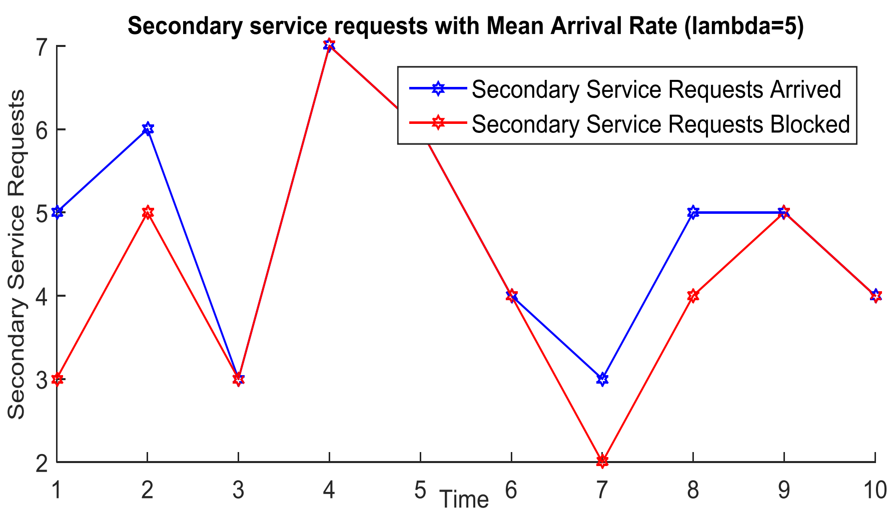

Figure 4.5: Arrived and served secondary service requests with arrival rate 5

- **Experiment 5**

In this experiment, the service request rate is decreased to 4. Figure 4.6 depicts a slight improvement in serving the secondary services.

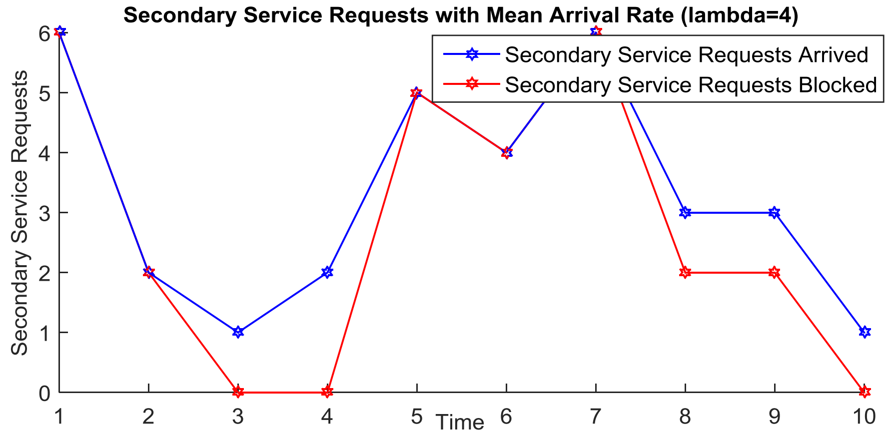

Figure 4.6: Arrived and served secondary service requests with arrival rate 4

- **Experiment 6**

Further, the secondary service rate is decreased to 3. Observation from figure 4.7 is that after decreasing the request rate to 3, blocking of the secondary requests are decreased significantly.

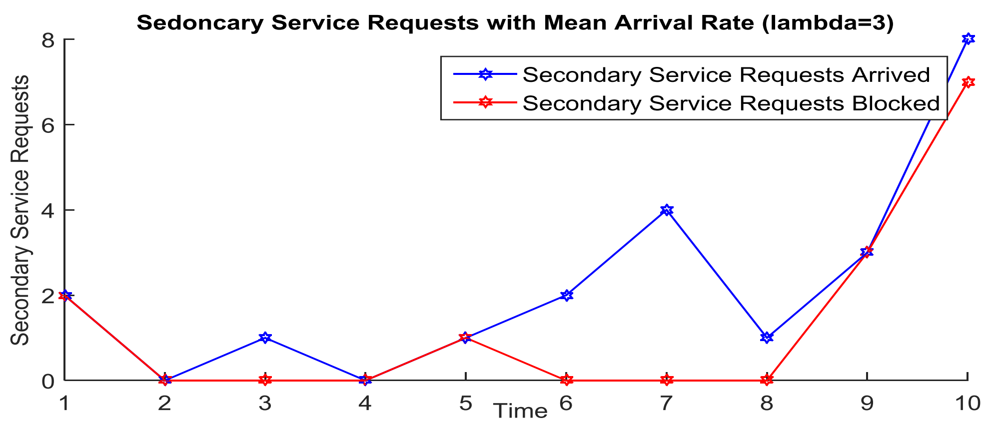

Figure 4.7: Arrived and served secondary service requests with arrival rate 3

Observation from figures 4.2, 4.3 and 4.4 show that when the primary request arrival rate is decreased then almost all primary requests are served. Figures 4.5, 4.6, and 4.7 show that when the secondary request arrival rate is low, blocked secondary requests are also reduced significantly.

4.3.2 Primary and Secondary Services Analysis on Varying Number of Channels

This set of experiments is carried out on the varying numbers of channels to observe the service performance of the primary and secondary requests. The input parameters, in the experiment, are as follows: the mean arrival rate of both primary and secondary requests is 5. Channel's bandwidth is in the range of 128 kbps to 256 kbps. The experiment is carried out for 500 units of time and results of the last 10-time units are taken i.e. when the system is stabilized.

First, three experiments show the analysis of arrived and blocked primary requests.

- **Experiment 1.** Number of channels per cell is 10.

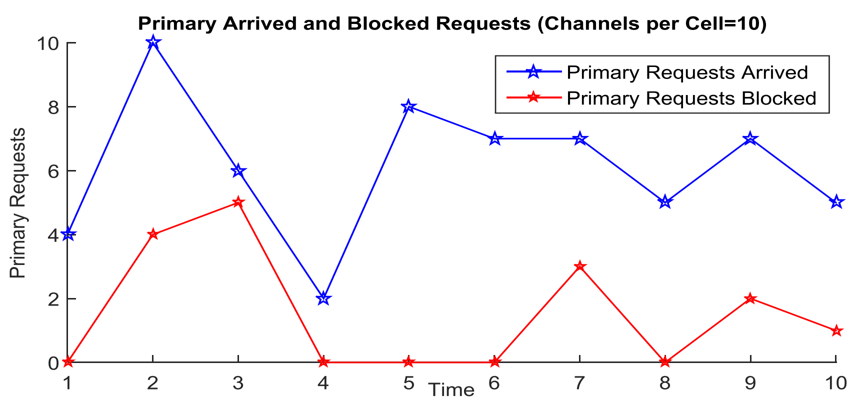

Figure 4.8: Arrived and Blocked Primary requests on 10 channels per cell

- **Experiment 2.** Same experiment is carried out with number of channels per cell as 15.

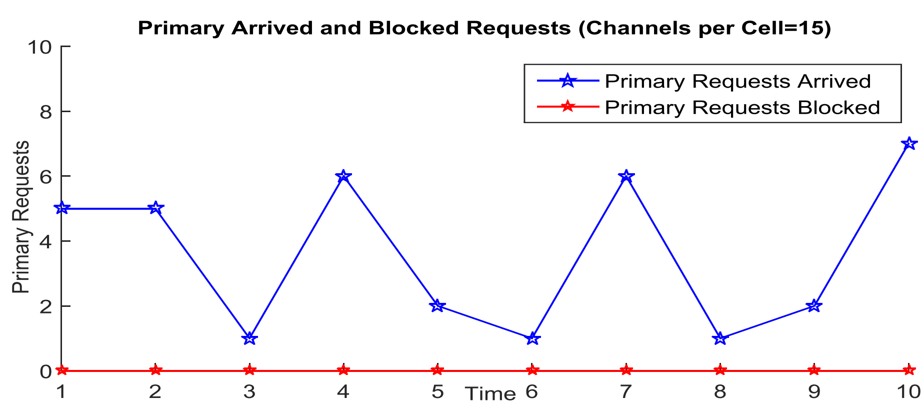

Figure 4.9: Arrived and Blocked Primary requests on 15 channels per cell

- **Experiment 3.** Again the experiment is repeated with number of channels per cell as 20.

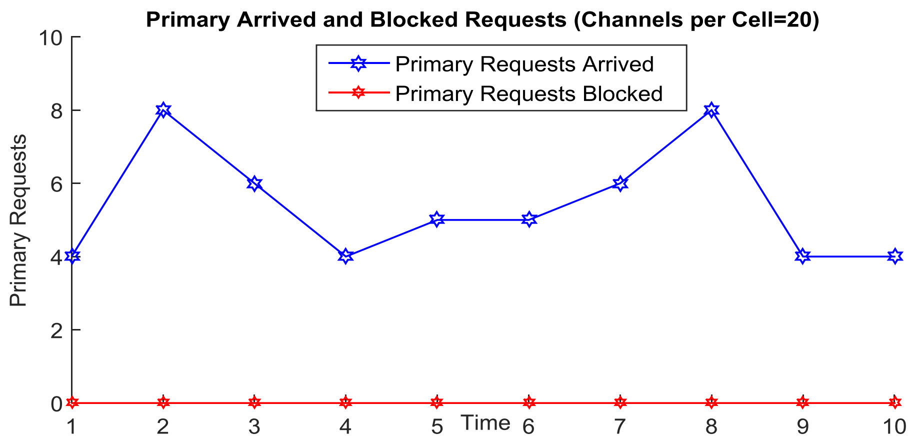

Figure 4.10: Arrived and Blocked Primary requests on 20 channels per cell

Observations from figures 4.8, 4.9 and 4.10 show that for fixed arrival rate, on increasing the number of channels per cell from 10 to 15, the requests are served better. On 20 channels per cell, all the arrived requests are being served.

Further, experiments are carried out to analyze the arrived and blocked secondary services on increasing number of channels.

- **Experiment 1.** Number of channels per cell is 10.

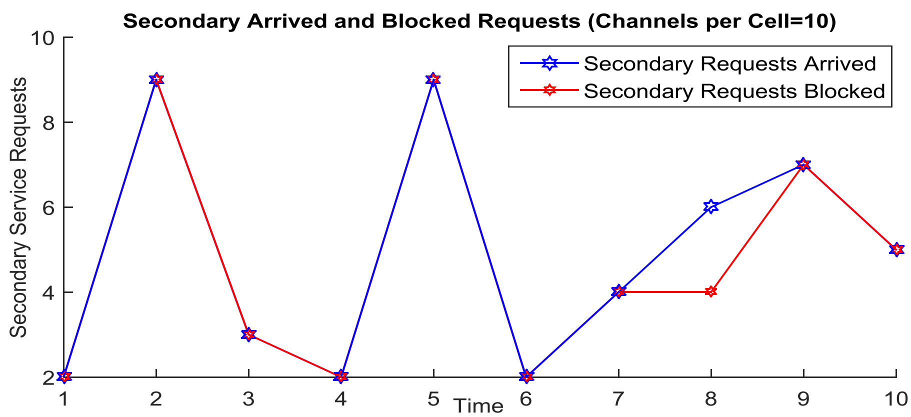

Figure 4.11: Arrived and Blocked Secondary requests on 10 channels per cell

- **Experiment 2.** Same experiment is carried out with number of channels per cell as 15.

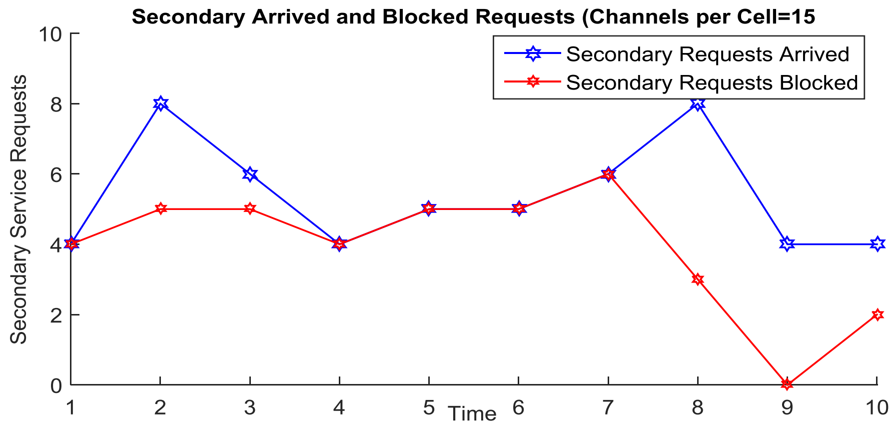

Figure 4.12: Arrived and Blocked Secondary requests on 15 channels per cell

- **Experiment 3.** Again the experiment is performed with number of channels per cell as 20.

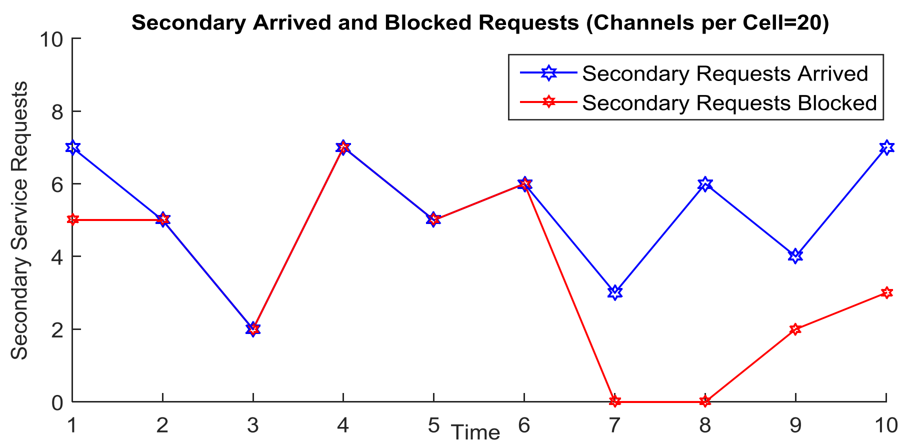

Figure 4.13: Arrived and Blocked Secondary requests on 20 channels per cell

- **Experiment 4.** In this experiment, the number of channels per cell is increased to 25.

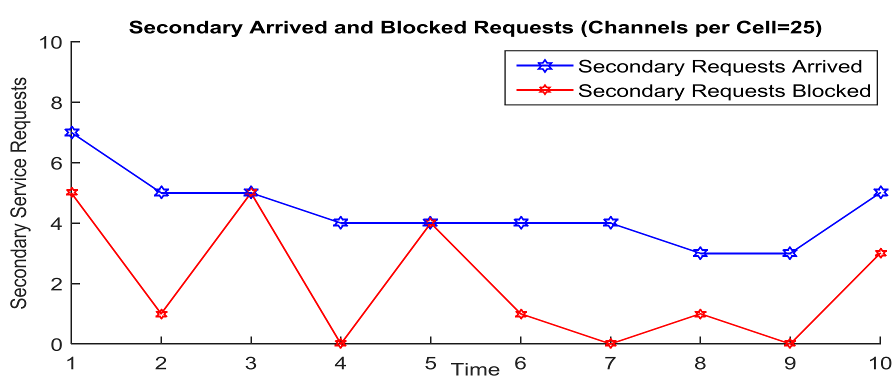

Figure 4.14: Arrived and Blocked Secondary requests on 25 channels per cell

- **Experiment 5.** Further, number of channels per cell is increased to 30.

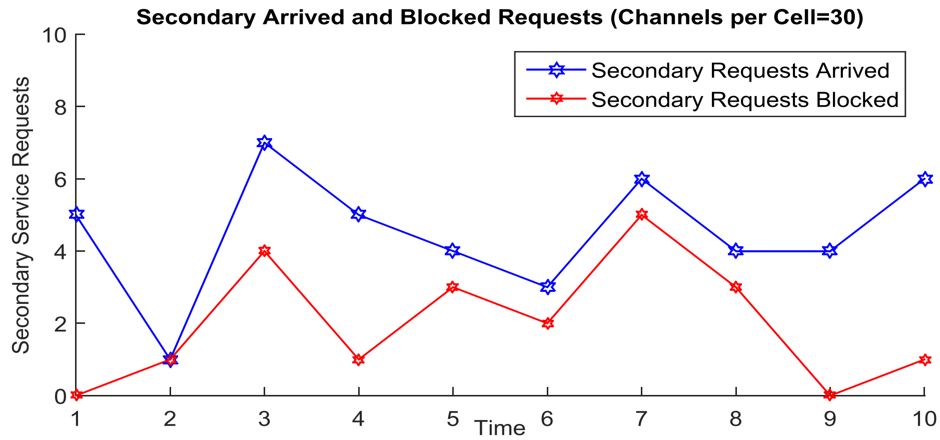

Figure 4.15: Arrived and Blocked Secondary requests on 30 channels per cell

- **Experiment 6.** In this experiment, number of channels per cell is 35.

