Channel Assembling Policies for Heterogeneous Fifth Generation (5G) Cognitive Radio Networks

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NOVEMBER, 2016

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Submitted to the School of Engineering in fulfilment of the academic requirements for the degree of Doctor of Philosophy in Electronic Engineering

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2016

As the candidate’s Supervisor, I agree to the submission of this thesis

Signed: ……………………………………………....

Prof (Dr.) Viranjay M. Srivastava **Date 23-Feb-2017**

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Details of contributions to publications and workshop that form part and /or include research presented in this thesis (include publication in preparation, submitted, accepted, in press, published and given detail of the contribution of each author to the experimental work, simulation and writing of each publication).

Professional Development Workshop Undergone in the course of this Research

5G and Cognitive Radio Workshop" Poster Presentation: 25th-28th July 2016, Pretoria, South Africa.

DoHET Accredited/Peer Reviewed Conferences

1. **E. Esenogho**. and Viranjay M. Srivastava, "Performance Evaluation of Channel Handover Exchange Scheme between Two Cognitive Radio Base Stations" Presented and Published in IEEE ICET'16, Karpagam India, December 16-17th, 2016.. [*Overlapping chapter 2 and 4*]
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6. **E. Esenogho** and T. Walingo, "Impact of primary users on secondary user's channel in a centralized cognitive radio Network", Presented at the *2nd International Conference on Wireless and Mobile Communication System (WMCS'14)* Lisbon Portugal Published pp.284-289, ISBN 978-960-397-1 [*Overlapping chapter 3*].

DoHET Accredited Journals Publications (Published, Accepted and Under Review)

1. **E. Esenogho**. and Viranjay M. Srivastava, “Channel Assembling Strategy in Cognitive Radio Networks: A Queuing Based Approach” (in-press vol. 6 no. 4) in International Journal on Communications Antennas and Propagation (IRECAP, Scopus-Elsevier), ISSN-20395086, vol. 6 no. 2 Italy, October 2016. [*Overlapping chapter 6*].
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3. **E. Esenogho** and Viranjay M. Srivastava, “Impact of Primary User on Secondary Channels in Cognitive Radio Network: An Overlay Performance Analysis” (***Awaiting final acceptance upon payment of previous Article***) in International Journal on Communications Antennas and Propagation (IRECAP, Scopus-Elsevier), Italy January, 2017. [*Overlapping chapter 3*].
4. **E. Esenogho** and Viranjay M. Srivastava, “Cognitive Radio MAC Protocols: A Holistic Overview” **Submitted** in Wireless Personal Communications Networking-Springer, November 2016. [Overlapping chapter 2].

The candidate for all the publications is the main and corresponding author respectively.

Dedication

This thesis is dedicated to my lord Jesus Christ who has kept his promises all through this program. Also, to my wonderful wife, Cordelia, and sons: Godswill and Favour; without their sincere love, patience, understanding, and spiritual support I would not have finished the program.

To God be the Glory.

Acknowledgements

My honest gratitude goes to Dr. Viranjay M. Srivastava for his friendly supervision and sincerity in the course of this program. Special thanks to the Head of Discipline, Prof. Thomas Afullo for his fatherly encouragement at the point of giving up. My friends at the Telkom/CRART Center of Excellence especially Remmy Musumpuka, Modisa Mosalaosi, Festus Osayavwen, Kazeem Oyebode, Usiholo Iruansi, Igbinosa Ireyuwa, Babatunde Ajumobi, Segun Oladoyinbo, Dr. Aiyetoro, Dr Alonge, Dr Chiemela, Dr Andrew Eloka-Eboka, Emmanuel Onuh, Mike Asiyu and others. I am grateful for all your inspiration and the times we spent together, not for getting the difficult moments we went through together. I will not forget Dr. Tom Mmbasu Walingo and Professor Fambirai Takawira for supporting and impacting in me directly and indirectly. I am also indebted to my parents, Chief and Mrs. Esenogho, my wife and sons, my parent in-law, Sir and lady Ogbane. Thanks so much for investing in, May the good lord continue to keep you. I must not forget my brother in-law, Mr. Ibe Ogbane and family for their support, my siblings, Esther and family, Stella and family, John, Okeamute, Onajite, Ephraim, Andrew and Tina. You all are highly acknowledged for your prayers. Special thanks to CRART, Telkom SA, Alcatel-Lucent, Ericson, CEPS HVDC for their valued financial support for this work.

Abstract

The demand for licensed spectrum resources is rapidly on the rise. This is due to the proliferation of bandwidth consuming wireless services and multimedia applications which exacerbate pressure on the existing radio resources. Studies on licensed spectrum (primary user channel) have shown two basic facts. Firstly, that the static licensed spectrum allocation results in low utilization most of the time and secondly, spectrum holes (TV white space) exist yet, are scattered across the spectrum bands. These are wasting resources and therefore need harmonization achievable through channel assembling strategies (CAS) proposed and investigated in this research. Cognitive radio's channel assembling strategies (policies) enables unlicensed users (secondary users) to combine several unused channels (spectrum holes) into combinations of usable secondary user (SU) channels in order to enhance its throughput and other metrics.

However, this has improved the performance of SU in terms of capacity, spectrum utilization, reduced blocking and forced termination. With this, it is clear that CAS would be a panacea for the actualization of the set targets (Ultra-high capacity, Ultra-high data rate, lower latency, cost effective, cyber-alertness, self-awareness/self-reconfigurable and quality of experience delivery) of the next generation (5G) wireless networks. CAS can be categorized as static or dynamic and several have been suggested in relevant studies to optimize the use of the scarce but wasting resources. Similarly, most studies did not take into account the dynamics of a wireless channel hence assumed the signal to noise ratio (SNR) as identical which does not a real-world wireless networks scenarios. For CAS to be applied, it must consider: the classes of SU traffic, channel state condition (SNR) and other constraints that have direct effects on the qualities and capacities of the accessible channels vis a vis the varying wireless channel and the modulation scheme (adaptive modulation and coding).

Motivated by a realistic scenario in CAS in cognitive radio networks, three CAS for a multi-rate wireless channel integrating adaptive code and modulation (AMC) is presented. The strategies (policies) includes: the readjustment based strategy (RBS), immediate blocking strategy (IBS), and queuing based strategy (QBS) which was incorporated into RBS scheme in this study. In the RBS, the aggregated channels are adapted to minimize forced termination and/or blocking of new SU, whenever PU appears while in the IBS, the SUs are instantly pre-empted with if no sufficient spectrum resources is available. For the QBS scheme, instead of instant termination at no free channel for SU, the SUs are queued and served later. These novel strategies were compared with *No-assembling strategies (NAS)* and evaluated with single and multiclass SU traffic classes via extensive system simulations.

The numerical results obtained demonstrate that integrating queuing regime and AMC into CAS in cognitive radio network is a robust approach irrespective of the SU classes. This accounts for the reason why the QBS regime outperformed RBS and IBS respectively in all wireless link conditions. However, the NAS has the least performance since no special technique was applied. Furthermore, a system analytical framework to analyse the performance of the two proposed strategies (IBS and RBS) with a single class SUs was developed. A Continuous Time Markov Chain (CTMC) is used to develop and evaluate the analytical model. The developed strategies featuring AMC demonstrates that system performance in terms of blocking, forced termination and acceptance/admission probabilities respectively can be significantly improved. For the strategies to be much more robust in handling SUs of different traffic classes and quality of service requirements, a joint queuing based channel assembling strategies (CAS+Q) featuring AMC in varying wireless link which is another form of RBS with queuing was analysed .

Unlike the previous studies whose analysis were based on single class traffic flows without queues, this work expands the investigation by considering a multi-class SU traffic flows with separate queuing regimes using a CTMC. The essence is to further improve spectrum utilization, secondary network capacity and more especially, minimizing blocking and force termination of the SUs so that interrupted SU service will be queued and served later. The proposed strategies with queues (CAS+Q) is compared with the proposed strategies without queues and the results showed that the CAS+Q outperformed the existing once in terms of secondary network's capacity, spectrum utilization, blocking access/admission and forced termination probabilities respectively. This novel scheme reaffirms that AMC is a robust technique in improving CAS. Nevertheless, increasing the queue size, the blocking and forced termination probabilities could be reduced further but at the expense of system overall delays (longer-delay). This could be a road map if the set target (high data rate and high capacity) for the next generation/5G wireless network can be achieved.

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List of Acronyms

ACM	Adaptive Modulation and Coding
BER	Bit Error Rate
BS	Base Station
CA	Channel Assembling
CAC	Call Admission Control
CAS	Channel Assembling Strategy
CAF	Channel Assembling with Fragmentation
CF	Channel Fragmentation
CR	Cognitive Radio
CRN	Cognitive Radio Networks
CRBS	Cognitive Radio Base Station
CTMC	Continuous Time Markov Chain
CAS+Q	Channel Assembling Strategy with Queuing
DSA	Dynamic Spectrum Access
DSAP	Dynamic Spectrum Access Protocol
PDF	Probability Density Function
FCC	Federal Communication Commission
FIFO	First in First Out
FC	Fusion Centre
QoS	Quality of Service
SU	Secondary User
SUFC	Secondary User Fusion Centre
SNR	Signal to Noise Radio
PU	Primary User
PO	Primary Owner
MAC	Media Access Control
TVWS	TV White Space
OSAS	Opportunistic Spectrum Access Strategy
QBS	Queuing Based Strategy
RBS	Readjustment Based Strategy

IBS	Immediate Blocking Strategy
NAS	No-Assembling Strategy
ITU	International Telecommunication Union
ESTI	European Telecommunication Standard Institute
1G	First Generation
2G	Second Generation
3G	Third Generation
4G	Fourth Generation
5G	Fifth Generation
GSM	Global System Mobile for Communications
CDMA	Carrier Code Division Multiple Access
MC-CDMA	Multi-Carrier Code Division Multiple Access
DC-CDMA	Direct Sequence Code Division Multiple Access
UTMS	Universal Mobile Telecommunications System
IMT-AS	International Mobile Telecommunications-Advanced System
HeNb	Home eNode B
3GPP	3rd Generation Partnership Project
LTE	Long Term Evolution
SDN	Software Define Networks
SDR	Software Define Radio
CTI	Channel State Information
TER	Targeted Error Rate
PER	Packet Error Rate
BER	Bit Error Rate
IEEE	Institute of Electrical and Electronics Engineers
PMP	Point to Multi-Point
CFD	Cyclostationary Features Detection
LO	Local Oscillator
POMD	Partially Observable Markov Decision Process
VCA	Variable Channel Assembling
CCA	Constant Channel Assembling
OFDMA	Orthogonal Frequency Division Multiple Access

HMC	Hidden Markov Chain
FCFS	First Come First Serve
FSMC	Finite State Markov Chain
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
FT	Forced Termination
PUBS	PU Base Station
NGN	Next Generation Network
CAFA	Channel Assembling/Fragmentation with AMC
CAFA+Q	Channel Assembling/Fragmentation featuring AMC and Queuing
NMT	Nordic Mobile Telephone
TACS	Total Access Communication System
AMP	Advanced Mobile Phone System (AMPS),
TDMA	Carrier Code Division Multiple Access
EDGE	Enhanced Data rates for GSM Evolution
HSCSD	High Speed Circuit Switched Data
GPRS	General Packet Radio Service
UWC	Universal Wireless Communications
EGPRS	Enhanced General Packet Radio Service
ECSD	Enhanced Circuit-Switched Data
WIMAX	Worldwide Interoperability for Microwave Access
WIFI	Wireless Fidelity
LTE	Long term Evolution
LTE-A	Long term Evolution-Advanced

“The better a work is,

The more it attracts criticism;

It is like the fleas who rush to jump on white linens”

Gustave Flaubert.

CHAPTER ONE

General Introduction

1.1 Introduction

The growing demand for mobile applications and multimedia services have greatly motivated the exploration and utilization of wider spectrum bands to support high data rate communications over air medium [1]. In order to resolve the challenge of spectrum scarcity resulting from static near-full allocation of spectrum, cognitive radio is proposed as one innovative technique that supports both current and next generation wireless communications networks. In cognitive radio networks (CRN), two classes of users with different priority access exist; which are the primary users (licensed users) and secondary users (SUs). The unlicensed users been the secondary users, coexist in the same frequency band with the primary users (licensed users), and opportunistically utilize the spectrum bands, when the PUs are idle or inactive. Characterized with diversity in time and frequency, spectrum access opportunities differ for each individual secondary user in CRN.

Therefore, to protect the primary users, the SUs opportunistically access the spectrum resource when PUs are idle with an allowable interference level at the primary receiver and vacate the spectrum when the PU arrives. Such behaviour result to the PUs ON/OFF channel usage pattern to SUs. With the traditional concept of cognitive radio, high data rate can be achieved to support the bandwidth consuming wireless services and multimedia applications. However, investigations have shown that more can be achieved with cognitive radio since the PU channel usage pattern have been characterized as ON/FF. This is evident that spectrum holes (TV white space) exist and are scattered across spectrum with poor utilization. Thus, it is appropriate to coordinate these scarce and wasting spectrum resources that is scattered across time and frequency. Therefore, channel assembling strategies is proposed in cognitive radio networks recognizing its promising potentials.

This dissertation will help to expand the knowledge of channel assembling (CA) by considering other factors like: the dynamics of a wireless link, the queuing regime, the SU classes and other promising techniques such as adaptive code and modulation (AMC). However, incorporating queuing regime makes channel assembling strategies (CAS) a panacea for achieving high data rate for next generation/5G wireless networks.

1.2 Evolution of Wireless Technologies toward 5G-Cognitive Radio Networks

The evolution of wireless technology towards 5G cognitive radio is shown in Figure 1.1 and Figure 1.2. The first generation (1G) communication system was deployed in the 80’s with a data rate of 2.41-2.51kbps.