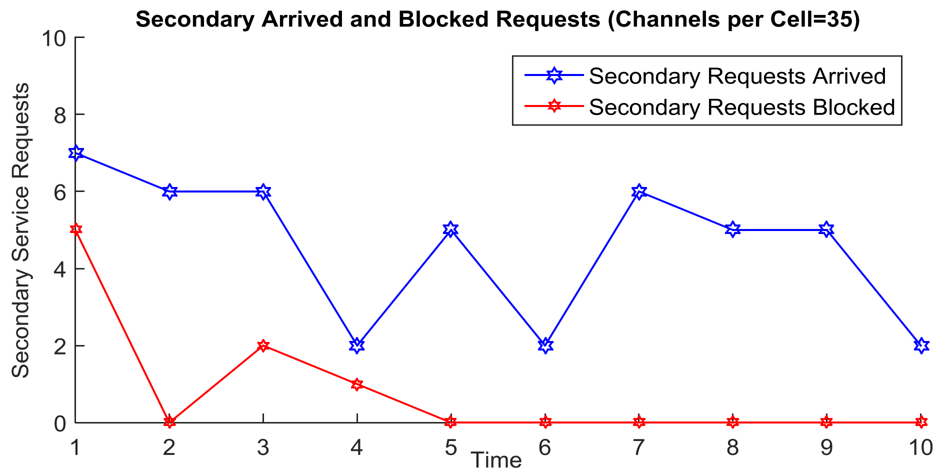

Figure 4.16: Arrived and Blocked Secondary requests on 35 channels per cell

Observations of the above set of experiments from figures 4.11, 4.12, 4.13, 4.14, 4.15 and 4.16 show that when the number of channels per cell is 10 then almost all the secondary requests are blocked. But on increasing the number of channels to 15, 20, 25, and 30, secondary blocked requests are being reduced significantly with the iteration. When the number of channels are 35, almost all the secondary requests are served.

4.3.3 Analysis of Average Blocked and Interrupted Secondary Services

These sets of experiments are carried out to observe the average blocked and interrupted secondary services. The input parameters for the experiment are as follows: the mean arrival rate of the primary service request is 4 and secondary service request is 6. Secondary service sizes are in the range of (100Kb to 2000Kb) in the first set of experiments whereas in the next set of experiments, it is in the range of (100Kb to 1000Kb). Primary service is in the range of 1 to 3 time units to complete its service. The experiment is carried out on 10, 20, 30, 40, and 50 channels to observe the performance of the model, in which channels bandwidth is in the range of 128 Kbps to 256 Kbps. The average result of 5000 iterations has been taken.

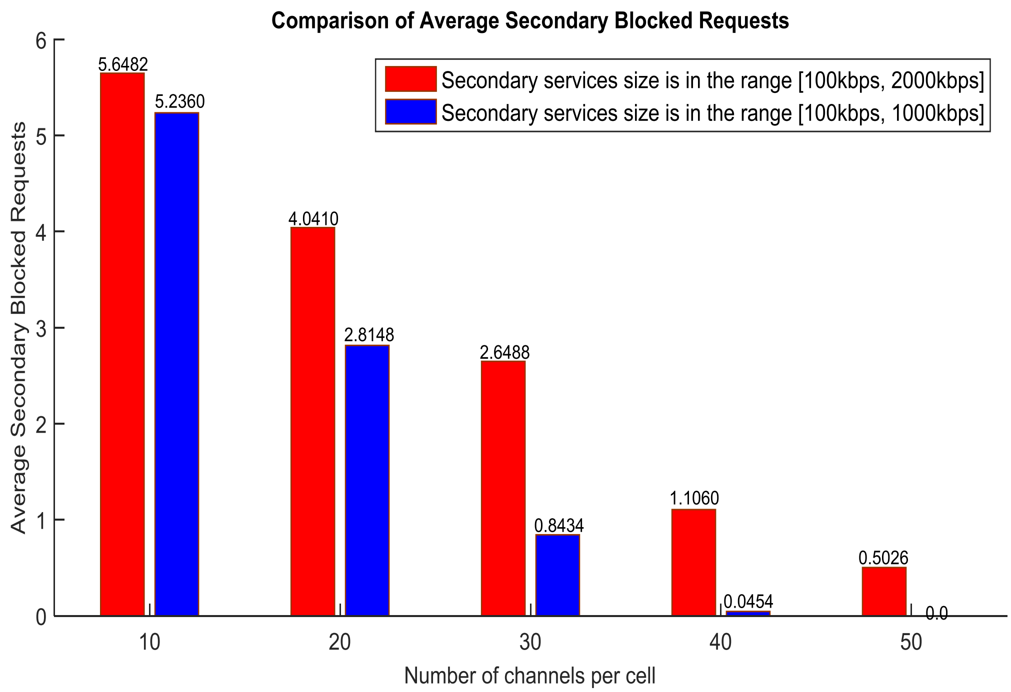

Figure 4.17: Average secondary blocked requests on a varying number of channels

Figure 4.17 shows that when secondary service size is in the range of (100kb to 1000kb) then average blocking of secondary services is low however on increasing the number of channels, average blocking is reduced significantly. Average blocked requests are negligible when the number of channels is increased to 50. Thus, it concludes that when secondary services size is low and the number of channels is high, the average blocked requests are negligible.

4.3.4 Analysis of Average Successful Rate on Varying Channel Bandwidth

In this section, a set of experiments are conducted to observe the impact of varying bandwidth. The input parameters for the experiment are as follows; the mean arrival rate of primary requests is 2 and the mean arrival rate of secondary requests is varying from 2 to 6 with incremental steps of 1. The number of channels per cell is 20. To observe the impact of channel bandwidth, three sets of experiments have been conducted by varying the channel bandwidth from 128 to

256Kbps, 512 to 4×512Kbps, and then 1024 to 5×1024Kbps. The observation is taken of 1000 iterations. It has been observed that when the mean arrival rate of secondary request is low, the average successful completion rate of secondary request is almost equal in all three cases of bandwidth. Also, when we increase the channel bandwidth then it is observed that the average successful completion rate of secondary requests is quite high with higher bandwidth channels.

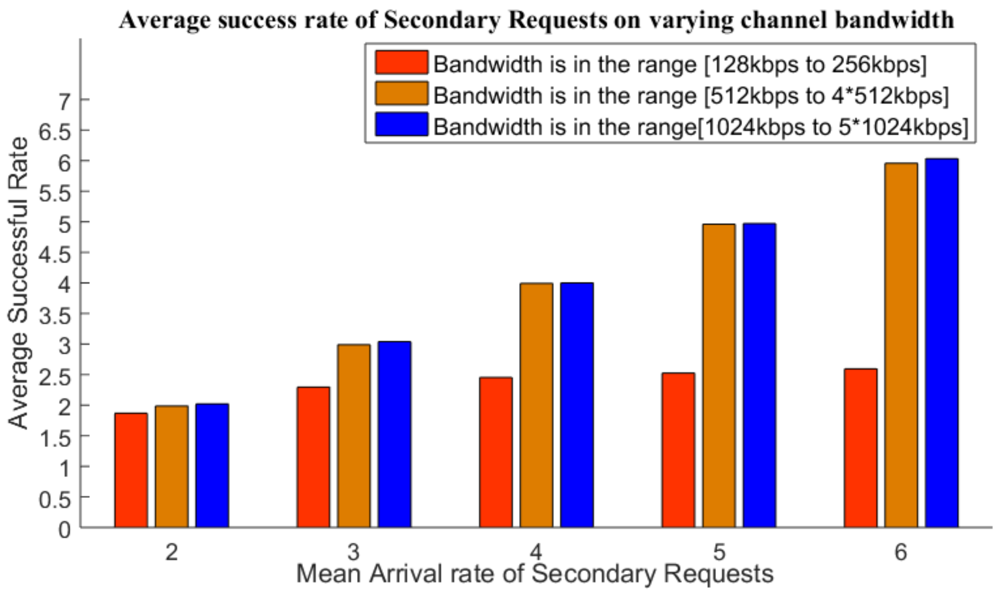

Figure 4.18: Comparison of Average successful request completion of Secondary Requests

Therefore, from figure 4.18, it can be concluded that the model performs better for secondary services, especially when bandwidth is high. Thus, this model can be suitable for both 4G and 5G types of wireless communication systems which are especially based on higher channel capacity.

4.3.5 A Comparative Study

A comparative study has also been performed to see the impact of the model on the throughput of the system. In the CR-enabled cellular system, the arrival of primary users often has an impact on the secondary users. It is because, on the arrival of a primary user, the secondary user needs to release the channel immediately. In order to complete its service, it has to locate some other available channels from the list of its accessible channels. Sudden interruption to secondary users may affect the throughput of the system. This section does a comparative study on secondary users' throughput with a recent model given by Amjad Ali et al. [9].

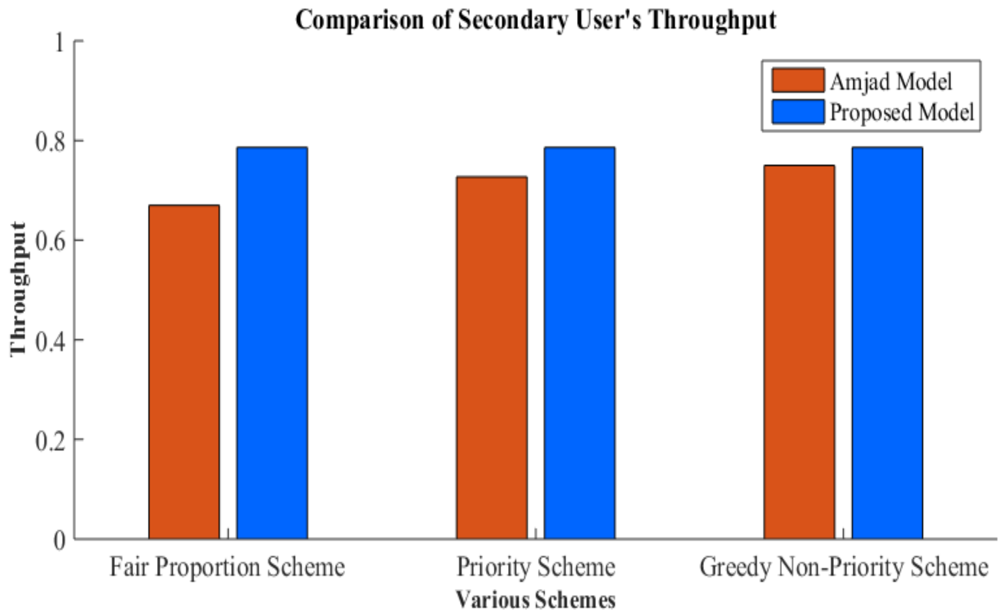

Figure 4.19: Average throughput of Secondary Users

For fair analysis, the input conforms to [9]. Secondary users' arrival follows a Poisson distribution with an average exponential call holding time of 120s. On average, 16 channels are available to secondary users at any moment of time. The result, shown in figure 4.19, is of 100 unit time when the system is stabilized.

Figure 4.19 shows that the proposed model performs better than Amjad Models [9] when various service providers are cooperating with each other and enable the secondary users to run their services on each other networks opportunistically.

4.4 Concluding Remarks

Fairness in allocation of channels, in cellular network for multimedia services, is one of the important requirement. In this chapter, a bandwidth requirement-based channel allocation is proposed in the CRN, which considers the minimum bandwidth requirement for allocating the channels. We applied the spectrum handover and cognitive radio technique on the requirement-based service requests for channel allocation effectively in this work. This model attempt to serve the maximum number of users possible. Simultaneously, the model has provisions to distribute the free channels to the currently running users to achieve fairness in channel allocation. Experimental evaluation, on varying request arrival rates, shows that primary services are being served effectively. When the mean arrival rate is low, both primary as well as secondary requests are served using the cognitive radio and spectrum handover concepts. The experiment conducted shows that even on the high mean arrival rate, both primary and secondary services are being served effectively and call block is minimized with the increasing number of channels. It has been also observed that non-real-time services are performing well on high channel bandwidth and being served effectively. Therefore, this system has the ability to perform better on higher generation wireless system, i.e. 4G and 5G wireless communication systems. A comparative study on secondary users' throughput indicates that the proposed model performs better in comparison to a few other recent models, which signifies the importance of the model.

Chapter 5

A Hybrid Dynamic Aggregation and Fragmentation Model for Cognitive Channel Allocation

Dynamic channel allocation and permissible aggregation can be a key technology to serve the limited resources among the increasing number of users. Cognitive Radio (CR) can be used as a key concept to further enhance the radio spectrum utilization at a higher level [152]. Channel aggregation enables a user to use more than one channel with enhanced bandwidth. Channel aggregation results in enhanced channel capacity. It can improve the quality of service (QoS) especially when the service is running on minimum bandwidth. Channel fragmentation (CF) can also be a better idea to accommodate the number of services. In this approach, one can split a channel into more than one channels to serve the requests with an acceptable QoS. At the same time, if the channels are free then they can be assembled to allocate the higher bandwidth to the required services. In general, users in cellular systems have interests in fetching higher bandwidth, flexibility in service provider selection, reliability, security, QoS, QoE, and low cost of bandwidth usage. At the same time, service providers are interested in least complex, scalable, reliable, and secure system, with low management cost and a good business model in terms of revenue [15]. Channel aggregation and fragmentation can be quite relevant in an advanced LTE standard also for serving the maximum number of users with a decent level of QoS [15], [165]-[166]. Cognitive Radio is playing a crucial role to enhance the radio spectrum utilization by applying various techniques for real-time and non-real-time services. The proposed work applies the channel aggregation and fragmentation concepts, along with the cognitive radio, to serve the maximum number of users with desired QoS/QoE. The major contributions of the work, presented in this chapter, can be summarized as follows.

- It minimizes the call block and call drop by splitting the allocated bandwidth dynamically which also helps in admitting maximum possible service requests.
- It increases the channel capacity for an ongoing communication by allocating available free bandwidth to the services in order to improve the QoS.
- It proposes a probabilistic channel allocation for the forced handover of the cognitive services.
- The model enhances the overall radio spectrum utilization.

5.1 The Problem and The Proposed Model

In this work, four priority levels of heterogeneous services have been considered with the division in real time and non-real time services. Real-time services are categorized into two; primary new (type 1) and primary handoff services (type 2). Similarly, non-real-time services are also of two categories; secondary new (type 1) and secondary handoff services (type 2). Preferably primary services will be served in F_CRN and secondary in D_CRN. In case of shortage of channels, primary services may be served in D_CRN by considering the bandwidth requirement and channel fragmentation concepts. Secondary services are not having any preference over each other while being served in D_CRN but in case of shortage of channels in D_CRN, even after applying the channel fragmentation technique, secondary handoff services may be served in F_CRN as per the availability of channels.

The proposed model for channel allocation uses the cognitive radio based dynamic channel aggregation and channel fragmentation techniques. It also uses the probabilistic channel selection to minimize the handover, especially of low priority services i.e., secondary services.

5.1.1 Probability-Based Channel Selection for Spectrum Handover

Cognitive users are required to perform spectrum handover in order to release the channel for serving the primary users. In this work, we have applied a probabilistic approach [11] to select the best-suited channel for performing the handover operation. For this, the probability of being a channel idle at a time has been calculated as given in equation 5.1. This indicates that the channel will be free at the time of performing the handover.

$$PIC_i = \left\{ \frac{NI_i}{NT_i} \quad \forall\, i \in (1, N) \right\} \tag{5.1}$$

Where NI_i is determined as in equation 5.2. NT_i is the number of trials on i^{th} channel to check whether the channel is idle or not.

$$NI_i = \left\{ \begin{matrix} NI_i = NI_i + 1 & if\ channel\ is\ idle \\ NI_i = NI_i & if\ channel\ is\ busy \end{matrix} \right\} \quad \forall\, i \in (1, N) \tag{5.2}$$

Equation 5.1 calculates the probability of a particular channel being idle that can be used to serve a new or handover request. Equation 5.2 is used to count on how many times a channel i is idle out of NT_i trials. For example, if a channel is accessed 5 times out of which 3 times it is found idle, then NI_i and NT_i will be 3 and 5 respectively.

5.1.2 Spectrum Allocation Scenario

In a study in [8], Cognitive Radio Network (CRN) based centralized architecture has been considered that comprised of two types of network; Primary Network (PN) and Secondary Network (SN). Two types of users have also been assumed in the network; Primary users (PU) and Secondary Users (SU). Primary users are further categorized into two; primary new users and primary handoff users and secondary users are also further categorized into two; secondary new users and secondary handoff users. Among all, primary handoff users are considered as the highest priority users.

In the proposed work, the whole radio spectrum allocated to the network is divided into two parts; the first one is aggregation-based non-reserved dynamic bandwidth, and the second is a reserved fixed bandwidth. Reserved fixed bandwidth channels preferably will be allocated to the primary users. It may be allocated to interrupted or suspended secondary services from D_CRN also as per the availability.

In figure 5.1, it is shown that PN is running on $M \in \mathrm{Z}^{+}$ channels, where Z^{+} is the set of positive integers. M channels are comprised of Non-reserved (L) as well as Reserved (R) channels as shown in equation 5.3.

$$M = L + R \tag{5.3}$$

Where $L \in \mathrm{Z}^{+}$ is the number of non-reserved channels, not necessarily of equal bandwidth as it may vary during aggregation and splitting of channels. $R \in \mathrm{Z}^{+}$ is the number of equal capacity reserved channels.

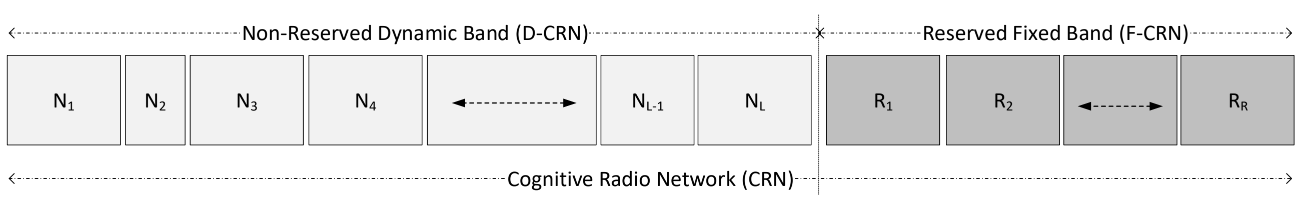

Figure 5.1: Non-Reserved Dynamic and Reserved Fixed band channel

5.1.3 The System Model

The proposed model considers four priority levels of the services assuming that higher priority services will be served first. This has been modeled as a continuous-time Markov-chain based cognitive radio network model assuming four types of users (PU_1, PU_2, SU_1, and SU_2) sharing the channels in F_CRN and D_CRN. Users' arrival follows a Poisson distribution with the rates as $\lambda_{PU1}, \ \lambda_{PU2}, \ \lambda_{SU1}, and \ \lambda_{SU2}$. Service time follows an exponential distribution with the rates $\mu_{PU1}, \ \mu_{PU2,} \ \mu_{SU1}, \ and \ \mu_{SU2}$ for the users $PU_1, \ PU_2, \ SU_1$, and SU_2 respectively.