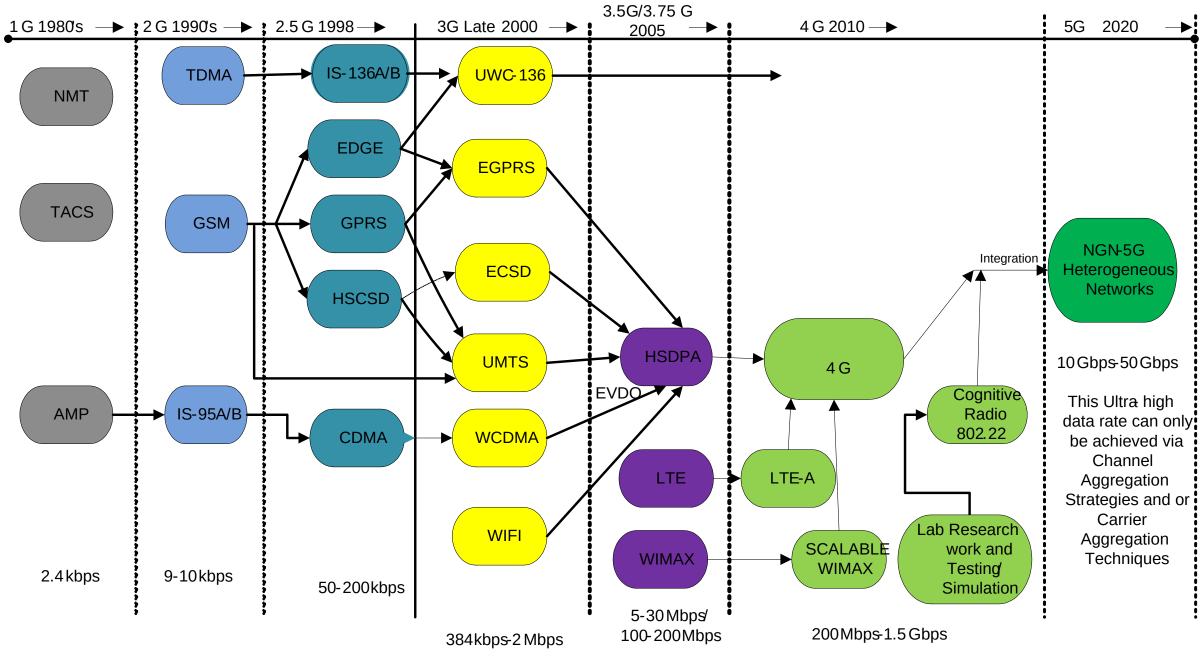

Figure 1.1 Evolution of Cellular Network towards 5G Cognitive Radio Networks

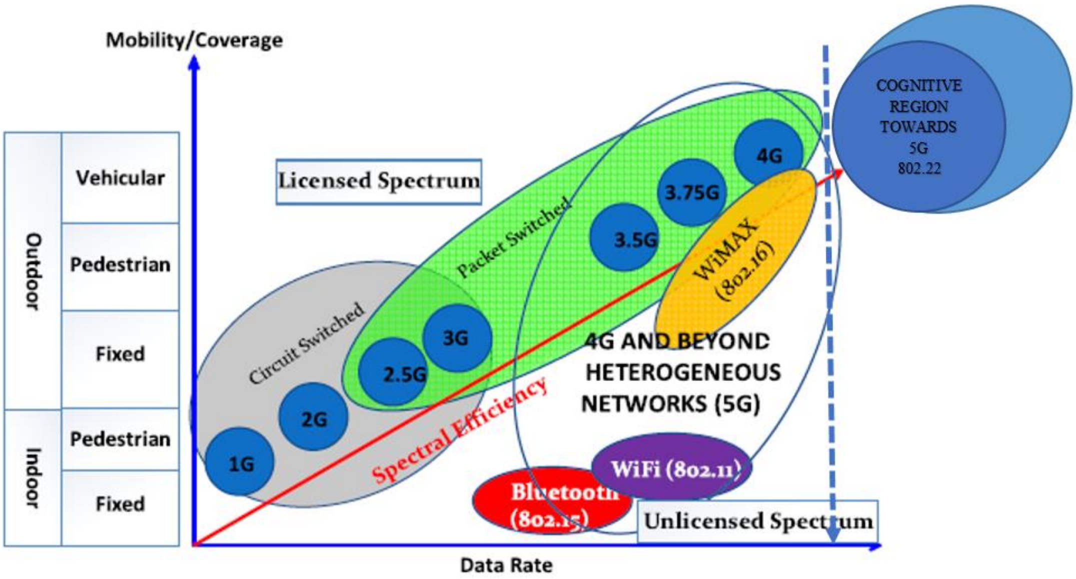

Figure 1.2 Advancement of wireless technologies towards 5G cognitive radio networks [2]

As at then, the main stake-holders were: the Total Access Communication System (TACS), Advanced Mobile Phone System (AMPS), Total Access Communication System (TACS) and Nordic Mobile Telephone (NMT). However, their main drawbacks are low data rate, low voice quality, frequent calls drop, low connectivity etc. The Global Systems for Mobile communications (GSM) been foremost 2nd generation (2G) network was rolled out in the 90's. However, more advanced technology was introduced in its deployment which made it possible to be used for voice, message service and e-mailing as an additional service. Since much applications and services are supported, the power consumption is relatively low and as such, the battery-life of the 2G portable device lasts longer. Other supporting technologies of 2Gs are: IS-95A/B, Code Division Multiple Access (CDMA) and Time Division Multiple Access (TDMA) [2]. In order to improve the drawbacks of the previous technologies, a switching system was introduced which run on the design of 1G and 2G.

Precisely, the 2.5G is implemented on a package and circuit switching protocol respectively with an improved data rate of 128-144kbps. Unlike 2G, it supported by CDMA, IS-136A/B, High-Speed Circuit-Switched Data (HSCSD), Enhanced data for GSM Evolution (EDGE) and General Packet Radio Services (GPRS). As a result of the demand from subscribers, couple with many drawbacks of 2.5G down to 1G, the 3G was announced and rolled out in late 2001. Its features included high data rate of 1.5-2Mbps, Internet Protocol (IP) compliant, good quality of service (QoS), and ability to roam in order to cater for user's mobility with guarantee users' experience. However, with these services and applications, the 3G devices are obviously expensive with high energy consumption. Technologies that support the 3G networks are the Code Division Multiple Access (CDMA-2000) 2000, General Packet Radio Service (EGPRS), Wideband Code Division Multiple Access (WCDMA), Enhanced Circuit-Switched Data (ECSD) and Universal Mobile Telecommunications Systems (UMTS).