In the model, PU_1 and PU_2 can access the entire cognitive radio network spectrum and PU_1 has priority over PU_2 i.e. during the shortage of free channels, PU_2 may be interrupted to facilitate PU_1. SU_1 and SU_2 will be served in D_CRN by applying the best possible channel aggregation and fragmentation approach. In case arrival rates of SU_1 and SU_2 are too high and can not be served in D_CRN, then depending upon the availability of channels in F_CRN, it may be served therefrom also.

To serve the requests as much as possible with considered QoS, dynamic splitting and aggregation of channels are shown in figure 5.4. It is obvious that allocation of higher bandwidth to non-real-time services will minimize the service time i.e. will increase the throughput.

There is no bandwidth constraint for the primary and secondary services over each other i.e. primary users' bandwidth can be more or less than the secondary users' bandwidth and vice versa. Secondary user's service duration may vary as per the allocated channel bandwidth after the aggregation. If higher bandwidth is allocated then service duration will be reduced and vice versa. In this work, $BW_{PU1}, \ BW_{PU2}, \ BW_{SU1}^{min} \ to \ BW_{SU1}^{max}$ and $BW_{SU2}^{min} \ to \ BW_{SU2}^{max}$ refers to the bandwidth for each category of users PU_1, PU_2 , SU_1, and SU_2 respectively.

In the model, primary users PU_1 and PU_2 can access the entire CRN (F_CRN + D_CRN) spectrum. Preferably, they will access F_CRN in case of normal traffic load. SU_1 and SU_2 will access the D_CRN, in which the number of channels may vary as per the aggregation and fragmentation of the radio spectrum. States of all four types of services can be represented as a tuple (i, j, k, l) where i, j, k and l are the number of active PU_1s, PU_2s, SU_1s and SU_2s respectively. Finally, its possible state space can be represented as shown in equation 5.4, and TRS can be calculated equation 5.5.

$$\Omega = \{ (i,j,k,l) | 0 \le i \le \left\lfloor \frac{TRS}{BW_{PU1}} \right\rfloor, 0 \le j \le \left\lfloor \frac{TRS}{BW_{PU2}} \right\rfloor, 0 \le k \le \left\lfloor \frac{TRS - F_{CRN}}{BW_{SU1}} \right\rfloor, 0 \le l \le \left\lfloor \frac{TRS - F_{CRN}}{BW_{SU2}} \right\rfloor, where$$

$$(i \times BW_{PU1}) + (j \times BW_{PU2}) + (k \times BW_{SU1}) + (l \times BW_{SU2}) \le TRS \} \quad (5.4)$$

Where, $TRS = \text{F\_CRN} + \text{D\_CRN}$ (5.5)

In case of high traffic in the network, the bandwidth to SU_1 and SU_2 will be allocated as shown in equation 5.6.

$$BW_{SU1/SU2}(i,j,k,l) = \begin{cases} \min\{BW^{max}_{SU1/SU2}, \max\{ BW^{min}_{SU1/SU2}, \frac{TRS - F_{CRN} - (i-x) \times BW_{PU1} - (j-y) \times BW_{PU2}}{k+l}\}\}, \\ \quad if\ 0 \le (i \times BW_{PU1}) + (j \times BW_{PU2}) \le (TRS - \max\{BW^{min}_{SU1}, BW^{min}_{SU2}\}) \\ 0, \quad otherewise \end{cases}$$

$$x \times BW_{PU1} + y \times BW_{PU2} \le F\_CRN \quad (5.6)$$

Where x and y are the numbers of active PU_1 and PU_2 in the F_CRN.

If the system state indicates (i,j,k,l) as the number of requests in the system then the idle bandwidth can be calculated as shown in equation 5.7.

$$idleBW = TRS - (i \times BW_{PU1}) - (j \times BW_{PU2}) - \left(k \times BW_{SU1}(i,j,k,l)\right) - \left(l \times BW_{SU2}(i,j,k,l)\right) \quad (5.7)$$

Thus, it is possible to calculate the available bandwidth in the system at any stage of the communication.

5.1.4 Free Channel Update

Channel status will be updated from busy state to free state when $RRS_{size} \le 0$ and $RRS_{time} = 0$ and the free channel will be returned to F_CRN or D_CRN.

$$RRS_{size} = TRS_{size} - BW_{SU1/SU2} \times time \quad (5.8)$$

$$RRS_{time} = TRS_{time} - time \quad (5.9)$$

Equation 5.8 is used to calculate the remaining required data size for non-real-time services and equation 5.9 gives the required time to complete the real-time services. After completing the services, channels will be returned into the respective free channels pool.

5.2 The Flowchart

The flowcharts on the activities of the primary and secondary users' arrivals, are drawn in figures 5.2 and 5.3 respectively for better understanding.

5.2.1 PU Arrivals

The request arrival of primary users' is possible in two categories; primary new users and primary handoff users. Amongst them, primary handoff users will be of high priority. Both primary handoff and new users can use the channels in D_CRN as well as in F_CRN. The flowchart of the activities, on the primary users’ arrival, is shown in figure 5.2.

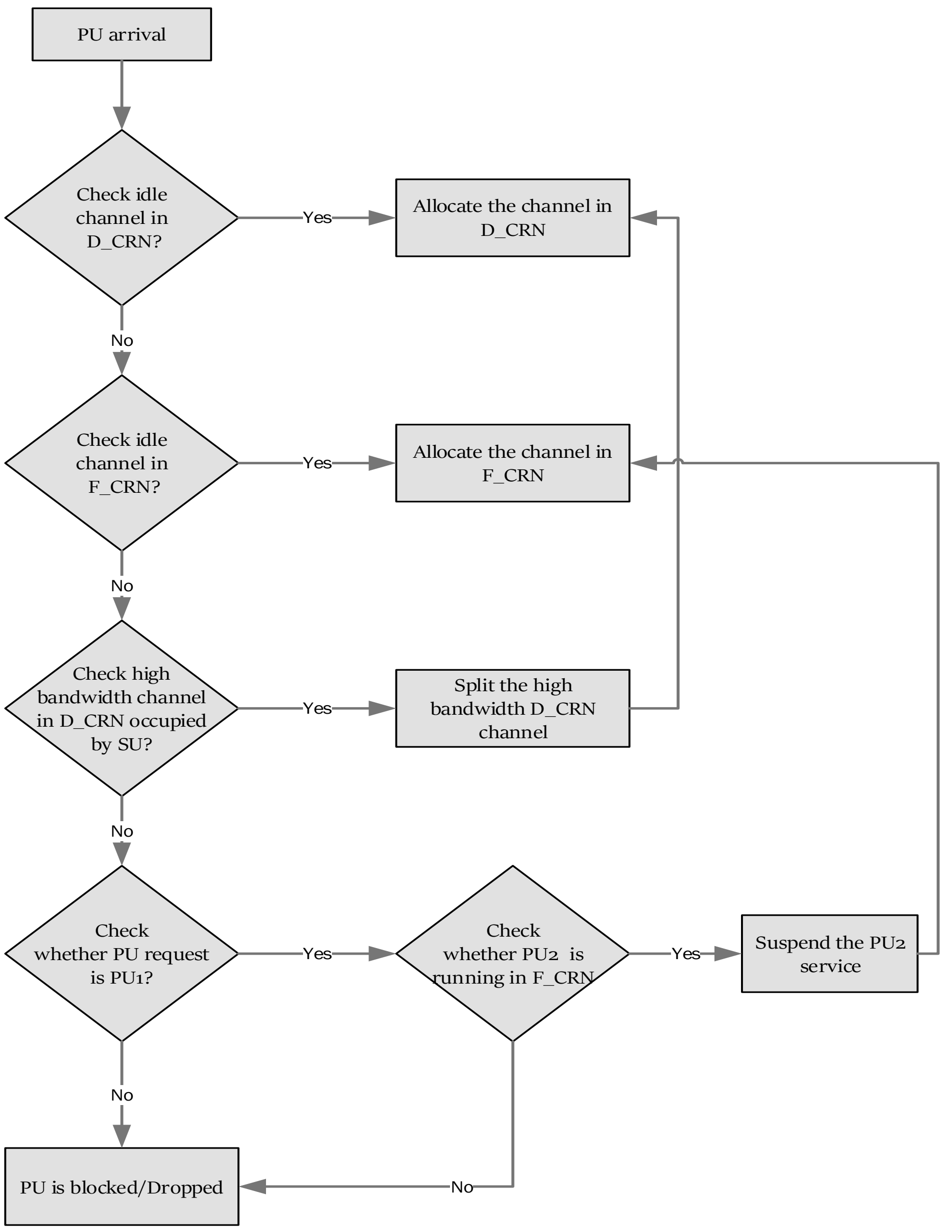

Figure 5.2: Channel allocation on PU arrival

5.2.2 SU Arrivals

The channel allocation activities, on the arrival of secondary users, is shown in figure 5.3.

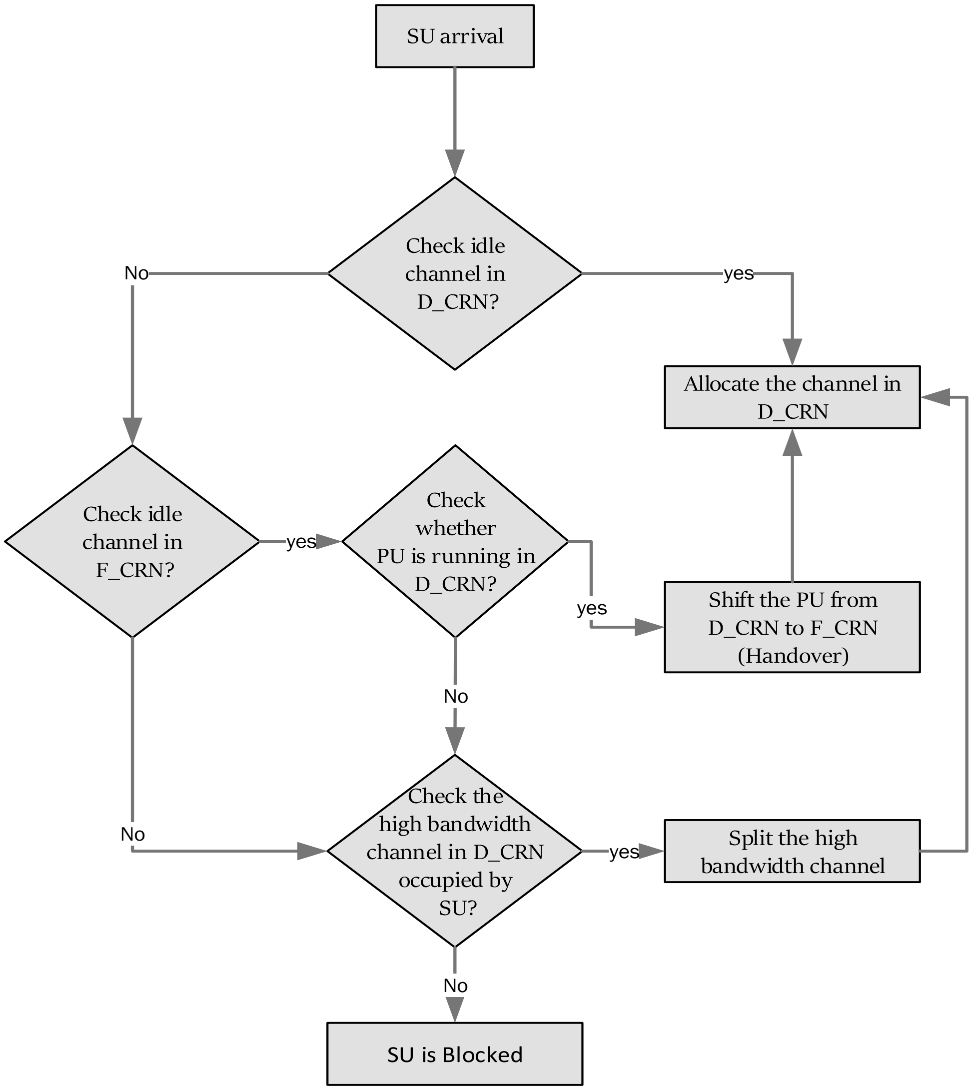

Figure 5.3: Channel Allocation on SU arrival

5.3 Channel Fragmentation and Aggregation

Channel aggregation follows the concept of buddy algorithm, applied in memory management by the operating systems. This considers the aggregation of the channel to the same fragment of the channel from wherefrom it was split. The aggregation concept helps the system to provide a better quality of service especially when traffic is low. In the buddy algorithm [164], [167], splitting takes place in equal fragments but in the proposed model splitting is done as per the requirement. However, the aggregation concept is the same as in the buddy algorithm [167]-[168]. The entire aggregation process is shown in figure 5.4.

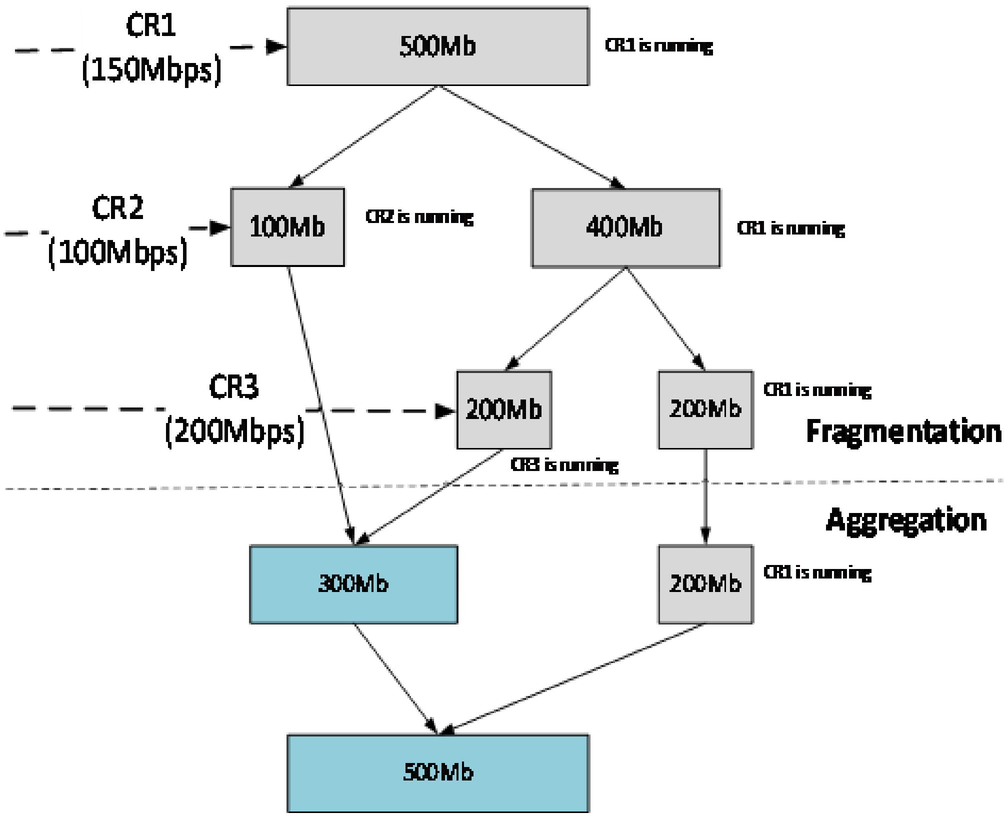

Figure 5.4 : Heterogeneous fragmentation of channels

5.3.1 Channel Selection for Handover

To minimize the PU_1 handover on the arrival of PU_2, we have applied the probabilistic channel selection if more than one channel is available. The channel with a high probability value indicates that the channel has a high probability to remain idle for a long period of time whereas the channel with low probability has higher chances to be occupied again. Therefore, for handover, the channel with high probability is good because such channel allocation will minimize the chances for a request to enter into handover repeatedly. Both these probabilities of the channels are calculated using equation 5.1 and equation 5.2 respectively.

5.4 The Algorithm

The algorithm for the channel allocation, based on the concept of aggregation and channel splitting, is as follows.

Algorithm 5.1: Channel Allocation using Aggregation and splitting

Input

Enter the Mean Arrival rate of PU_1, PU_2, PU_3 and PU_4

Initialize BW^{min} and BW^{max} for each request of PU_1, PU_2, PU_3 and PU_4

Initialize the number of channels for F_CRN

Initialize the bandwidth for D_CRN

Enter the Max_ITR for taking the observation

Output

Average blocking of PU_1 and SU_1

Average dropping of PU_2 and SU_2

Steps

1. $\boldsymbol{if}$ $F\_CRN_{channels} > 0$ and $PU_1\ requests > 0$ then

    $\boldsymbol{if}$ $F\_CRN_{channels} > PU_1 requests$ then

        Allocate the channel to all the PU_1 requests
        Update the F_CRN free channels
        Update $PU_1 requests = 0$

2. $\boldsymbol{else}$

        Allocate the channels to $PU_1\ requests$ as per available free channels
        Update the PU_1 unserved requests
        Update $F\_CRN\ free\ channels = 0$

3. Repeat steps 1 and 2 for channel allocation to PU_2 requests.

4. If any one of $PU_1 and\ PU_2\ requests$ are unserved then

    Check $\boldsymbol{if}$ $D\_CRN_{BW} > 0$ then

        Split the channel from D_CRN_{BW} as per BW^{max} requirement for

PU_1 *and* PU_2

Update the D_CRN_{BW} by removing the allocated part

Repeat step 4 till all the PU_1 *and* PU_2 are served

Else

Block the PU_1 *requests*

Drop the PU_2 *requests*

5. End

The algorithm for channel allocation to the secondary users is as follows.

Algorithm 5.2: Channel Allocation to SU_1 and SU_2

$\rhd$ *Allocate the channel in D_CRN band by splitting bandwidth*

1. ***if*** SU_1 *requests* > 0 *and* $D\_CRN_{BW} > 0$

   Split the channel BW^{min} and allocate the channel to SU_1 requests

   Update the D_CRN_{BW} by removing the allocated part

   Repeat step 1 until all the $SU_1$are served.

2. ***if*** SU_2 *requests* > 0 *and* $D\_CRN_{BW} > 0$

   $\rhd$ *In this maximum required BW will be allocated if it is available.*

3. ***if*** $D\_CRN_{BW} > BW^{max}$ *required for* SU_2 then

   Split the channel BW^{max} and allocate the channel to SU_2

   Update the D_CRN_{BW} by removing the allocated part

   Repeat step 3 until the condition is true

4. ***else if*** $D\_CRN_{BW} < BW^{max}$ *and* $D\_CRN_{BW} > BW^{min}$

   Allocate the entire D_CRN_{BW} to SU_2

   else

   Allocate the D_CRN_{BW} to SU_2

Update $D\_CRN_{BW} = 0$

5. $\rhd$ *if* SU_1 *and* SU_2 *requests are still unserved then allocate the channel in*

   F_CRN as per channel avalability.

6. Drop the SU_1 *requests*

   Block the SU_2 requests

7. Go to Algorithm 3 to update the free channel information and merge the D_DRN free channels.

The Algorithm for updating the F_CRN free channels and D_CRN_{BW}

Algorithm 5.3 : Update the F_CRN free channels and D_CRN_{BW}

$\rhd$ *Update the channel status using equation* 8 *and equation*

$\rhd$ *channels have two tags*:

$tag - 0$ *indicates that service is running on* F_{CRN} *channel* and

$tag - 1$ *indicates that service is on* D_CRN *channel*

---

1. *if* channel $tag = 0$ and $(RRS_{size} \leq 0 \; OR \; RRS_{time} \leq 0)$ then

   Return the channel into F_CRN free channel list

2. *if* channel $tag = 1$ and $(RRS_{size} \leq 0 \; OR \; RRS_{time} \leq 0)$ then

   $\rhd$ *Merge the released* $BW = (BW^{min} \; OR \; BW^{max} \; OR \; BW)$ *channel into* D_CRN_{BW}

$$D\_CRN_{BW} = D\_CRN_{BW} + BW$$

In algorithm 5.1, the initial steps are for the initialization of input parameters, steps 1-2 states the channel allocation process for PU_1 and PU_2' s in F_CRN. Unserved PU_1 and PU_2' s will be served in D_CRN by performing the channel splitting which is stated from steps 3-5. The output in terms of primary blocked and dropped requests is indicated in step 7.

Algorithm 5.2 is aimed to indicate the channel allocation process for SU_1 and SU_2. In this, step 1 shows the channel allocation to SU_1 if the free channel is available. Otherwise, it will split the channel as per the possibility of min and max bandwidth requirement for the channel allocation. Steps 2-4 indicate the channel allocation to SU_2 along with updating the bandwidth status. Storing the blocked and dropped information of secondary services are listed in steps 5 and 6.

Updating the free channel information is mentioned in algorithm 5.3 with the help of tag 0 and tag 1 for identifying the real and non-real-time services.

5.5 Performance Analysis

To analyze the performance of the proposed model, simulation is done by writing the program in MATLAB. Heterogeneous services, i.e. real-time and non-real-time services, are considered that are used by primary and cognitive users. Primary services are of two categories; new services and handoff services. Similarly, non-real-time services are also categorized into new and handoff services. Radio spectrum is categorized into two categories; fixed band spectrum and dynamic band spectrum. In a fixed band, the channel is fixed with its specified bandwidth while in the dynamic band, initially entire dynamic band is treated as one channel and dynamic splitting takes place as per the requirement of the bandwidth and the availability of the radio spectrum. Aggregation takes place as per the availability of different free slots.

5.5.1 Experiment 1

In this experiment, it is assumed that the mean arrival rate of all four types of services PU_1, PU_2, SU_1 and SU_2 are quite high i.e. 5 for each. Two types of channels are considered to serve the requests; fixed channels in the bandwidth range of 250Kb to 300 Kb whereas dynamic spectrum is allocated as a whole to serve the requests. It splits and merges as per the requirement. In the experiment, fixed channel and dynamic bands for each types of users (shown in tuple) are as follows: <20, 4096>, <30, 8192>, <40, 16384>, <50, 32768>, and <60, 65536>. For example <20, 4096> means there are 20 channels in the fixed bandwidth, and 4096 is the available dynamic bandwidth. Experiments are repeated for 5000 times and average results are shown in figure 5.5.

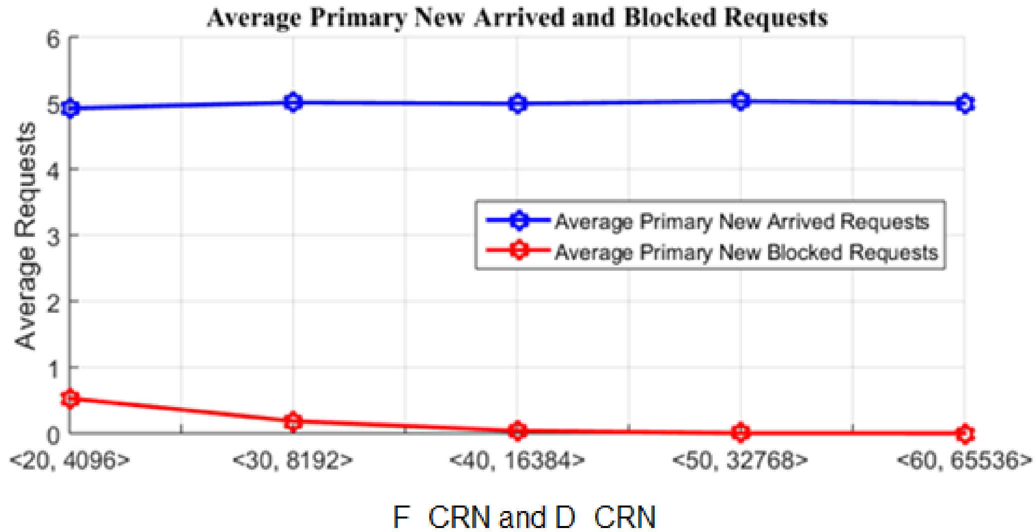

Figure 5.5: Average Primary Blocked Requests with mean arrival rate 5

From figure 5.5 one can observe that even at high mean arrival rate, requests are being served quite effectively which is almost zero when fixed channels and dynamic frequency band is <40, 16384>.

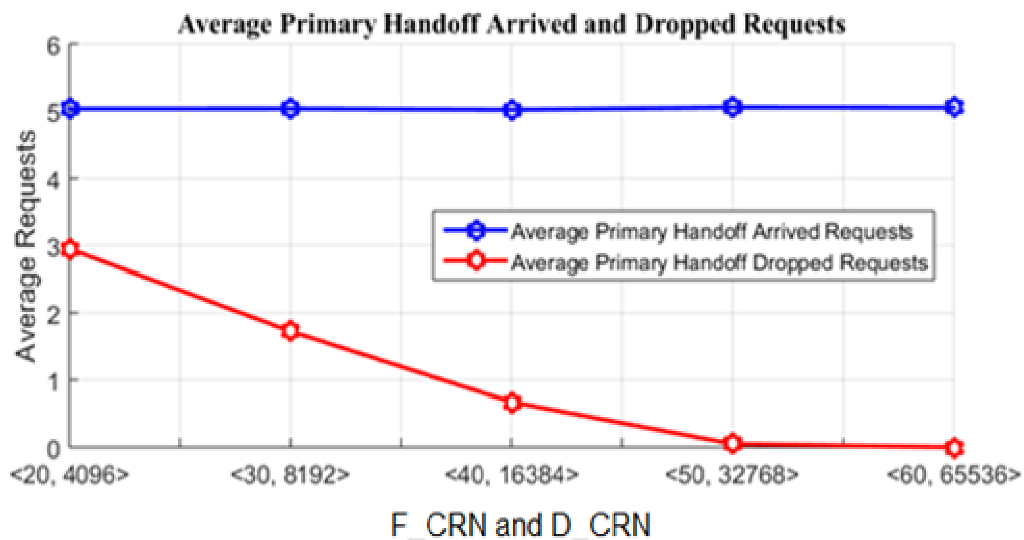

Figure 5.6: Average Primary Dropped Requests with mean arrival rate 5

Figure 5.6 shows that primary handoff requests are also being served quite effectively using the dynamic aggregation concept.

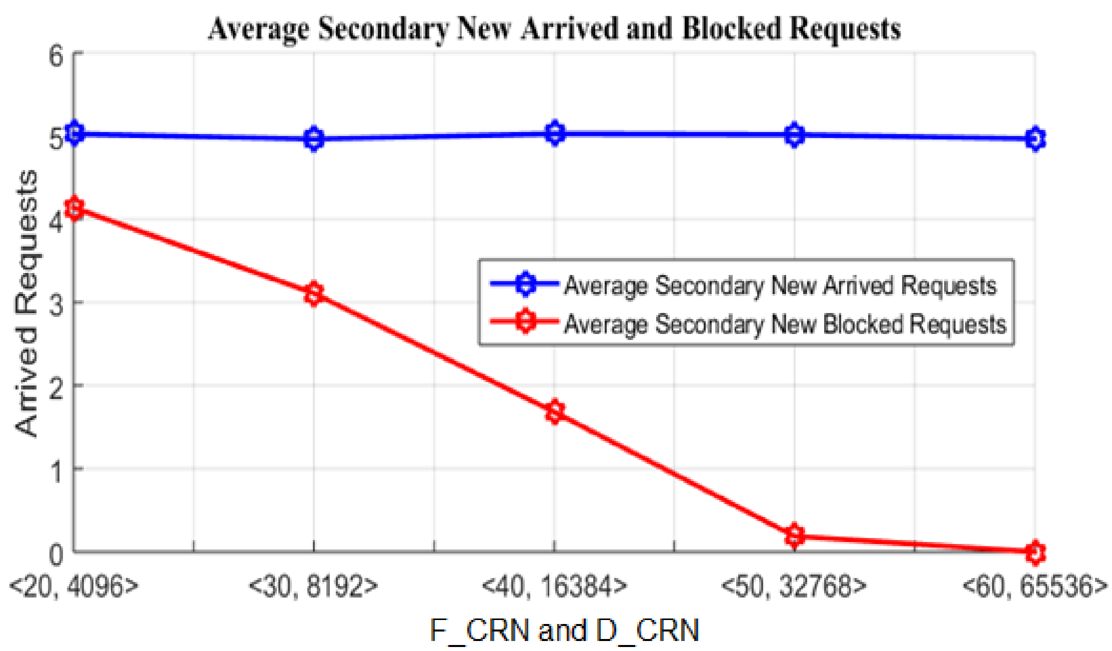

Figure 5.7: Average Secondary Blocked Requests with mean Arrival rate 5

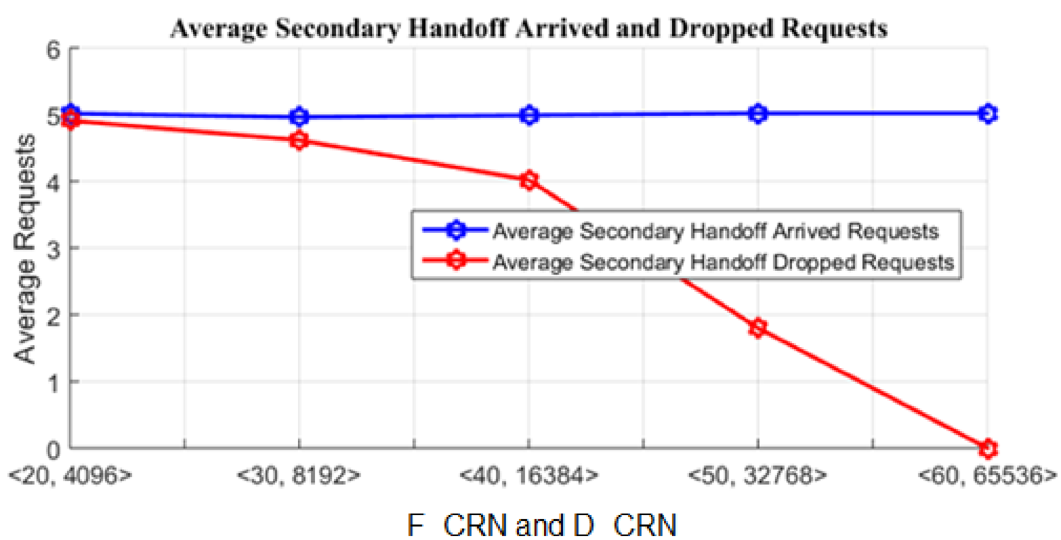

Figure 5.8: Average Secondary Dropped Requests with mean Arrival rate 5

Figures 5.7 and 5.8 show that although the blocking and dropping rate of secondary services are a bit high, after increasing the fixed and dynamic channels, it is reduced effectively and eventually becomes negligible.

It can be concluded, therefore, that even with the high mean arrival rate of requests, the proposed model can serve the requests effectively using the dynamic splitting and the aggregation concepts with the help of Cognitive Radio.

5.5.2 Experiment 2

This experiment is performed to test the performance of the secondary services by reducing the traffic of primary services. In this experiment, the mean arrival rate of primary new and primary handoff is kept low i.e. 2 for each. However, secondary services are quite high i.e. secondary handoff and secondary new services 5 each. The fixed number of channels considered is 20. D-CRN channel is varied from 10000Kb to 50000Kb.

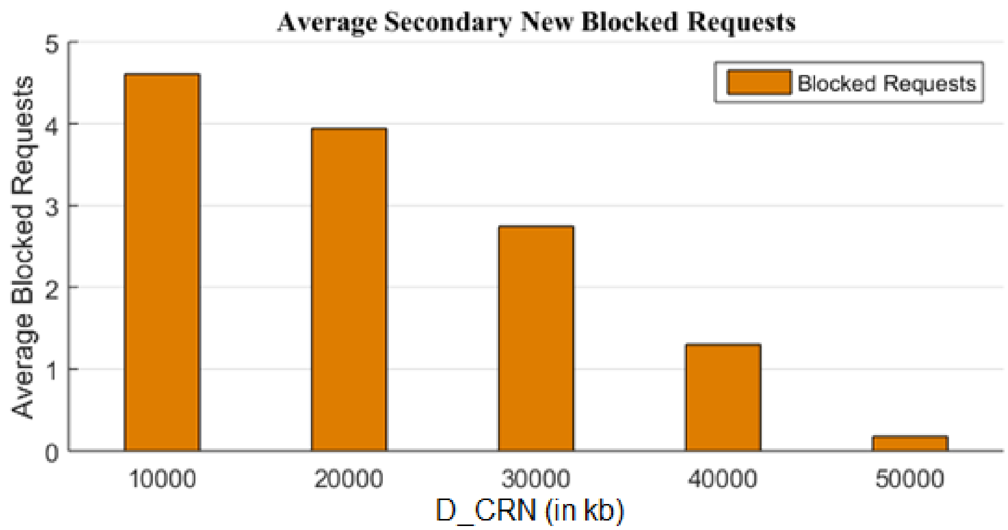

Figure 5.9: Average Secondary Blocked requests by increasing the D_CRN bandwidth

Observation from figure 5.9 reflects that on increasing the D_CRN_{BW}, average blocking of the requests is reduced. When D_CRN_{BW} is 50000Kb, the average blocking is quite low.

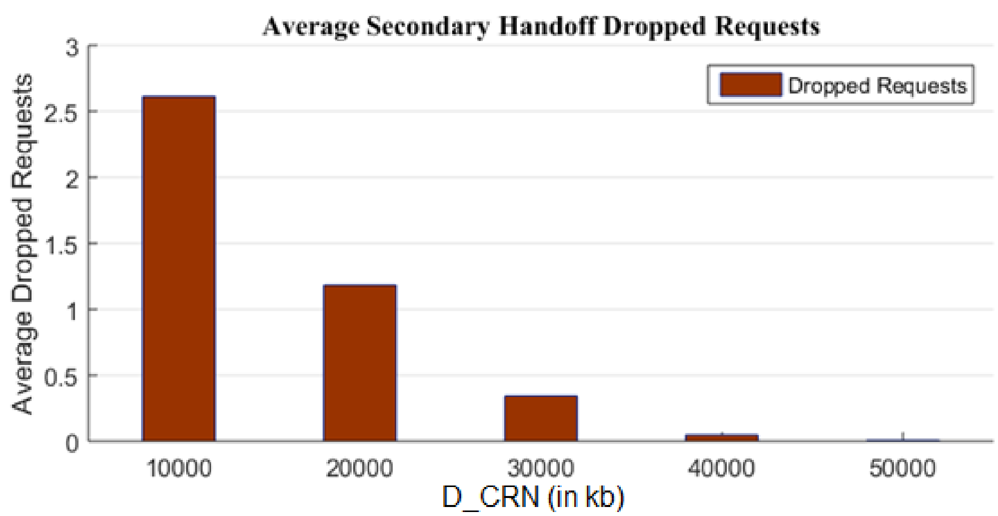

Figure 5.10: Average Secondary Dropped Requests by increasing D_CRN bandwidth

Figure 5.10 shows that the average dropping rate is almost negligible even when there is no increase in F_CRN channels. Therefore, one can conclude that on comparatively high D_CRN_{BW}, there is no need to increase the number of F_CRN channels and it will serve the requests effectively using the channel fragmentation and aggregations concepts.