However, the emergence of new solutions such as High Speed Uplink Packet Access (HSUPA), Evolution-Data Optimized (EVDO), High Speed Downlink Packet Access (HSDPA) has developed a mid-third generation wireless networks (3.5G) having better throughput of 6-30Mbps. Between 2001 and 2005, a more robust technology (3.75G) that has the latency to complement the size of the networks and delivers a significant amount of subscribers the opportunity to a wide range of fast services and applications was rolled out. Specifically, the Worldwide Interoperability for Microwave Access (WIMAX) and the Long-Term Evolution technology (LTE) has potentials of delivering higher data rate, better coverage at low cost thus referred to as the next generation mobile data services. The offspring of 3G and 2G networks is currently refers to as 4G of today. Examples of 4G networks are the WIMAX-Scalable and LTE/LTE-A. Thus, this regulation is made possible through the 3rd

Generation Partnership Project (3GPP). The 4G networks has an advance services much better than the previous models by conveying a broad with dependable frame work based on Internet Protocol (IP). In 4G system, the "*whenever wherever*" users experience is on services such as voice, data and videos, high definition television, multimedia-messaging package etc.

However, there are key tasks that 5G networks must address which 4G did not. This includes; very-high capacity, very-high data rate, cost effective, multiple connectivity (MD2D), very lower latency (1ms), resistance toward cyber-attack, self-awareness/self-reconfigurable (intelligence) and quality of experience provisioning. The reason is simply because of the exponential rise in the number of users with smart devices (bandwidth consuming devices). Just as 4G uses Orthogonal Frequency Duplexing Multiple Access (OFDMA) scheme, the 5G network will deployed a scalable OFDMA technique called Beam Division Multiple Access (BDMA). BDMA scheme works in such a way that the mobile switching centre assign a beam to individual base station and with the BDMA policy, splits the antenna beam with respect to positions of the handset (mobile station) therefore granting multiple admissions to the users, which in turn grows the network capacity [3]. For 5G, the data rate is very key and as such this ultra-high data rate (10-50Gbps) can possible be achieved through channel assembling/aggregation policy. The policy allows for aggregation of several unused/idle TV white space (spectrum-holes) or combination of unused channels into one logical channel. Lastly, the IEEE 802.22, 802.16, 802.11ac, 802.11ad and 802.11af are the foundation towards the standardization of 5G cognitive radio networks thus the 5G-cognitive radio architecture overview is presented in Figure 1.3.

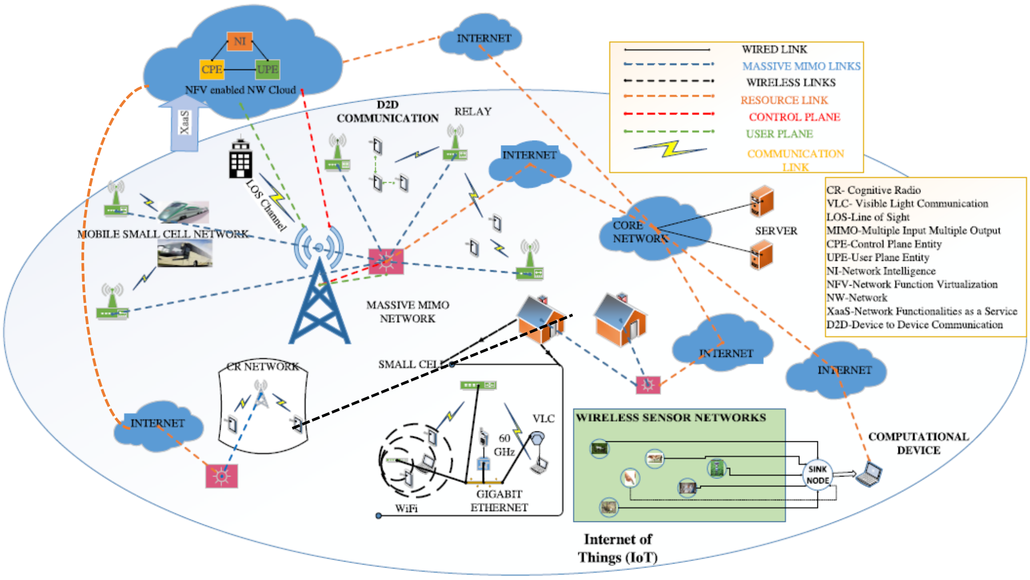

Figure 1.3 Overview of 5G-cognitive radio network architecture [2]

1.3 Research Problems

The significance of channel assembling strategies is of two folds: first, it improves SU data rate (higher throughput) since more channel will be aggregated and second, to ensure that the ongoing SUs packets (data) would have possibly transmitted before the PU arrives since SUs opportunistically utilizes the licensed spectrum. However, to realize these objectives, several research problems encountered need to be overcome hence can be categorized as follows:

- **SU Traffic Classification -** The traffic classes of SUs are dissimilar and each with different quality of service (QoS) requitements. This presents a difficult challenge to the network model for providing users experience. Traffic types could be multimedia which can be further categorized into real time and non-real time. Packetized calls and teleconferencing (video calls) are good examples of real-time traffic class while file downloading, internet surfing, are non-real-time class. SU real-time traffic classes are delay sensitive while SU non-real-time can tolerate delays, which implies that no strict delay requirement is needed despite its errors sensitivity unlike real time services. These different SU traffic classes pose a problem in network model development, implementation and deployment as it should efficiently accommodate all classes of the users and guarantee good user experience. A key feature of this proposed scheme is to accommodate SUs of all classes.

- **Dynamics of the wireless link -** Unlike [4], [5] which assumed that the wireless channel condition or signal to noise ratio is homogenous, it is not always the case because wireless channel cannot be static or homogeneous all the time but rather dynamic. At this juncture, the challenge is on how to characterize the wireless channel to reflect the varying nature of the proposed wireless channel. Also, incorporating adaptive code and modulation (AMC) scheme in this research further affirms the fact that heterogeneous wireless channel condition or signal to noise ratio is tasking.

- **The queuing regime-** Since our system model accommodates two classes of secondary users with different quality of service (QoS) constraint, designing a queuing regime that ensure that these different SU classes are queued in two separate buffers becomes a challenge. Specifically, developing and implementing a queue selecting algorithms (queue controller) for the different classes of SUs is very key so that real time SUs do not arrive into the same buffer that accommodates non-real time SUs. Secondly, since the proposed model accommodates SUs of different delay tolerance, it is crucial to employ a priority queuing regime so that the real time secondary users will not be dropped or forced to terminate. This is also another major challenge in this work which was overcome.

1.4 Thesis Organization

The thesis is made up of seven chapters. Each chapter offers an insight into the contents, objective and depth of work carried out. Chapter one discussed the general introduction into the subject matter: evolution of wireless technologies toward 5G-cognitive radio network, research challenges, and contribution to knowledge.

In Chapter two, a survey/overview of the research paradigm called cognitive radio network was presented. In the same vein, the make-up of cognitive radio was discussed in details. The concept of channel assembling strategies was also presented from relevant and recent literatures.

Chapter three presents two important aspects of cognitive radio networks. The first aspect investigates the primary users ON/OFF behaviour models while the second part focused on the impact of PU on secondary channels in cognitive radio networks using an overlay performance analysis.

Chapter four emphasizes the need for the scarce and wasting resources to be organized, assembled and used optimally for SUs. The chapter is also of two parts: The first part investigate, proposes and evaluates three channel assembling strategies in a single class SUs traffic in cognitive radio networks while the second part furthered the investigation by considering multiclass users' scenario. The investigation also considered the effect of integrating queuing technique and AMC into channel assembling strategies in cognitive radio networks.

Chapter five extends the investigation of the first part of chapter four by developing an analytical frame work to evaluate the performance of the two proposed strategies (IBS and RBS) with a single (homogenous) class. It gave an insight of the impact of the PU on SUs' networks in a dynamic wireless link and the potentials of integrating AMC in channel assembling strategies.

Chapter six extends the investigation of chapter four and chapter five respectively. It proposed, developed and analysed a joint queuing based channel assembling strategies (CAS+Q) featuring AMC, in a varying wireless link. Unlike the previous chapter that focused on single class SU traffic flows without queues. This one expands the investigation by considering a multi-class SU traffic flows with separate queuing regimes. More especially, it considered how to minimize blocking and force termination of the SUs and ensure that interrupted SUs could be possibly queued and served later.

Chapter seven concludes the study undertaken in this research with detailed appraisal of the contributions, significance and recommendations. It also highlighted accordingly the research dynamics with emphasis on possible future research focus and direction.

1.5 Thesis Contributions

This thesis initiated, proposed and analysed three CAS in CRN thus providing new evidence data. However, these can be seen as the thesis main contributions as listed below:

- Proposed three channel assembling strategies which considered the dynamic of a wireless channel featuring AMC. The strategies are evaluated with single and multiclass SU traffic classes.
- Developed a systematic framework to analyse the performance of the proposed strategies/policies with a single class SUs. Part of which was recently published in IEEE WVITAE and IEEE ICET conferences [6], [7], [8, 9]. The detailed systematic model has shown to improve the overall system performance in terms of acceptance/admission, blocking, and forced termination probabilities respectively.

- Proposed, developed and analysed a joint queuing based channel assembling strategies (CAS+Q) featuring AMC in a varying wireless link. Unlike the previous work that focused on single class SU traffic flows without queues, this work expands these investigation by considering a multi-class SU traffic flows with separate queuing regimes. The motivation is to further improve spectrum utilization, secondary network capacity and more especially, minimize blocking and force termination of the SUs so that interrupted SU service will be queued and served later. The proposed strategies with queues (CAS+Q) is compared with the proposed strategies without queues (CAS) and the results shows that the CAS+Q outperformed the existing one [8] in terms of blocking and forced termination probability, secondary network's capacity, access/admission probability and spectrum utilization. Moreover, the proposed policy confirms that integrating AMC with a queuing regime is a robust technique in enhancing CAS.

- Since next generation/5G wireless network is targeted at providing ultra-high capacity, ultra-high data rate, lower latency, self-awareness/self-reconfigurable (intelligence) and quality of experience delivery, therefore these proposed CR strategies would be a recipe for the realization of the set targets.

It is expected that this discussion will provide insight for extension of the work in this thesis and based in the lessons learnt so far. The work done in this thesis resulted to several published papers as shown in the next section.

1.6 Publications in Journals and Conference Proceedings from the Research work

The list of publication below are materials forming major parts of the thesis with appearance in peer reviewed and accredited journals, as well as conference proceedings

DoHET Accredited/Peer Reviewed Conferences

1. **Esenogho E**. and Viranjay M. Srivastava, "Performance Evaluation of Channel Handover Exchange Scheme between Two Cognitive Radio Base Stations" Presented and Published in IEEE ICET'16, Karpagam India, December 16-17th, 2016. [*Overlapping chapter 2 and 4*]

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DoHET Accredited Journals Publications (PhD Output: Published, Accepted and Under Review)

7. **Esenogho E**. and Viranjay M. Srivastava, “Channel Assembling Strategy in Cognitive Radio Networks: A Queuing Based Approach” (in-press vol. 6 no. 4) in International Journal on Communications Antennas and Propagation (IRECAP, Scopus-Elsevier), ISSN-20395086, vol. 6 no. 2 Italy, October 2016. [*Overlapping chapter 6*].
8. **E. Esenogho.** and Viranjay M. Srivastava, “Performance Analysis of Heterogeneous Channel Assembling Strategies in Cognitive Radio Networks” Published in International Journal of Engineering and Technology Innovation (IJETI, Scopus-Elsevier), vol. 7 no. 2, pp 98 – 116 ISSN-2226809X/22235329 Taiwan, 2017. [*Overlapping chapter 5*].
9. **E. Esenogho** and V.M. Srivastava, “Impact of Primary User on Secondary Channels in Cognitive Radio Network: An Overlay Performance Analysis” (***Awaiting final acceptance upon payment of previous Article***) in International Journal on Communications Antennas and Propagation (IRECAP, Scopus-Elsevier), Italy January, 2017. [*Overlapping chapter 3*].
10. **E. Esenogho** and V.M. Srivastava, “Cognitive Radio MAC Protocols: A Holistic Overview” **Submitted** in Wireless Personal Communications -Springer, November 2016. [Overlapping chapter 2].

CHAPTER TWO

Literature Review

2.1 Introduction

In this chapter, overview and related works on cognitive radio networks and the dynamic spectrum access technology are introduced. The SU interaction techniques including spectrum allocation and utilization (assembling) investigated in literatures are discussed. Emphasis is placed on research work on channel assembling strategies and its associated protocols.

2.2 Cognitive Radio Networks (CRN): An Overview

A CRN is an intelligent multi-user wireless communication system that embodies many tasks [10]. It has been considered also as one of the key drivers for the 5th generation (5G) wireless network due to its capability to: sense, make decision, reconfigure-self, manage, allocates and share spectrum resources [10]. CRN is projected to deliver cost effective spectrum access and elastic system utilization for the constantly increasing wireless application and multimedia services. In the present inelastic spectrum distribution policy, some spectrum-band is reserved for special access as stipulated by the International Telecommunication Union (ITU) and The European Telecommunication Standard Institute (ETSI) [11]. Suitable frequency band for communications remains a rare commodity, and request for additional resource generally involves huge financial responsibility for authorization. Spectrum shortage as a consequence of the almost exhausted allocation of resources becomes an obvious challenge to further motivate wireless infrastructures.