5.5.3 Experiment 3

This set of experiments are conducted to observe the average blocked and dropped requests by changing the F_CRN while keeping D_CRN same. The input parameters for the experiment is as follows; mean arrival rate of PU_1 and PU_2 are 5 and 4 respectively while mean arrival rate of SU_1 and SU_2 are comparatively low to 3 and 2 respectively. Bandwidth for D_CRN (in Kb) is 10240 and channels in F_CRN are varied from 20, 40, 60, 80, and 100. Average results are taken of 1000 iterations. In this experiment, it is assumed that PU_1 and PU_2 can share the D_CRN bandwidth as per the requirement but SU_1 and SU_2 will not share the F_CRN channels.

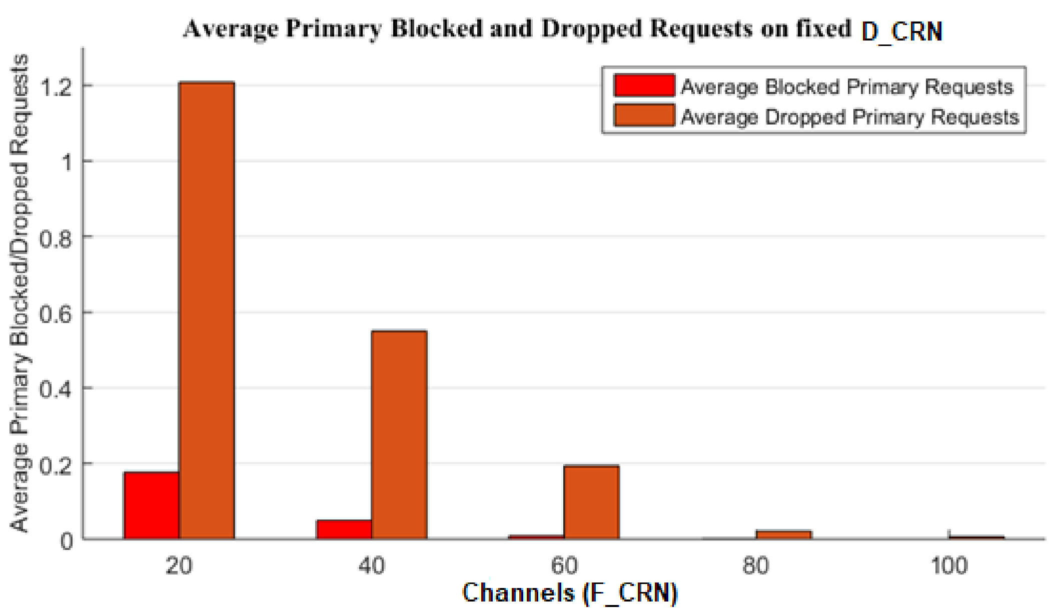

Figure 5.11: Average Primary Blocked and Dropped Requests by increasing the F_CRN channels

Observation, from figure 5.11, shows that on increasing the number of channels in F_CRN average primary blocked and dropped requests are being reduced significantly. Also, when the number of F_CRN channels are 100 then primary blocked and dropped requests are almost negligible.

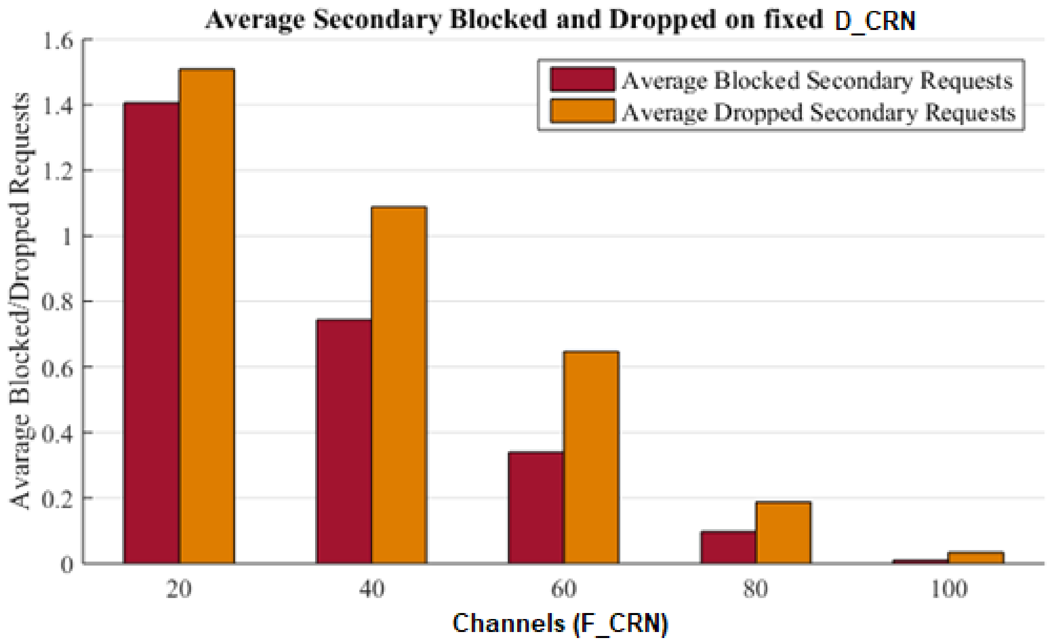

Figure 5.12: Average Secondary Blocked and Dropped Requests by increasing the F_CRN channels

From figure 5.12 it can be observed that when we increase the number of channels in F_CRN then also average secondary blocked and dropped requests are being reduced significantly even when SU_1 and SU_2 requests are not sharing the F_CRN channels. It concludes that with the comparatively high number of channels in F_CRN, PU_1 and PU_2 requests are negligibly sharing the D_CRN and D_CRN bandwidth is able to serve almost all the SU_1 and SU_2 requests. Figure 5.12 depicts that with 100 number of channels, average secondary blocked and dropped requests are almost negligible.

5.6 Comparative Analysis

A comparative study with the model in [24] by Falcao et al. has been done to show the effectiveness of the proposed model in terms of blocking probability of SU_1 and SU_2 services. To perform the comparative study, PU_1 and PU_2 are collectively considered as PU as the model in [24] does not consider PU_1 and PU_2 separately. Therefore, the mean arrival rate is mapped as $\lambda_{PU_1} + \lambda_{PU_2} = \lambda_{PU}$. The input parameter for the experiment are as follows; the mean arrival rate of secondary users $\lambda_{SU_1} = 1$ and $\lambda_{SU_2} = 1$. Number of F_CRN channels in the network is 4 and D_CRN bandwidth is considered to perform channel aggregation and fragmentation dynamically. The observation is taken for 1000 iteration on varying λ_{PU} as 1, 2, 3, and 4.

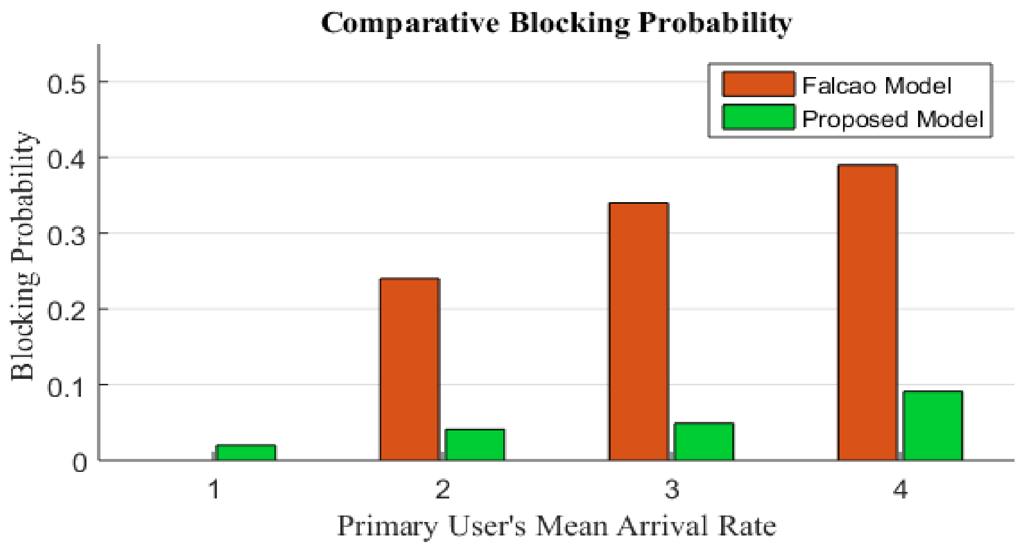

Figure 5.13: Blocking Probability of SU_1 on varying Primary Users Arrival Rate

Figure 5.13 shows the comparison of blocking probability of SU_1 of the proposed model and the Falcao model [24]. It can be observed that when the primary arrival rate $\lambda_{PU} = 1$ then Falcao model performs better but with the increase in the primary user's arrival rate, the proposed model performs better and gives the lower probability for SU_1 users.

Figure 5.14 exhibits the comparison of the blocking probability of SU_2 with the Falcao model. It can be observed that on the low arrival rate of primary users, the Falcao model is good but with the increase in the arrival rate of primary users, the blocking probability of the proposed model is significantly lower than the Falcao model.

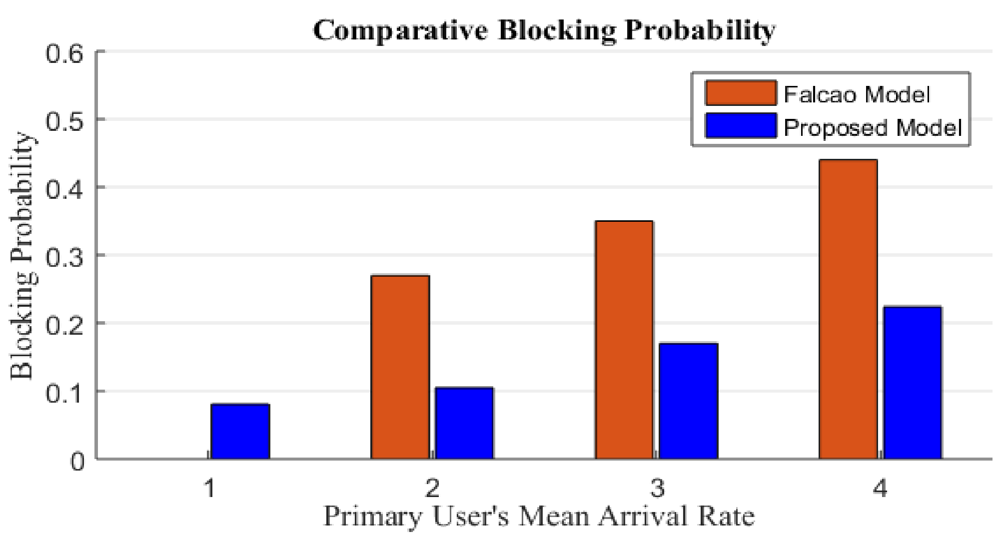

Figure 5.14: Blocking Probability of SU_2 on varying Primary Users Arrival Rate

Observations from figures 5.13 and 5.14 are derived as follows. With the increase in the mean arrival rate of primary users, blocking probability of the proposed model for both SU_1 and SU_2 is lower than the Falcao model.

5.7 Concluding Remarks

Developing channel allocation models for CRN need to consider both QoS and QoE simultaneously as service users are interested in getting higher bandwidth, flexibility in service provider selection, reliability, and security. Simultaneously, service providers are interested in least complex, scalable, reliable, and secure system, with low management cost and a good business model in terms of revenue. In this chapter, the channel allocation model proposed for CRN uses the concepts of channel aggregation and fragmentation with the cognitive radio technology to serve as many uses as possible. In the model, services are categorized as primary new, primary handoff, secondary new, and secondary handoff. Primary services are being served in F_CRN on priority basis considering their required bandwidth. Secondary services are being served by applying the techniques of channel splitting and channel aggregation. Probabilistic channel handover is applied to minimize the multistage handoff.

Experimental evaluation verifies that F_CRN and D_CRN networks are collectively able to minimize the call block and call drop effectively. It also provides a better quality of service because channels are allocated as per the bandwidth requirement. It has been also observed that on varying the D_CRN bandwidth, secondary new and secondary handoff requests are being served well. Furthermore, with good number of F_CRN channels, D_CRN can serve all the secondary services by performing the channel splitting and channel aggregation only.

A comparative study on the varying mean arrival rate of primary services has been done to observe the impact on secondary services wherein it has been observed that the proposed model is effectively able to serve both kinds of secondary services (SU_1 and SU_2). Thus, blocking probability is minimized for both types of secondary services. The lower blocking probability, in comparison to a few recent models, signifies the importance of the proposed model. This model can be implemented in real CRN to gain in terms of better QoS and efficient channel utilization.

Chapter 6

Conclusion

Cognitive radio network (CRN) is an intelligent network which is based on the concept of software-defined radio (SDR). The CR is intelligent technology which dynamically adjusts to the operating parameters and makes it more adaptive, self-configuring, self-organizing, self-healing, and self-recovering. Cognitive network maximizes frequency channel utilization by opportunistically accessing the free spectrum holes. CR capability to improve the spectrum utilization makes it a promising technology and a potential solution to 5G cellular network spectrum management.

This chapter derives the conclusion on the findings of the thesis with a discussion for each of the proposed models for channel allocation in cognitive radio enabled cellular networks.

6.1 Concluding Remarks and Discussion

The chapter wise concluding remarks are as follows.

In chapter 1, we focused on the channel allocation problem in the mobile cellular system. This chapter introduces the cellular system and the related technology for the channel allocation problem in cellular system. It also points out the research issues therein which is the motivation behind the work performed in this thesis. The concept of CR has been discussed along with the FCC definition of CR. Then the idea of DSA and SDR are elaborated and also on how CR is different from SDR. Frequency channels are the key resources used for communication in the wireless environment. This chapter describes the frequency band, frequency channels, and the frequency range proposed for 5G cellular networks. This chapter also introduces the Shannon–Hartley theorem for the channel capacity. Subsequently, the channel allocation problem in the CRN has been discussed. This chapter also highlights why new channel allocation schemes are required for serving both PUs and SUs in the CRN with better QoS/QoE by considering proper spectrum mobility management and the use of channel aggregation.

In chapter 2, the channel allocation problem has been properly described and CRN architecture is explained. The concept of spectrum holes, which is very important for opportunistic channel utilization, has been described. In this chapter, the essential functions of the cognitive radio network have been described. Different approaches to communication such as underlay, overlay and interweave are explained. Users always expect to get better services assurance from the service providers, and at the same time service providers aim to improve their revenue and assure better service quality. Particularly for multimedia services, QoE expectation from the users is quite apparent. This chapter discussed QoS and QoE in detail in the context of CRN. Mobility management is one of the essential aspects of providing better QoE and managing the spectrum handoff. It can be managed using different ways namely; proactive spectrum handoff, reactive spectrum handoff, and hybrid spectrum handoff. In this chapter, these handoff schemes have been explained in detail with their advantages and disadvantages. The centralized approach of channel allocation and the distributed approach of channel allocation are mainly used to manage channel allocation and control activities in the cellular systems. The pros and cons of both these approaches are explained in this chapter in the context of CRN. In literature, an extensive study of channel allocation has been reported. We have also presented a detailed literature review adding the newer and modern approaches and technologies such as artificial intelligence, channel reservation, clustering, auction techniques, fairness in channel allocation and channel aggregation. Finally, this chapter identifies the research gaps in the area of channel allocation in the CRN.

In chapter 3, we have presented our first proposed model to enhance the radio spectrum utilization by using the opportunistic access of radio resources by the OPUs and enabling cognitive radio base stations to dynamically collect the free channel information. This model applies the CR's concept to facilitate both the PUs and SUs services in the collocated primary network's vicinity. Services have been categorized into two; real-time and non-real-time, which is to be used by three types of users. Primary users (PUs) and opportunistic primary users (OPU) both have been using real-time and non-real-time services, while secondary users (SUs) have used only non-real-time services. The proposed model has been evaluated by carrying out rigorous experiments which concludes that when primary users of a primary network share other collocated primary network channels for their services as an opportunistic primary user (OPU), the primary users' service requests are effectively addressed. When the arrival rate of primary services is low, the request blocking is almost negligible. The work also studied the performance of the secondary services on varying number of channels. It has been observed that when the number of channels is increased to a certain level, the average secondary blocked requests are negligible. The secondary services' performance is also studied on varying number of primary networks and it has been observed that they perform very well. Model is also tested with and without opportunistic primary users (OPU) and it is observed that the performance of the model is quite encouraging when it uses the OPUs to utilize the radio spectrum opportunistically. The comprehensive study, about the proposed model, suggests that it can be implemented for future communication networks for the channel allocation problem for better QoS/QoE.

Next, in chapter 4, a model for Requirement based Channel Allocation in Cognitive Radio Network has been proposed. We applied the spectrum handover and cognitive radio technique on the requirement-based service requests for channel allocation effectively in this work. Two types of services have been considered in this model: primary and secondary. Channels have been allocated based on the minimum bandwidth requirement of the services. For facilitating the primary services, the model uses the spectrum handover as per the channels' availability with other service providers in the network. This model attempts to serve the maximum possible number of users. Simultaneously, the model has provisions for distributing the free channels to the currently running users to achieve the fairness in channel allocation. Experimental evaluation, on varying request arrival rates, shows that primary services are being served effectively. When the mean arrival rate is low, both primary as well as secondary requests are served using the cognitive radio and spectrum handover concepts. The experiment shows that even on high mean arrival rate, both primary and secondary services are being served effectively and call block is minimized with the increasing number of channels. It has also been observed that non-real-time services perform well on the high channel bandwidth and are served effectively. Therefore, this system can perform better with higher generation wireless system, i.e. 4G and 5G wireless communication systems. A comparative study on varying secondary service size indicates that when the number of channels increases, the average call blocking is reduced significantly. It also shows that when secondary service size is low, the performance is better even without interrupting the primary services' behaviour. A comparative study on secondary users' throughput indicates that the proposed model performs better, in comparison to few other recent models, which signifies the importance of the model.

Channel aggregation enables a user to use more than one channels to enhance its bandwidth. A large number of users can be served using DSA with permissible aggregation with the limited resources. In chapter 5, the channel allocation model is proposed for CRN using the concept of channel aggregation and fragmentation with the cognitive radio technology to serve as many users as possible. This model uses a hybrid (Dynamic + Fixed) channel aggregation and fragmentation approach by considering primary and secondary users' bandwidth requirement. This model attempts to admit the maximum possible service requests by splitting the allocated bandwidth dynamically with the objective to minimize the call blocking and call dropping. In this model, the bandwidth of the ongoing services is increased by allocating the available free bandwidth which contributes to improve QoS. Experimental evaluation on fixed channels and dynamic spectrum is performed and we observe that average requests are served quite effectively even at high mean arrival. It is also observed that even on high mean arrival rate of requests; this model can serve effectively using the dynamic splitting and aggregation concepts with the help of CR. Also, it is noticed that when the D_CRN_{BW} is increased, average blocking of the requests is reduced. Experimental evaluation indicates that F_CRN and D_CRN networks are collectively able to minimize the call block and call drop effectively. It also provides a better QoS because channels are allocated as per the bandwidth requirement. It is evident that on varying the D_CRN bandwidth, secondary new and secondary handoff requests are being served well. Performance analysis of this model has established that it serves the requests effectively by using the channel fragmentation and aggregations concepts. A comparative study on the varying mean arrival rate of primary services has been done to observe the impact on secondary services. The proposed model is effectively able to serve both kinds of secondary services (SU_1 and SU_2). Thus, blocking probability is minimized for both types of secondary services. Compared to a few recent models, the lower blocking probability signifies the importance of the proposed model.

Overall, the proposed models and their study in this thesis provide novel channel allocation techniques for efficient and effective channel utilization in cognitive radio enabled cellular networks. All the proposed models, in this thesis, are simulated and evaluated under realistic service modeling.

6.2 Future Research Directions

In this thesis, we proposed some techniques for channel allocation in the CRN, which attempts an efficient utilization of frequency channels for better QoS/QoE of networks and users respectively. However, there are still many relevant issues that need further consideration and may result in the development of new channel allocation mechanisms in the CRN.

In most of the research work, static networks are assumed where secondary users' movement is not studied. In a realistic situation of upcoming 5G cellular system, mobility consideration of secondary users is desirable for better QoE delivery. In the heterogeneous environment of the CRN, both PUs and SUs can access the free spectrum of any of the base station/service provider for their services. Even with the evolution in the communication technology, running more than one services simultaneously by a user is not far from reality. In such a scenario, the users can access the free frequency channels of different bands belonging to different service providers. To manage such scenario, channel allocation schemes that consider both, the heterogeneity of the network and QoS/QoE requirements, need to be developed.

QoE assessment and offering QoS guarantee in CRN is challenging and still an open problem for offering multimedia transmission over CRNs. The problem becomes more challenging when both the PUs services and the SUs services are real-time in nature and more resource-demanding. Our works, proposed in chapters 3, 4, and 5 can further be extended to address such possible situations.

To address the future need of emerging 5G services, including IoT applications, while considering better QoS and QoE for high-speed users, ultra-reliable communication and very low latency requirement of time-critical applications (e.g. driverless car) need more attention of the researcher. In future, "IoT devices would be equipped with CRT to enable them to think, learn, and make decisions via awareness of both physical and social environments" [9]. This opens the door for more collaborative communication and utilize frequency channels opportunistically as never before.

References:

[1] Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2017–2022, White Paper (https://s3.amazonaws.com/media.mediapost.com/uploads/CiscoForecast.pdf , last accessed 31-10-2020).

[2] Cisco Annual Internet Report (2018–2023), White Paper (https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.pdf, last accessed 31-10-2020).

[3] IMT Vision – Framework and Overall Objectives of the Future Development of IMT for 2020 and Beyond. Recommendation ITU-R M.2083-0; 2015 (https://www.itu.int/dms_pubrec/itu-r/rec/m/R-REC-M.2083-0-201509-I!!PDF-E.pdf , last accessed on 15.11.2020).

[4] M. Jalil Piran, N. H. Tran, D. Y. Suh, J. B. Song, C. S. Hong and Z. Han, "QoE-Driven Channel Allocation and Handoff Management for Seamless Multimedia in Cognitive 5G Cellular Networks," IEEE Trans. on Vehicular Tech., vol. 66, no. 7, pp. 6569-6585, 2017, doi: 10.1109/TVT.2016.2629507.

[5] S. K. Singh and D. P. Vidyarthi, "A Heuristic Channel Allocation Model with Multi Lending in Mobile Computing Network," Int. J. of Wireless and Mobile Computing, vol. 16, no. 4, pp. 322-339, 2019, doi: 10.1504/IJWMC.2019.100064.

[6] W. Xu, R. Qiu and J. Cheng, "Fair Optimal Resource Allocation in Cognitive Radio Networks with Co-Channel Interference Mitigation," IEEE Access, vol. 6, pp. 37418-37429, 2018, doi: 10.1109/ACCESS.2018.2845460.

[7] A. Ali, L. Abbas, M. Shafiq, A. K. Bashir, M. K. Afzal , H. B. Liaqat, M. H. Siddiqi and K. S. Kwak, "Hybrid Fuzzy Logic Scheme for Efficient Channel Utilisation in Cognitive Radio Networks," IEEE Access, vol. 7, pp. 24463-24476, 2019, doi: 10.1109/ACCESS.2019.2900233.

[8] I. A. M. Balapuwaduge, F. Y. Li and V. Pla, "Dynamic Spectrum Reservation for CR Networks in the Presence of Channel Failures: Channel Allocation and Reliability Analysis," IEEE Trans. on Wireless Comm., vol. 17, no. 2, pp. 882-898, 2018, doi: 10.1109/TWC.2017.2772240.

[9] A. Ali, Li Feng, A. K. Bashir, S. El-Sappagh, S. H. Ahmed, M. Iqbal and G. Raja, “Quality of Service Provisioning for Heterogeneous Services in Cognitive Radio-Enabled Internet of Things,” IEEE Trans. on Network Science and Eng., vol. 7, no. 1, pp. 328-342, 2020, doi: 10.1109/TNSE.2018.2877646.

[10] K. A. Yau, J. Qadir, C. Wu, M. A. Imran and M. H. Ling ,“Cognition-Inspired 5G Cellular Networks: A Review and the Road Ahead,” IEEE Access, vol. 6, pp. 35072-35090, 2018, doi: 10.1109/ACCESS.2018.2849446.

[11] M. Aggarwal, T. Velmurugans, M. Karuppiah, M. M. Hassan, A. Almogren and W. N. Ismail, “Probability-Based Centralised Device for Spectrum Handoff in Cognitive Radio Networks,” IEEE Access, vol. 7, pp. 26731-26739, 2019, doi: 10.1109/ACCESS.2019.2901237.

[12] D. P. Vidyarthi and S. K. Singh, “A Heuristic Channel Allocation Model Using Cognitive Radio,” Wireless Personal Comm., vol. 85, no. 3, pp. 1043-1059, 2015, doi: 10.1007/s11277-015-2824-1.

[13] D. Wang, B. Song, D. Chen and X. Du, “Intelligent Cognitive Radio in 5G: AI-Based Hierarchical Cognitive Cellular Networks,” IEEE Wireless Comm., vol. 26, no. 3, pp. 54-61, 2019, doi: 10.1109/MWC.2019.1800353.

[14] M. Aloqaily, H. B. Salameh, I. Al Ridhawi, K. Batieha and J. B. Othman, “A Multi-Stage Rresource-Constrained Spectrum Access Mechanism for Cognitive Radio IoT Networks: Time-Spectrum Block Utilization,” Future Generation Computer Systems, vol. 110, pp. 254-266, 2020, https://doi.org/10.1016/j.future.2020.04.022.

[15] A. Popescu, “Cognitive Radio Networks,” in Proc. of 9th Int. Conf. on Comm., 2012, pp. 11-15, doi: 10.1109/ICComm.2012.6262533.

[16] M. Agiwal, A. Roy and N. Saxena, “Next Generation 5G Wireless Networks: A Comprehensive Survey,” IEEE Comm. Surveys & Tutorials, vol. 18, no. 3, pp. 1617-1655, 2016, doi: 10.1109/COMST.2016.2532458.

[17] E. Z. Tragos, S. Zeadally, A. G. Fragkiadakis and V. A. Siris ,“Spectrum Assignment in Cognitive Radio Networks: A Comprehensive Survey,” IEEE Comm. Surveys & Tutorials, vol. 15, no. 3, pp. 1108-1135, 2013, doi: 10.1109/SURV.2012.121112.00047.

[18] Z. Wei and B. Hu, “A Fair Multi-Channel Assignment Algorithm with Practical Implementation in Distributed Cognitive Radio Networks,” IEEE Access, vol. 6, pp. 14255-14267, 2018, doi: 10.1109/ACCESS.2018.2808479.

[19] J. Mitola and G. Q. Maguire, “Cognitive Radio: Making Software Radios more Personal,” IEEE Personal Comm., vol. 6, no. 4, pp. 13-18, 1999, doi: 10.1109/98.788210.

[20] J. I. Mitola, “Cognitive Radio: An Integrated Agent Architecture for Software Defined Radio Dissertation,” Dissertation Royal Institute of Technology Sweden, vol. 294, no. 3, 2000.

[21] N. Saeed, H. Nam, T. Y.Al-Naffouri and M.-Slim Alouini ,“Primary User Localization and its Error Analysis in 5G Cognitive Radio Networks,” Sensors, vol. 19, no. 9, 2019, doi:10.3390/s19092035.

[22] P. Thakur, G. Singh, and S. Satasia, “Spectrum Sharing in Cognitive Radio Communication System Using Power Constraints: A Technical Review,” Perspectives in Science, vol. 8, pp. 651-653, 2016, https://doi.org/10.1016/j.pisc.2016.06.048.

[23] L. Khalid and A. Anpalagan, “Emerging Cognitive Radio Technology: Principles, Challenges and Opportunities,” Computers and Electrical Engineering J., Elsevier, vol. 36, no. 2, pp. 256-366, 2009, doi: 10.1016/j.compeleceng.2009.03.004.

[24] M. R. M. Falcão, A. M. Balieiro, and Kelvin L. Dias, “A Flexible-Bandwidth Model with Channel Reservation and Channel Aggregation for Three-Layered Cognitive Radio Networks,” Computer Networks, vol. 135, pp. 213-225, 2018, https://doi.org/10.1016/j.comnet.2018.02.002.

[25] B.S. Awoyemi, A.S. Alfa, and B.T.J. Maharaj, “Resource Optimisation in 5G and Internet-of-Things Networking,” Wireless Personal Communication vol. 111, no.1, pp. 2671-2702, 2020, https://doi.org/10.1007/s11277-019-07010-9.

[26] B. Awoyemi , B. Maharaja and A. Alfa, Optimal Resource Allocation -Solutions for Heterogeneous Cognitive Radio Networks ,” Digital Comm. and Networks, vol. 3, no. 2, pp. 129-139, 2017, https ://doi.org/10.1016/j.dcan.2016.11.003.

[27] Z. Zhang, W. Zhang, S. Zeadally, Y. Wang and Y. Liu, “Cognitive Radio Spectrum Sensing Framework based on Multi-Agent Architecture for 5G Networks,” IEEE Wireless Comm., vol. 22, no. 6, pp. 34-39,2015, doi: 10.1109/MWC.2015.7368822.

[28] Federal Communications Commission, “Notice of Proposed Rulemaking and Order”, ET Docket no. 03-222.FCC, 2003 (https://web.cs.ucdavis.edu/~liu/289I/Material/FCC-03-322A1.pdf , last accessed on 10.08.2019).

[29] J. Mitola, “The Software Radio Architecture,” IEEE Comm. Magazine, vol. 33, no. 5, pp. 26-38, 1995, doi: 10.1109/35.393001.

[30] I. F. Akyildiz, Won-Yeol Lee, M. C. Vuran and S. Mohanty, “Next Generation/ Dynamic Spectrum Access/Cognitive Radio Wireless Networks: A Survey,” Elsevier Computer Networks, vol. 50, no. 13, pp. 2127 - 2159, 2006, https://doi.org/10.1016/j.comnet.2006.05.001.

[31] S. Haykin, “Cognitive Radio: Brain-Empowered Wireless Communications,” IEEE J. on Selected Areas in Comm., vol. 23, no. 2, pp. 201-220, 2005, doi: 10.1109/JSAC.2004.839380.

[32] S. M. Mahamuni, V. Mishra and R. Fernandes, “Detection of Spectrum in Cognitive Radio Network for Efficient Spectrum Handoff Mechanism,” in Proc. of 2nd Int. Conf. on Emerging Tech. Trends in Electronics, Comm. and Networking, pp, 2014, 2014, doi: 10.1109/ET2ECN.2014.7044955.

[33] Y. Wu, F. Hu, S. Kumar, Y. Zhu, A. Talari, N. Rahnavard and J. D. Matyjas, “A Learning-Based QoE-Driven Spectrum Handoff Scheme for Multimedia Transmissions over Cognitive Radio Networks,” IEEE J. on Selected Areas in Comm., vol. 32, no. 11, pp. 2134-2148, 2014, doi: 10.1109/JSAC.2014.141115.

[34] Y. Wu, Q. Yang, X. Liu and K. S. Kwak, “Delay-Constrained Optimal Transmission with Proactive Spectrum Handoff in Cognitive Radio Networks,” IEEE Trans. on Comm., vol. 64, no. 7, pp. 767-2779, 2016, doi: 10.1109/TCOMM.2016.2561936.

[35] J. Mitola III , J. R. Guerci, J. H. Reed, Yu-Dong Yao, Y. Chen, T. C. Clancy, J. Dwyer, H. Li, H. Man, R. Mcgwier and Yi Guo, “Accelerating 5G QoE via Public-Private Spectrum Sharing,” IEEE Comm. Magazine, vol. 52, no. 5, pp. 77-85, 2014, doi: 10.1109/MCOM.2014.6815896.

[36] Saad Z. Asif , “5G Mobile Communications Concepts and Technologies”, First ed. , Boca Raton, CRC Press, 2019, ISBN 9780429466342 (e-book).

[37] E. Ahmed, A. Gani, S. Abolfazli, L. J. Yao and S. U. Khan, “Channel Assignment Algorithms in Cognitive Radio Networks: Taxonomy, Open Issues, and Challenges,” IEEE Comm. Surveys & Tutorials, vol. 18, no. 1, pp. 795-823, 2016, doi: 10.1109/COMST.2014.2363082.

[38] E. FCC, “Docket no 03-237 Notice of Inquiry and Notice of Proposed Rulemaking,” Nov. 2003.

[39] R. Sumathi, M. Poornima and M. Suganthi , "User Aware Mobility Management in Cognitive Radio Cellular Network," in Proc. of Int. Conf. on Electronics and Comm. Systems (ICECS), pp. 1-5, 2014, doi: 10.1109/ECS.2014.6892568.

[40] Xin Liu, D. He and M. Jia,"5G-Based Wideband Cognitive Radio System Design with Cooperative Spectrum Sensing," Physical Communication, vol. 25, Part 2, pp 539-545, 2017, https://doi.org/10.1016/j.phycom.2017.09.010.

[41] Federal Communications Commission 2008, Auction 73: 700 MHz band – Fact Sheet (http://wireless.fcc.gov/auctions/default.htm?job=auction_factsheet&id=73, last accessed on 31.10.2020).

[42] G. Ancansa, V. Bobrovsa, A. Ancansb and D. Kalibatiene, "Spectrum Considerations for 5G Mobile Communication Systems," Procedia Computer Science, vol. 104, pp.509-516, 2017, https://doi.org/10.1016/j.procs.2017.01.166.

[43] Federal Communications Commission, "Spectrum Policy Task Force Report, ET Docket No. 02-135," Nov. 2002.

[44] J. van de Beek, J. Riihijarvi, A. Achtzehn and P. Mahonen, "TV White Space in Europe," IEEE Trans. Mobile Computing, vol. 11, no. 2, pp. 178–188, 2012, https://doi.org/10.1109/TMC.2011.203.

[45] G. Kesidis, J. Walrand and C. -S. Chang, "Effective Bandwidths for Multiclass Markov Fluids and other ATM Sources," IEEE/ACM Trans. on Networking, vol. 1, no. 4, pp. 424-428,1993, doi: 10.1109/90.251894.

[46] M. P. Mishra and P. C. Saxena, "Issues, Challenges and Problems in Channel Allocation in Cellular System," in Proc. of 2nd Int. Conf. on Computer and Communication Tech., pp. 321-328, 2011, doi: 10.1109/ICCCT.2011.6075157.

[47] D. Lopez-Perez, A. Valcarce, G. de la Roche and J. Zhang, "OFDMA Femtocells: A Roadmap on Interference Avoidance," IEEE Comm. Magazine, vol. 47, no. 9, pp. 41-48, 2009, doi: 10.1109/MCOM.2009.5277454.

[48] 5G Radio Access, Ericsson White paper (https://www.ericsson.com/en/reports-and-papers/ericsson-technology-review/articles/5g-radio-access, last accssed on 15.11.2020).