However, the allotted resources are unequally structured with erratic exploitations between 10 to 90% in both time and frequency domains [12]. In built-up area, many access opportunities for secondary transactions exist in all domains (frequency, time and space). The typical tenancy over some physical locations is about 7-9% with the highest spectrum occupancy of 15-16% between 35 MHz and 3.5 GHz in the United States and lowest tenancy 2-3% in remote area [13]. Since research is far from developing a robust spectrum allocation strategy that allows allotting spectrum based on request at real-time estimation, Cognitive radio proposing spectrum recycle into recent wasting idle channels has grown appreciation as a vital technique to mitigate the spectrum scarcity challenge [14]. Investigation has shown that Europe [15], [16], [17], [18] has greater spectrum occupancy compared to North America, however, still low. In general, it could be summarized that spectrum tenancy is moderately low between 1-2 GHz worst above 3.5GHz. The differences in channel sharing task with physical spectrum utilization shows that spectrum deficiencies are the consequence of outdated regulation strategy. In order to realize the European digital plan and continuous quest for wireless application and multimedia services, it is thought wise to envisage the employment of 5th generation wireless networks and services which needs fast and more dynamic access to the spectrum resources. The common tendency to supplier and effective spectrum management policy is motivated by the unceasing increase in new multimedia application and services. To cope with these trade-offs of: underutilization, bottleneck and spectrum allocation, cognitive radio approach was proposed [19], [20], [21] [22]. In CRN, the users are categorized into two distinct groups according to the channel access privilege: SUs and PUs. Individually SUs form cluster (network) with corresponding transactions and protocols. The primary users are the owners of the spectrum (licensed users) with the highest priority to access the spectrum. On the contrary, the SUs do not have licensed channels of their own. However, with cognitive radios (Mitola radio), SUs can intelligently sense and detect the idle channels when PUs are not present, and utilized it for secondary transactions among themselves.

Vacant spectrum generally extends over the frequency band thus opens up an interval for secondary transactions, known as spectrum-holes. The terminology spectrum-holes and white-space created by [23] also were generally used in representing the vacant idle spectrum. However, because of this white-space (spectrum-holes) used by the SUs which is usually found in the TV band, the term was completely renamed as “TV White space” (TVWS) [24], [25]. Cognitive radio networks operate using a well-organized spectrum access scheme that gives secondary users (cognitive users) the capacity to access the PU spectrum which requests secondary users to speedily adapt to the spectrum variations and appropriately coordinate the user operations to avoid destructive meddling with PUs activities. Thus, SUs are equipped to identify vacant/idle spectrum prior to communications and constantly checking/sensing the spectrum for PUs arrival. Once several SUs are ON (busy) in the system, the organization and interaction between SUs generally affects the exploitation of the spectrum resources and other useful SU services.

In CRN, the hierarchy spectrum admission strategy is its unique feature and thus relevant in real-world wireless networks application [19], [26]. Centralized CRN architecture is standardized to utilize the idle TV spectrum in wide coverage area networks. Cognitive radio standard (IEEE 802.22) stipulates the OSI layer for a static node to multi-node air boundary, that a cognitive radio-base station (CRBS) coordinates channel detection (sensing) together with the conventional base station characteristics, for example, spectrum allotment and users request management. Similarly, it is very challenging to attain fast and seamless transition which reduces interference to the licensed user and performance reduction of SUs during channel handover/handoff procedure. This task becomes even trickier in ad hoc networks to control the spectrum mobility [17], [27], as compared to the centralized network (server-model) which handles handoff/handover procedures [28]. Since channel access is within a window period, due to the random appearance of PUs, there is need for SUs to have a coordinator (CRBS) that will cooperatively manage the associated SUs, and identify spectrum-resources thus enhancing channel access reliability with little or no inference with the PUs [7]. This is made possible by the SUs sensing the spectrum with corresponding feedback information (sensed information) sent to the central node of SUs. With this procedure, the central node is aware of the behavioral (ON/OFF) pattern of the PUs, as such reduce the deployment cost of the interference which in most cases cannot be tolerated. With the speedy evolution of wireless services and multimedia applications, without corresponding increases in licensed band, CRN highlights the need to design more robust schemes to cater for this constantly increasing demand for good user experience [4]. For instance, the installation of small-cells for interior signal enhancement is impaired by accessible channel resources [5]. Currently, CRN networks models is proposed for small-cell networks to deliver additional out of spectrum resources for static and dynamic users [29]. Through the employment of cost effective, low-range, small cell base stations (home eNode B in 3GPP LTE standard), the users of small cell can use the identified spectrum-holes to satisfy the users requirement for online services and applications.

The concept of CRN's dynamic spectrum access (DSA) discipline sounds interesting and innovative from both Mitola point of view and other researchers. However, designing and developing CRN platform is a complicated assignment together with other open research questions which include but not limited to: cross-layer design, access strategy, network routing and discovery protocol, spectrum sensing/sharing, intelligent-antenna policy, self-configuration/awareness (spectrum adaptation), and software-defined network (SDN) platform design. Amongst all mentioned, the probing and utilization of spectrum-holes is the main issue in CRN research. Recent researchers have proposed some unique techniques to sense and track spectrum utilization patterns of the PUs. Since the PU idle (white space) channels are scattered across the spectrum band, there is needs for coordination to improve the users QoS requirements hence the need for aggregation. CAS enables SUs to combine more than one idle channel in order to optimize SU performance. This have shown to enhance SUs performance in terms of throughput, blocking probability, spectrum utilization, access/admission probability and dropping/forced termination of the secondary network [8], [30]. However, finding a preferred spectrum access scheme that will aggregate unused channels in an effective way considering: the varying nature of a wireless link featuring AMC, robust queuing regime and the classes of SUs is still an open question seeking for answer, hence, the need of the main focus of this study.

2.3 Cognitive Cycle of Cognitive Radio

Cognitive radio adaptively adjusts its communication parameters and opportunistically accesses the PU channel without causing undue meddling on PUs transactions. The CR operations are illustrated in Figure 2.1. As earlier indicated, the capabilities of the radio intelligence (cognitive) are embedded in its dynamic functionalities to: dynamically access spectrum, sense spectrum, share spectrum, make spectrum decisions and are spectrum mobile [31].

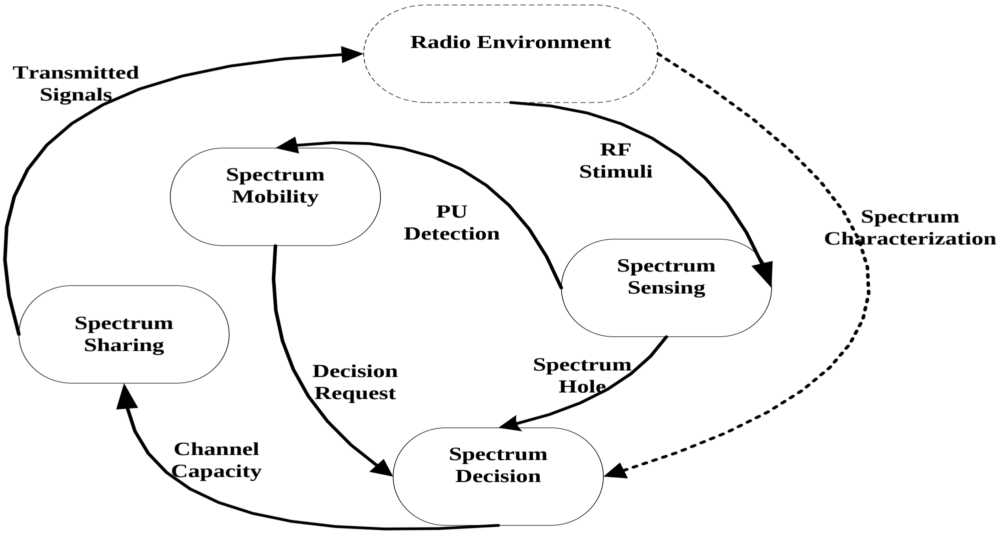

Figure 2.1 Capabilities of a cognitive radio

2.3.1 Spectrum Access

Communications of SUs in cognitive radio networks are restricted by the activities of PUs operating in the similar spectrum. However, with the advent of robust spectrum identifying schemes, like the wide spectrum detecting/sensing schemes, the ability of SUs to probe and identify wide-band opportunities is improved. Nevertheless, there are possibilities to identify ample TVWS wasting and waiting to be used for SUs communications. At this juncture, the task then shifts to the aspect of how to organise these wasting but scarce resources for optimal usage, considering the short window period for transmitting SU packets. As a result, the concept of channel assembling strategy was proposed for CRN [8], [27], [30]. Several CA strategies have been proposed in an attempt to improve the performance of CRNs, this will be discussed in a later section of this thesis.