[49] Upen Dalal, "Wireless Communication", First ed., New Delhi, Oxford University Press, ISBN-13:978-0-19-806066-6, 2009.

[50] M. P. Mishra and P.C.Saxena, "Survey of Channel Allocation Algorithms Research for Cellular Systems," Int. J. of Networks and Comm., vol.2, no.5, pp- 75-104, 2012, doi: 10.5923/j.ijnc.20120205.02.

[51] S. Khattak, G. Fettweis, P. Thanneeru and R. Bhattacherjee, "SIR based Adaptive Subchannel Allocation in OFDMA Cellular System," in Proc. of 16th IST Mobile and Wireless Comm. Summit, pp. 1-5, 2007, doi: 10.1109/ISTMWC.2007.4299125.

[52] T. Wang and L. Vandendorpe, "Resource Allocation for Maximizing Weighted Sum Min-Rate in Downlink Cellular OFDMA Systems," in Proc. of 2010 IEEE Int. Conf. on Comm., pp. 1-6, 2010, doi: 10.1109/ICC.2010.5501904.

[53] J. Gozalvez, M. C. L. Estan and J. S. Soriano, "User QoS-based Multi-Channel Assignment Schemes under Multimedia Traffic Conditions," in Proc. of 4th Int. Symposium on Wireless Communication Systems, pp. 113-117, 2007 doi: 10.1109/ISWCS.2007.4392312.

[54] E. Foutekova, P. Agyapong, and H. Haas, "Channel Asymmetry in Cellular OFDMA-TDD Networks," EURASIP J. on Wireless Comm. and Networking, Article number: 121546, 2008, https://doi.org/10.1155/2008/121546.

[55] H. SHI, R. V. Prasad, E. Onur and I. G. M. M. Niemegeers, "Fairness in Wireless Networks: Issues, Measures and Challenges," IEEE Comm. Surveys & Tutorials, vol. 16, no. 1, pp. 5-24, 2014, doi: 10.1109/SURV.2013.050113.00015.

[56] Cheng-xiang Wang, F. Haider, X. Gao, X. You, Y. Yang, D. Yuan, H. M. Aggoune, H. Haas, S. Fletcher and E. Hepsaydir, "Cellular Architecture and Key Technologies for 5G Wireless Communication Networks," IEEE Comm. Magazine, vol. 52, no. 2, pp. 122-130, 2014, doi: 10.1109/MCOM.2014.6736752.

[57] I. Budhiraja, S. Tyagi, S. Tanwar, N. Kumar and J. J. P. C. Rodrigues ,"Tactile Internet for Smart Communities in 5G: An Insight for NOMA-Based Solutions," IEEE Trans. on Industrial Informatics, vol. 15, no. 5, pp. 3104-3112, 2019, doi: 10.1109/TII.2019.2892763.

[58] C. G. Tsinos, F. Foukalas and T. A. Tsiftsis, "Resource Allocation for Licensed/Unlicensed Carrier Aggregation MIMO Systems," IEEE Trans. on Comm., vol. 65, no. 9, pp. 3765-3779, 2017, doi: 10.1109/TCOMM.2017.2710343.

[59] J. Zhang, X. Chen, K. P. Peppas, Xu Li and Y. Liu , "On High-Order Capacity Statistics of Spectrum Aggregation Systems over κ-μ and κμ Shadowed Fading Channels," IEEE Trans. on Comm., vol. 65, no. 2, pp. 935-944, 2017, doi: 10.1109/TCOMM.2016.2637926.

[60] E. Ebenezer, T. G. Swart and T. Shongwe, "Leveraging on the Cognitive Radio Channel Aggregation Strategy for Next Generation Utility Networks,", Energies 12, no.14, 2019, doi: 10.3390/en12142753.

[61] B. Gao, Y. Yang and J. Park, "Channel Aggregation in Cognitive Radio Networks with Practical Considerations," in Proc. of IEEE Int. Conf. on Comm., pp. 1-5, 2011, doi: 10.1109/icc.2011.5962717.

[62] L. Li, S. Zhang, K. Wang and W. Zhou, "Combined Channel Aggregation and Fragmentation Strategy in Cognitive Radio Networks," arXiv:1203.4913v2, 2012.

[63] L. Jiao, I. A. M. Balapuwaduge, F. Y. Li and V. Pla, "On the Performance of Channel Assembling and Fragmentation in Cognitive Radio Networks," IEEE Trans. on Wireless Comm., vol. 13, no. 10, pp. 5661-5675, 2014, doi: 10.1109/TWC.2014.2322057.

[64] J. Dai and S. Wang, "Clustering-Based Spectrum Sharing Strategy for Cognitive Radio Networks," IEEE Journal on Selected Areas in Comm., vol. 35, no. 1, pp. 228-237, 2017, doi: 10.1109/JSAC.2016.2633698.

[65] S. H. Wong and I. J. Wassell, "Application of Game Theory for Distributed Dynamic Channel Allocation," in Proc. of IEEE 55th Vehicular Tech. Conf. vol.1, pp. 404-408, 2002, doi: 10.1109/VTC.2002.1002742.

[66] A. Malla, M. El-Kadi, S. Olariu and P. Todorova, "A Fair Resource Allocation Protocol for Multimedia Wireless Networks," IEEE Trans. on Parallel and Distributed Systems, vol. 14, no. 1, pp. 63-71, 2003, doi: 10.1109/TPDS.2003.1167371.

[67] N. Ul Hasan, W. Ejaz, N. Ejaz, H. S. Kim, A. Anpalagan and M. Jo, "Network Selection and Channel Allocation for Spectrum Sharing in 5G Heterogeneous Networks," IEEE Access, vol. 4, pp. 980-992, 2016, doi: 10.1109/ACCESS.2016.2533394.

[68] N. Devroye, M. Vu and V. Tarokh, "Cognitive Radio Networks," IEEE Signal Processing Magazine, vol. 25, no. 6, pp. 12-23, 2008, doi: 10.1109/MSP.2008.929286.

[69] S. Hoque and W. Arif, "Impact of Residual time Distributions of Spectrum Holes on Handoff Rate in Cognitive Radio Networks," in Proc. of 2017 IEEE Calcutta Conference, pp. 82-89, 2017, doi: 10.1109/CALCON.2017.8280701.

[70] B. Kumar, S. K. Dhurandher and I. Woungang, "A Survey of Overlay and Underlay Paradigms in Cognitive Radio Networks", Int. J. of Communication System , vol. 31, no.2 , 2017, doi: 10.1002/dac.3443.

[71] M. P. Mishra and D. P. Vidyarthi, “Spectrum Handoff in Cognitive Radio Cellular Network: A Review,” in Proc. of 8th Int. Conf. System Modeling and Advancement in Research Trends, pp. 210-215, 2019, doi: 10.1109/SMART46866.2019.9117491.

[72] O. B. Akan, O. B. Karli and O. Ergul, “Cognitive Radio Sensor Networks,” IEEE Network, vol. 23, no. 4, pp. 34-40, 2009, doi: 10.1109/MNET.2009.5191144.

[73] R . Han, Y. Gao, C. Wu and D. Lu, “An Effective Multi-Objective Optimization Algorithm for Spectrum Allocations in the Cognitive-Radio-Based Internet of Things,” IEEE Access, vol. 6, pp. 12858-12867, 2018, doi: 10.1109/ACCESS.2017.2789198.

[74] A. Al-Dulaimi, A. Anpalagan, S. Al-Rubaye and Q. Ni, “Adaptive Management of Cognitive Radio Networks Employing Femtocells,” IEEE Systems J., vol. 11, no. 4, pp. 2687-2698, 2017, doi: 10.1109/JSYST.2016.2537644.

[75] Y. Song, J. Xie and X. Wang, “A Novel Unified Analytical Model for Broadcast Protocols in Multi-Hop Cognitive Radio Ad Hoc Networks,” IEEE Trans. on Mobile Computing, vol. 13, no. 8, pp. 1653-1667, 2014, doi: 10.1109/TMC.2013.60.

[76] M. El Tanab and W. Hamouda, “Resource Allocation for Underlay Cognitive Radio Networks: A Survey,” IEEE Comm. Surveys & Tutorials, vol. 19, no. 2, pp. 1249-1276, 2017, doi: 10.1109/COMST.2016.2631079.

[77] F. Salahdine and H. E. Ghazi, “A Real Time Spectrum Scanning Technique Based on Compressive Sensing for Cognitive Radio Networks,” in Proc. of IEEE 8th Annual Ubiquitous Computing, Electronics and Mobile Communication Conf., pp. 506-511, 2017, doi: 10.1109/UEMCON.2017.8249008.

[78] W. Ejaz, N. Ul Hasan and H. S. Kim, “Distributed Cooperative Spectrum Sensing in Cognitive Radio for Ad Hoc Networks,” Computer Communication, vol. 36, no. 12, pp. 1341-1349, 2013, https://doi.org/10.1016/j.comcom.2013.05.002.

[79] S. Bayhan, G. Gur and F. Alagoz, “Satellite Assisted Spectrum Agility Concept,” in Proc. of MILCOM 2007 IEEE Military Comm. Conf., pp. 1-7, 2007, doi: 10.1109/MILCOM.2007.4454876.

[80] Y. Arjoune and N. Kaabouch, “A Comprehensive Survey on Spectrum Sensing in Cognitive Radio Networks: Recent Advances, New Challenges, and Future Research Directions,” Sensor, vol. 19, issue 1, 2019, doi:10.3390/s19010126.

[81] V. Gupta, N. S.Beniwal, K. K. Singh and S.N. Sharan,"Cooperative Spectrum Sensing Optimization Using Meta-Heuristic Algorithms," Wireless Personal Comm., vol. 113, pp. 1755-1773, 2020, https://doi.org/10.1007/s11277-020-07290-6.

[82] F. Salahdine, "Spectrum Sensing Techniques for Cognitive Radio Networks," ArXiv abs/1710.02668 , 2017.

[83] F. F. Digham, M. Alouini and M. K. Simon, "On the Energy Detection of Unknown Signals Over Fading Channels," IEEE Trans. on Comm., vol. 55, no. 1, pp. 21-24, 2007, doi: 10.1109/TCOMM.2006.887483.

[84] N. Saeed and H. Nam, "Robust Multidimensional Scaling for Cognitive Radio Network Localization," IEEE Trans. on Vehicular Tech., vol. 64, no. 9, pp. 4056-4062,2015, doi: 10.1109/TVT.2014.2366515.

[85] Y. Liu, X. Shi, S. He and Z. Shi, "Prospective Positioning Architecture and Technologies in 5G Networks," IEEE Network, vol. 31, no. 6, pp. 115-121, 2017, doi: 10.1109/MNET.2017.1700066.

[86] F. Zafari, A. Gkelias and K. K. Leung, "A Survey of Indoor Localization Systems and Technologies," IEEE Comm. Surveys & Tutorials, vol. 21, no. 3, pp. 2568-2599, 2019, doi: 10.1109/COMST.2019.2911558.

[87] A. Popescu, D. Erman, M. Fiedler, A. Popescu and D. Kouvatsos , "A Middleware Framework for Communication in Cognitive Radio Networks," Int. Congress on Ultra Modern Telecom. and Control Systems, 2010, pp. 1162-1171, doi: 10.1109/ICUMT.2010.5676527.

[88] N. Pandi and A. Kumar, "Review on Cognitive Radio for Next Generation Cellular Network and its Challenges", American J. of Eng. and Applied Sciences, vol.10, no. 2, pp. 334.347, 2017, doi: 10.3844/ajeassp.2017.334.347.

[89] S. Ekin, M. M. Abdallah, K. A. Qaraqe and E. Serpedin, "Random Subcarrier Allocation in OFDM-Based Cognitive Radio Networks," IEEE Trans. on Signal Processing, vol. 60, no. 9, pp. 4758-4774, 2012, doi: 10.1109/TSP.2012.2203126.

[90] L. Wang, J. Yang and X. Song, "A QoE-Driven Spectrum Decision Scheme for Multimedia Transmissions over Cognitive Radio Networks," in Proc. of 26th Int. Conf. on Computer Communication and Networks, pp. 1-5, 2017, doi: 10.1109/ICCCN.2017.8038356.

[91] P. K. Agyapong, M. Iwamura, D. Staehle, W. Kiess and A. Benjebbour, "Design Considerations for a 5G network Architecture," IEEE Comm. Magazine, vol. 52, no. 11, pp. 65-75, 2014, doi: 10.1109/MCOM.2014.6957145.

[92] V. A. Siris, K. Balampekos and M. K. Marina, "Mobile Quality of Experience: Recent Advances and Challenges," in Proc. of IEEE Int. Conf. on Pervasive Computing and Communication Workshops, pp. 425-430, 2014, doi: 10.1109/PerComW.2014.6815244.

[93] V. Menkovski, G. Exarchako, A. Liotta and A. C. Sánchez, "Quality of Experience Models for Multimedia Streaming," Int. J. of Mobile Computing and Multimedia Comm., vol. 2, no. 4, pp. 1-20, 2010.

[94] D. Srinivasa Rao and G. B. S. R. Naidub, "A Study of the Effects on QoS in WiFi-Cellular Offloading Scenarios," Int. J. of Mathematical, Eng. and Management Sciences vol. 4, no.3, pp.795–802, 2019, https://dx.doi.org/10.33889/IJMEMS.2019.4.3-062.

[95] G. Cao and M. Singhal, "Efficient Distributed Channel Allocation for Mobile Cellular Networks," Computer Comm., vol. 23, no. 10, pp. 950–961, 2000, https://doi.org/10.1016/S0140-3664(00)00173-0.

[96] M. Andrews, S. C. Borst, F. Dominique, Predrag R. Jelenkovic, K. Kumaran, K. G. Ramakrishnan and P. A. Whiting, "Dynamic bandwidth allocation algorithms for high-speed data wireless networks," in Bell Labs Technical Journal, vol. 3, no. 3, pp. 30-49, July-Sept. 1998, doi: 10.1002/bltj.2114.

[97] J. Yang, D. Manivannan and M. Singhal, "A Fault-Tolerant Dynamic Channel Allocation Scheme for Enhancing QoS in Cellular Networks," in Proc. of 36th Annual Hawaii Int. Conf. on System Sciences, pp. 306-315, 2003, doi: 10.1109/HICSS.2003.1174857.

[98] Lei Huang, S. Kumar and C. -C. J. Kuo, ,"Adaptive Resource Allocation for Multimedia QoS Management in Wireless Networks," IEEE Trans. on Vehicular Tech., vol. 53, no. 2, pp. 547-558, 2004, doi: 10.1109/TVT.2003.823290.

[99] Chi-Jui Ho, Chin- Tau Lea and G. L. Stuber, "Call Admission Control in the Microcell/ Macrocell Overlaying System," IEEE Trans. on Vehicular Tech., vol. 50, no. 4, pp. 992-1003, 2001, doi: 10.1109/25.938575.

[100] S. Z. Ahmad, M. A. Qadir and M.S.Akbar, "A Distributed Resource Management Scheme for Load-Balanced QoS Provisioning in Heterogeneous Mobile Wireless Networks," in Proc. of 4th ACM Symposium on Quality of Service and Security for Wireless and Mobile Networks, pp. 63-70, 2008, https://doi.org/10.1145/1454586.1454598.

[101] L. M. O. Khanbary and D. P. Vidyarthi, “A GA-Based Effective Fault-Tolerant Model for Channel Allocation in Mobile Computing,” IEEE Trans. on Vehicular Tech., vol. 57, no. 3, pp. 1823-1833, 2008, doi: 10.1109/TVT.2007.907311.

[102] L. M. O. Khanbary and D. P. Vidyarthi, “Reliability-Based Channel Allocation Using Genetic Algorithm in Mobile Computing,” IEEE Trans. on Vehicular Tech., vol. 58, no. 8, pp. 4248-4256, 2009, doi: 10.1109/TVT.2009.2019666.

[103] N. Nathani and G. C. Manna, “A Quality of Service Based Model for Supporting Mobile Secondary Users in Cognitive Radio Technology, Cognitive Radio in 4G/5G Wireless Communication Systems,” Shahriar Shirvani Moghaddam, IntechOpen, 2018, doi: 10.5772/intechopen.80072.

[104] Jamal Raiyn, “A Cognitive Radio Scheme for Dynamic Resource Allocation Based on QOE,” Int. Journal of Wireless & Mobile Networks , vol. 8, no. 1, 2016, doi : 10.5121/ijwmn.2016.8101.

[105] J. Dai and S. Wang, “QoE-Driven Resource Allocation Method for Cognitive Radio Networks,” in Proc. of IEEE Int. Conf. on Comm., pp. 1-6, 2016, doi: 10.1109/ICC.2016.7510791.

[106] A. Khan, L. Sun and E. Ifeachor, “Content Clustering Based Video Quality Prediction Model for MPEG4 Video Streaming over Wireless Networks,” in Proc. of IEEE Int. Conf. on Comm., pp. 1-5, 2009, doi: 10.1109/ICC.2009.5198850.

[107] J. Zhang and N. Ansari, “On Assuring End-to-End QoE in Next Generation Networks: Challenges and a Possible Solution,” IEEE Commun. Magazine, vol. 49, no. 7, pp. 185–191, 2011, doi: 10.1109/MCOM.2011.5936172.

[108] M. Dryjanski and M. Szydelko, “A Unified Traffic Steering Framework for LTE Radio Access Network Coordination,” IEEE Comm. Magazine, vol. 54, no. 7, pp. 84-92, 2016, doi: 10.1109/MCOM.2016.7509383.

[109] Z. He, S. Mao and S. Kompella, “Quality of Experience Driven Multi-User Video Streaming in Cellular Cognitive Radio Networks With Single Channel Access,” IEEE Trans. on Multimedia, vol. 18, no. 7, pp. 1401-1413, 2016, doi: 10.1109/TMM.2016.2564104.

[110] E. Chromy, T. Misuth and A.Weber, “Application of Erlang Formulae in Next Generation Networks,” Int. J. of Computer Network and Information Security, vol.1, pp. 59-66, 2012, doi: 10.5815/ijcnis.2012.01.08.

[111] P. S. Yawada and M. T. Dong, "Intelligent Process of Spectrum Handoff/Mobility in Cognitive Radio Networks," J. of Electrical and Computer Eng., vol. 2019, Article ID 7692630 , https://doi.org/10.1155/2019/7692630.

[112] T. Jiang, H. Wang and S. Leng, "Channel Allocation and Reallocation for Cognitive Radio Networks," Wireless Comm. and Mobile Computing, vol. 13, no. 12, pp. 1073-1081, 2013, doi: 10.1002/wcm.1162.

[113] M. Rajaratnam and F. Takawira, "Handoff Traffic Characterization in Cellular Networks Under Nonclassical Arrivals and Service Time Distributions," IEEE Trans. on Vehicular Tech., vol. 50, no. 4, pp. 954-970, 2001, doi: 10.1109/25.938572.

[114] S. Raju, S. Boddepalli, N. Choudhury, Q. Yan and J. S. Deogun ,"Design and Analysis of Elastic Handoff in Cognitive Cellular Networks," in Proc. of IEEE Int. Conf. on Comm., pp. 1-6, 2017, doi: 10.1109/ICC.2017.7996835.

[115] Chung-Wei Wang and Li-Chun Wang, "Modeling and Analysis for Proactive-Decision Spectrum Handoff in Cognitive Radio Networks," in Proc. of IEEE Int. Conf. on Comm., pp. 1-6,2009, doi: 10.1109/ICC.2009.5199189.

[116] I. F. Akyildiz, W. Lee, M. C. Vuran and S. Mohanty, "A Survey on Spectrum Management in Cognitive Radio Networks," IEEE Comm. Magazine, vol. 46, no. 4, pp. 40-48, 2008, doi: 10.1109/MCOM.2008.4481339.

[117] W. Xiong, A. Mukherjee and H. M. Kwon, "MIMO Cognitive Radio User Selection With and Without Primary Channel State Information," IEEE Trans. on Vehicular Tech., vol. 65, no. 2, pp. 985-991, 2016, doi: 10.1109/TVT.2015.2400430.

[118] V. Sarasvathi and N. C. S. N. Iyengar, "Centralized Rank Based Channel Assignment for Multi-Radio Multi-Channel Wireless Mesh Networks," Procedia Tech., vol. 4, pp. 182–186, 2012, https://doi.org/10.1016/j.protcy.2012.05.027.

[119] M. Drieberg and F. Zheng, "Centralized Channel Assignment for IEEE 802.11 WLANs: Utilization MinMax-Sum," in Proc. of the 15th Int. Symposium on Wireless Personal Multimedia Comm., pp. 633-637, 2012.

[120] H. Jiang and S. S. Rappaport, "Prioritized Channel Borrowing Without Locking: A Channel Sharing Strategy for Cellular Communications," IEEE/ACM Trans. on Networking, vol. 4, no. 2, pp. 163-172,1996, doi: 10.1109/90.490744.

[121] G. Cao and M. Singhal, "Distributed Fault-Tolerant Channel Allocation for Cellular Networks," IEEE J. on Selected Areas in Comm., vol. 18, no. 7, pp. 1326-1337, 2000, doi: 10.1109/49.857932.

[122] H. Guo and V. C. M. Leung, "Orthogonal Transmissions for Spectrum Underlay MISO Cognitive Radio," IEEE Trans. on Wireless Comm., vol. 11, no. 4, pp. 1266-1270, 2012, doi: 10.1109/TWC.2012.021412.110705.

[123] R. Prakash, N. G. Shivaratri and M. Singhal, "Distributed Dynamic Fault-Tolerant Channel Allocation for Cellular Networks," IEEE Trans. on Vehicular Tech., vol. 48, no. 6, pp. 1874-1888, 1999, doi: 10.1109/25.806780.

[124] G. Cao and M. Singhal, "An Adaptive Distributed Channel Allocation Strategy for Mobile Cellular Networks", J. of Parallel and Distributed Computing, Special Issue on Mobile Computing ,vol. 60, no. 4, pp. 451–473, 2000, https://doi.org/10.1006/jpdc.1999.1614

[125] J. R. Gállego, M. Canales and J. Ortín, "Distributed Resource Allocation in Cognitive Radio Networks with a Game Learning Approach to Improve Aggregate System Capacity," Elsevier Ad Hoc Networks, vol. 10, no. 6, pp. 1076–1089, 2012, https://doi.org/10.1016/j.adhoc.2012.02.002.

[126] L. T. Tan and L. B. Le, "Channel Assignment With Access Contention Resolution for Cognitive Radio Networks," IEEE Trans. on Vehicular Tech., vol. 61, no. 6, pp. 2808-2823, 2012, doi: 10.1109/TVT.2012.2196532.

[127] B. Khalfi, M. B.ghorbel, B.Hamdaoui and M. Guizani, "Distributed Fair Spectrum Assignment for Large-Scale Wireless DSA Networks," in Proc. of Int. Conf. on Cognitive Radio Oriented Wireless Networks, pp. 631-642, 2015, https://doi.org/10.1007/978-30319-24540-9_52.

[128] F. Hu, B. Chen and K. Zhu, "Full Spectrum Sharing in Cognitive Radio Networks Toward 5G: A Survey," IEEE Access, vol. 6, pp. 15754-15776, 2018, doi: 10.1109/ACCESS.2018.2802450.

[129] W. Zhang, Y. Sun, L. Deng, C. K. Yeo and L. Yang ,"Dynamic Spectrum Allocation for Heterogeneous Cognitive Radio Networks with Multiple Channels," IEEE Systems J., vol. 13, no. 1, pp. 53-64, 2019, doi: 10.1109/JSYST.2018.2822309.

[130] W. Zhang, L. Deng and Y. C. Kiat, "Dynamic Spectrum Allocation for Heterogeneous Cognitive Radio Network," in Proc. of IEEE Wireless Comm. and Networking Conf., pp. 1-6, 2016, doi: 10.1109/WCNC.2016.7564838.

[131] J. Chang and H. Chen, "Service-Oriented Bandwidth Borrowing Scheme for Mobile Multimedia Wireless Networks," 2007, http://hdl.handle.net/10453/19653.

[132] H. P. Singh, S. Singh, J. Singh and S. A. Khan, "VoIP: State of Art for Global Connectivity—A Critical Review," Journal of Network and computer Applications, vol. 37, pp. 365-379, 2014, https://doi.org/10.1016/j.jnca.2013.02.026.

[133] A. Hatoum, R. Langar, N. Aitsaadi, R. Boutaba and G. Pujolle, "Cluster-Based Resource Management in OFDMA Femtocell Networks With QoS Guarantees," IEEE Trans. on Vehicular Tech., vol. 63, no. 5, pp. 2378-2391, 2014, doi: 10.1109/TVT.2013.2290125.

[134] A. Abdelnasser, E. Hossain and D. I. Kim, "Clustering and Resource Allocation for Dense Femtocells in a Two-Tier Cellular OFDMA Network," IEEE Trans. on Wireless Comm., vol. 13, no. 3, pp. 1628-1641, 2014, doi: 10.1109/TW.2014.011614.131163.

[135] S. K. Singh, A. Kaushik and D. P. Vidyarthi, "A Cognitive Channel Allocation Model in Cellular Network using Genetic Algorithm," Wireless Personal Comm., vol. 96, no. 4, pp. 6085-6110, 2017, doi: 10.1007/s11277-017-4465-z.

[136] S. K. Singh, A. Kaushik and D. P. Vidyarthi, "A Model for Cognitive Channel Allocation Using GA," in Proc. of Second Int. Conf. on Computational Intelligence & Communication Tech., pp. 528-532, 2016, doi: 10.1109/CICT.2016.110.

[137] D. P. Vidyarthi and S.K.Singh, " Independent Tasks Scheduling using Parallel PSO in Multiprocessor Systems," Int. J. of Grid and High-Performance Computing, vol. 7, no. 2, pp. 1-17, 2015, doi: 10.4018/IJGHPC.2015040101.

[138] G. P. Bharathi and K. M. A. Jeyanthi, "An Optimization Algorithm-Based Resource Allocation for Cooperative Cognitive Radio Networks," J. of Supercomputing, pp.1-21, 2018, https://doi.org/10.1007/s11227-018-2588-y.

[139] Meng-Dung Weng, Bih-Hwang Lee and Jhih-Ming Chen, "Two Novel Price-Based Algorithms for Spectrum Sharing in Cognitive Radio Networks," EURASIP J. on Wireless Communication Networking., Article number: 265, 2013, https://doi.org/10.1186/1687-1499-2013-265.

[140] T. Chakraborty and I. S. Misra, "Design and Analysis of Channel Reservation Scheme in Cognitive Radio Networks," Computers and Electrical Eng., vol. 42, issue C, pp. 148–167, 2015, https://doi.org/10.1016/j.compeleceng.2014.11.006.

[141] T. M. Chinh Chu, H. Zepernick and H. Phan, “Channel Reservation for Dynamic Spectrum Access of Cognitive Radio Networks with Prioritized Traffic,” in Proc. of IEEE Int. Conf. on Communication Workshop, pp. 883-888, 2015, doi: 10.1109/ICCW.2015.7247287.

[142] Y. Liu, X. Wang, J. Li and M. Huang, “A Wireless Spectrum Management Mechanism Based on the Theory of Double Auction in Cognitive Cellular Networks,” in Proc. of Int. Conf. on Wireless Comm., Networking and Applications pp.16–23 ,2017. doi:https://doi.org/10.1145/3180496.3180601.

[143] A. Shams Shafigh, P. Mertikopoulos, S. Glisic and Y. M. Fang, “Semi-Cognitive Radio Networks: A Novel Dynamic Spectrum Sharing Mechanism,” IEEE Trans. on Cognitive Comm. and Networking, vol. 3, no. 1, pp. 97-111, 2017, doi: 10.1109/TCCN.2017.2681081.

[144] Y. Liu and L. Dong, “Spectrum Sharing in MIMO Cognitive Radio Networks Based on Cooperative Game Theory,” IEEE Trans. on Wireless Comm., vol. 13, no. 9, pp. 4807-4820, 2014, doi: 10.1109/TWC.2014.2331287.

[145] M. Khaledi and A. A. Abouzeid, “Auction-Based Spectrum Sharing in Cognitive Radio Networks with Heterogeneous Channels,” in Proc. of Information Theory and Applications Workshop, pp. 1-8, 2017, doi: 10.1109/ITA.2013.6502923.

[146] N. H. Tran, C. S. Hong, Z. Han and S. Lee, “Optimal Pricing Effect on Equilibrium Behaviors of Delay-Sensitive Users in Cognitive Radio Networks,” IEEE J. on Selected Areas in Comm., vol. 31, no. 11, pp. 2566-2579, 2013, doi: 10.1109/JSAC.2013.131134.

[147] S. K. Singh and D. P. Vidyarthi, “ A Pricing Model for Effective Radio Spectrum Utilization,” Int. J. of Mobile Computing and Multimedia Comm., vol. 10, no. 4, pp. 41-65, 2019, doi: 10.4018/IJMCMC.2019100104.

[148] H. Lin, M. Chatterjee, S. K. Das and K. Basu, “ARC: An Integrated Admission and Rate Control Framework for Competitive Wireless CDMA Data Networks using Noncooperative Games,” IEEE Trans. on Mobile Computing, vol. 4, no. 3, pp. 243-258, 2005, doi: 10.1109/TMC.2005.35.

[149] N. Suganthi and S. Meenakshi, “Effect of Dynamic Spectrum Aggregation and Allocation Algorithms in Cognitive Radio Networks,” Int. J. of Recent Tech. and Eng., vol. 8, issue 4, 2019, doi:10.35940/ijrte.D9151.118419.

[150] J. Jia and Q. Zhang, “Hardware-Constrained Multi-Channel Cognitive MAC,” in Proc. of IEEE GLOBECOM, pp. 4653-4658, 2007, doi: 10.1109/GLOCOM.2007.883.

[151] Y. Wei, Q. Li, X. Gong, Da Guo and Y. Zhang, "The Dynamic Spectrum Aggregation Strategy for Cognitive Networks Based on Markov Model," 2016, (https://arxiv.org/ftp/arxiv/papers/1612/1612.03204.pdf, last accessed 15.11.2020).

[152] J. Lee and J. So, "Analysis of Cognitive Radio Networks with Channel Aggregation," in Proc. of IEEE Wireless Comm. and Networking Conf., pp. 1-6, 2010, doi: 10.1109/WCNC.2010.5506262.

[153] Y. Zhao, S. Jin and W. Yue,"An Adjustable Channel Bonding Strategy in Centralized Cognitive Radio Networks and its Performance Optimization," Quality Tech. & Quantitative Management, vol.,12 no.3, pp. 293-312, 2015, doi:10.1080/16843703.2015.11673382.

[154] X. Xiao, F. Zeng, Z. Hu and L. Jiao, "Dynamic Flow-Adaptive Spectrum Leasing with Channel Aggregation in Cognitive Radio Networks", Sensors vol. 20, issue 13, 2020, https://doi.org/10.3390/s20133800.

[155] W. Zhang, C. Wang, X. Ge and Y. Chen, "Enhanced 5G Cognitive Radio Networks Based on Spectrum Sharing and Spectrum Aggregation," IEEE Trans. on Comm., vol. 66, no. 12, pp. 6304-6316, 2018, doi: 10.1109/TCOMM.2018.2863385.

[156] H. Anandakumar and K. Umamaheswari, "Supervised Machine Learning Techniques in Cognitive Radio Networks during Cooperative Spectrum Handovers," Cluster Computing, vol.20, no.2, pp.1505-1515, 2007, https://doi.org/10.1007/s10586-017-0798-3.

[157] S. H. Alsamhi and N. S. Rajput, "Implementation of Call Admission Control Technique in HAP for Enhanced QoS in Wireless Network Deployment," Telecommunication Systems, vol. 63, no. 2, pp. 141-151, 2016, https://doi.org/10.1007/s11235-015-0108-4.

[158] I. Radhakrishnan, R. Souay, M. R. Palattellaz and T. Engel, "An Efficient Service Channel Allocation Scheme in SDN-Enabled VANETs," in Proc. of 16th Annual Mediterranean Ad Hoc Networking Workshop, pp. 1-7, 2017, doi: 10.1109/MedHocNet.2017.8001644.

[159] M. Seyedebrahimi, F. Bouhafs, A. Raschellà, M. Mackay and Q. Shi,, "SDN-Based Channel Assignment Algorithm for Interference Management in Dense Wi-Fi Networks," in Proc. of European Conf. on Networks and Comm., pp. 128-132, 2016, doi: 10.1109/EuCNC.2016.7561018.

[160] A. Bhattacharya, R. Ghosh, K. Sinha, D. Datta and B. P. Sinha, "Noncontiguous Channel Allocation for Multimedia Communication in Cognitive Radio Networks," IEEE Trans. on Cognitive Comm. and Networking, vol. 1, no. 4, pp. 420-434, 2015, doi: 10.1109/TCCN.2016.2549033.

[161] X. Li, J. Zhao, Y. Yao, T. Zhou, Y. Gong and L. Xiong, "Fault-Tolerant Topology Control Towards K-Channel-Connectivity in Cognitive Radio Networks," IEEE Access, vol. 6, pp. 65308-65320, 2018, doi: 10.1109/ACCESS.2018.2877404.

[162] M. P. Mishra, S. K. Singh and D. P. Vidyarthi, "Opportunistic Channel Allocation Model in Collocated Primary Cognitive Network," Int. J. of Mathematical, Eng. and Management Sciences, vol. 5, no. 5, pp. 995-1012, 2020,
doi: https://doi.org/10.33889/IJMEMS.2020.5.5.076.

[163] A. Khan, L. Sun, E. Jammeh and E. Ifeachor,"Quality of experience-driven adaptation scheme for video applications over wireless networks," IET Comm., vol. 4, no. 11, pp. 1337-1347, 2010, doi :10.1049/iet-com.2009.0422.

[164] K. Jiang, D. Sanan, Y. Zhao, S. Kan and Y. Liu, "A Formally Verified Buddy Memory Allocation Model," in Proc. of 24th Int. Conf. on Eng. of Complex Computer Systems, pp. 144-153, 2019, doi: 10.1109/ICECCS.2019.00023.

[165] M. Iwamura, K. Etemad, M. Fong, R. Nory and R. Love, "Carrier aggregation framework in 3GPP LTE-advanced [WiMAX/ LTE Update]," IEEE Comm. Magazine, vol. 48, no. 8, pp. 60-67, 2010, doi: 10.1109/MCOM.2010.5534588.

[166] Y. Cao, E. J. Sunde and K. Chen, "Multiplying Channel Capacity: Aggregation of Fragmented Spectral Resources," IEEE Microwave Magazine, vol. 20, no. 1, pp. 70-77, 2019, doi: 10.1109/MMM.2018.2875631.

[167] J. Meier, C. Gill and R. D. Chamberlain, "Towards More Effective Spectrum Use Based on Memory Allocation Models," in IEEE 35th Annual Computer Software and Applications Conf., pp. 426-435,2011, doi: 10.1109/COMPSAC.2011.63.

[168] Wai-Leung Wan and Wing-Shing Wong, "A heuristic algorithm for channel allocation of multi-rate data in hybrid TDMA/FDMA digital cellular systems," in Proc. of 9th IEEE Int. Symposium on Personal, Indoor and Mobile Radio Comm., vol. 2, pp. 853-858, 1998,
doi: 10.1109/PIMRC.1998.734683.