2.3.2 Spectrum Access Models

The main emphasis of spectrum access is to ensure that spectrum is recycled by secondary users (SUs). However, detecting and characterizing channel access motivates the enabling of flexible communications in the multi-layered channel access model. The manner at which Primary users (PUs) and SUs interact for spectrum recycle are basically categorized as: underlay, interweave and overlay model [17], [25], [31]. In the underlay model, both users are allowed to communicate concurrently unlike the the interleave architecture. However, with the underlay, the SU samples its signals across a range of band that is sufficiently wide to guarantee the extent of interference (signal to noise ratio) generated on primary signal within an acceptable limit. Interference of such, limits the use of underlay model for short distance transmission system. This implies that SUs needs a strong inter-layer connection to make transmission decisions. Thus, the underlay model is commonly utilized in the argument of the hypothetical performance borders of CRNs. In the interweave model, both users (PUs and SUs) operates individually with no signal exchange between. SUs detect idle spectrum through intelligent sensing, and detects the activities of the PUs through various detection techniques. The PU is either in “ON” or “OFF” mode indicating that PUs is either idle or busy. In the overlay model, simultaneous communications between PUs and SUs are permitted but this time, the PUs is involved in access decision of the SUs in the network [32], [33]. For desperate reason of communication opportunities, the SUs exchange information (negotiate) with PUs for communications by transmitting on PUs networks via a cooperative policy, which includes a sophisticated coding techniques. Normally, detecting errors are naturally unavoidable incidence in real-world networking procedures. For instance, signal sampling, delayed response and channel approximation, have corresponding adverse impact on the overall system performance. However, collaboration among SU can help SUs evade the detecting error challenges and improves channel admission opportunity for unlicensed users. Instead the collaboration calls for a dynamic PUs coordination for seamless internetworking with SUs.

2.3.3 PU Spectrum Opportunity Usage Pattern

Part of the reasons for spectrum underutilization is attributed to PUs ON/OFF behaviours. This has resulted in spectrum holes (TVWS) as shown in Figure 2.2 and 2.3 respectively [34], [35]. However, while Figure2.2 illustrates the PU ON/OFF behaviours, Figure 2.3 illustrates the assembling (aggregation) of spectrum-holes in idle state via the logical ON or discrete OFF procedure [36]. Thus, CR became a new model for the exploration and exploitation of spectrum-holes across time and frequency domain. Cognitive radio networks operate in several radio bands for opportunistic communication and the spectrum access opportunities shows dissimilarity in the both spectrum usage patterns, and statistics in the PU behaviours. Usually, from SU perspective, the spectrum accessibility for the SU communications could be modelled by an ON/OFF alternating procedures whose distribution would be exponential or geometric [8], [34, 37]. In [34], the duration of an OFF time when the channel M is available for secondary channel access is modelled as a random variable T_{OFF}^{M} with a probability density function (PDF) $f_{T_{OFF}^{M}}(x) > 0$. Likewise, the PDF of the interval of an ON period when the channel is busy is given as $f_{T_{ON}^{M}}(y) > 0$.

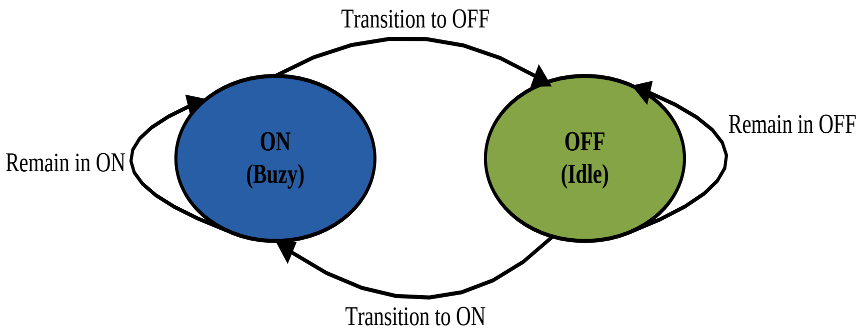

Figure 2.2 PU spectrum utilization pattern

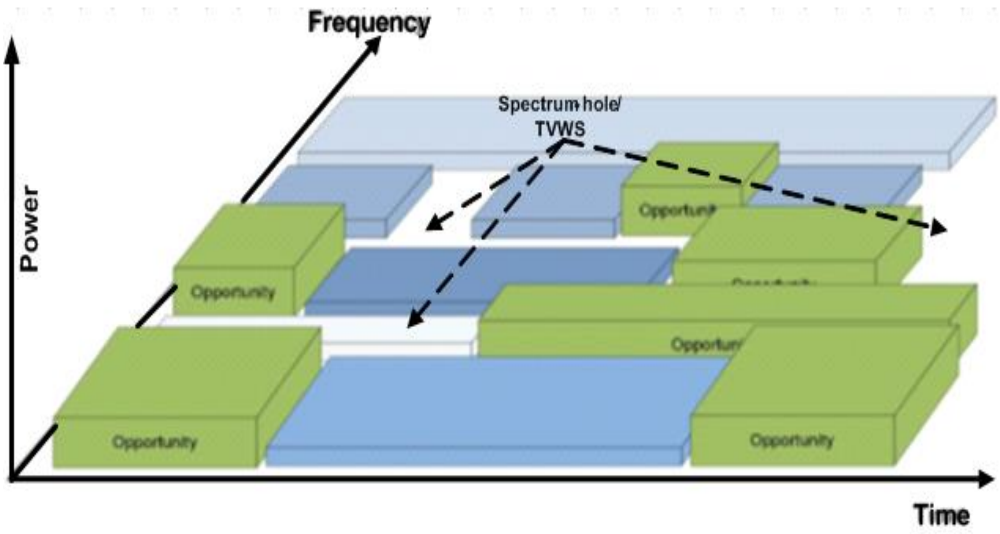

Figure 2.3 Aggregating spectrum opportunity across frequency and time

Studies have shown that most of PU spectrum seems to have the idle period very often however, the figures of the lengths of idle periods vary. Though, the ON/OFF periods are not homogenous over dissimilar spectrum according to the specific PU pattern. It can be naturally presumed that the spectrum holes (TVWS) released from a TV spectrum would be different from that of a busy 1G (GSM) networks. This variance demonstrates the channel heterogeneity for the support of SU request in CRN.

Furthermore, the diversity of spectrum band offers additional heterogeneous advantage in secondary communications. Characteristics of spectrum diversity are discussed in details in wireless propagation models [38], [39]. Spectrum reaction to wireless signals varies across frequency bands because of the spectrum selective nature of low-scale fading, with the frequency requirement of path-loss. In [40], a significant study on the subject relating to the heterogeneity of spectrum networks is highlighted. Irrespective of channel heterogeneity or variation in frequency, cognitive radio networks are designed with the capability which enables the SUs explore the scares/valuable spectrum opportunities by tuning to the unused/idle frequency bands in order to services the SUs. Because this TVWS lies in different spectrum band, there is possibility that it will indicate heterogeneity in their communication features. Presently, describing the features of the heterogeneous spectrum in cognitive radio networks remains an unanswered question. For instance, a SU probes the different adjacent channel because the PU behaviour and its transmitting parameters vary. For a particular adjacent terminal, there are multiple spectrums with diverse communication parameters to allow reliable connections. Studies in [41] proposed a novel index to quantify the performance of the heterogeneous channels for scheduling and routing. The higher layer (Transmission Control Protocol) performance of the OSI model for the node to node communication is estimated in [42], and the outcomes demonstrates that utilizing heterogeneous channels could enhance the performance through a clear definition of the heterogeneous boundaries. SU communication introduced interference on the PU transactions in the adjacent frequency bands [43]. To alleviate channel meddling, the packet handover of the SU alters its path to avoid the PU interference regions. This is anticipated based on the cross channel interference fading associated with the frequency domain.

From literature, the generality of heterogeneity of the spectrum opportunities can be characterised into four aspects: the PU behaviours; this entails the mean spectrum availability, the mean holding-time for the spectrum opportunity, and the maximum transmitting power allowed for the secondary user in order not to cause interference. Network-Layout Loads; this entails different loads for the similar channel in different links. Transactions features of the channel; this includes the channel size, the communication interval on the specified power level, symbol rate, and the supported modulation and coding systems. The spectrum procedure policy; spectrum shared with static or dynamic schemes aggregates neighbouring or adjacent idle channels to improve data rate [36]. However, the focus of this thesis will be centred on the spectrum procedure policy. Precisely, the next section will highlight the theory of CAS in CRN as a channel procedure strategy.

2.3.4 Spectrum Sensing

Since the SUs are not the licensed owner of the channels it intends to use, it first senses to detect the PU presence on the channel before usage to avoid interference. However, a dynamic spectrum agile procedure where CR observers its wireless surroundings, identifies usage information of PU and explores for TVWS, can be accomplished through single or multiple CR terminals cooperatively or otherwise. Furthermore, SUs can detect idle channels through several sensing and detection techniques like energy detection, matched filter detection, features detection and so on. However, the detection of PU activity in the absence of transactions between PUs and itself is still an open puzzle yet unsolved. Moreover, the sensing approach employed depends on the signal processing techniques used in the sensing procedure [17]. This is categorized into three basic techniques which are: the interference management sensing technique, transmitter sensing technique and receiver sensing technique. The transmitter sensing techniques comprised of the cyclostationary-features sensing technique, energy sensing technique, and matched-filter sensing technique. The energy sensing is a non-coherent sensing technique in which the PU sensing does not necessarily need erstwhile information of the signal to check if the spectrum is busy or idle. Hence, it is assumed as the simplest of all the sensing methods [35], [44], [45]. The advantages of this technique are: easy deployment, cost-effective, less complexity and do not necessarily need erstwhile information of the PU signal. These advantages make energy sensing the simplest method to identify PU presence [45]. The peculiarity of this technique is that the signal detection depends on comparing the energy-level of the known signal to the bench-marked level, while bench-marked level relies on the noise-floor which could be projected. However, the energy-level is challenging to predict since the variations is hinged on two factors: space between PUs/SUs and the communication features [35]; such as the choice of a suitable bench-marked level results in many shortcoming of the energy sensing technique. Thus, if the threshold is too low, this may result to erroneous alarm. Conversely, if the bench-marked level goes so high; missed sensing could occur due to the fact that fading primary signals would be overlooked.

Hence, the performance of energy sensing method is a function and appropriate choice of the bench-marked level in all domains. Additional drawback of the energy sensing technique is the exactness of signal detected as compared to other techniques [46], [47]. For matched-filter detection, the matched is gotten by comparing an identified PU signal with an unidentified signal to predict if the PU signal is active. More also, the matched filter detection is faster to obtain high precision on account of previous information of the PU signal such as the transmission scheme, signal shape, and the bit patterns. This implies that, if such statistics are not precise, the matched filter performance would be poor. The matched filter detection, nevertheless, is deployed when the targeted PU signal carries known signal features. This is another drawback. The cyclostationary-feature detection approach has improved performance even at very low signal to inference noise ratio (SINR) regions, even though higher computational complexity requires significantly long observation time which makes it the least option to consider.

This detection technique depends on the inherent redundancy in the PU communications [46]. One advantage of this technique is its ability to identify the modulation scheme even if it needs partial knowledge of the PU statistics [48], [49]. Moreover, it is not cost effective due to the limited information, hence, requires more knowledge to detect the PU. The performance of this sensing method depends on some criteria which include: noise ambiguity, idle transmissions and modulation scheme of the PU. Therefore, the trade-off between cost and time are used as a performance improvement criterion for the cumulative distribution function (CFD) [50], [51]. Among all the transmitter approaches mentioned, energy detection with the threshold based decision is widely applied because of obvious reasons identified. Though, it cannot differentiate signal types and does not work for spread spectrum [52]. The leakage energy from the local oscillator is used for the detection of PUs instead of the transmitted signals receiver detection technique. However, the leakage energy from the oscillator is sensed by the matched filter. Problem of uncertainty can be resolved using the receiver detection techniques. But, because the signal from the oscillator is weak, design and implementation of a dependable detector is still an open issue.

For the interference management detection approach, the interference boundary is characterized by the extent of meddling that the receiver could bear provided the SU avoids going beyond its bound by their activities, then, the channel can be used. The task of deployment becomes complicated. For instance, it is almost impossible for a SU to quantify the interference level received by the PU terminals. Also, the interference threshold of a PU is a function of position which is very difficult to define. Waveform based detecting is generally based on relationship with identified signal features. Identified features are generally used in wireless link to assist harmonization or for other purposes. Features include: spreading sequences, pilot features and preambles. It shows that waveform based detection technique is better than the energy sensing method in terms of convergence time and consistency. It also shows that the robustness of the detection procedure rises as the distance of the known signal features rises. This approach is employed when the targeted PU signal carries known signal features. These techniques and others (radio identification based sensing and multi-dimensional spectrum sensing) form the background called spectrum *awareness and sensing methods* as shown in Figure 2.4.

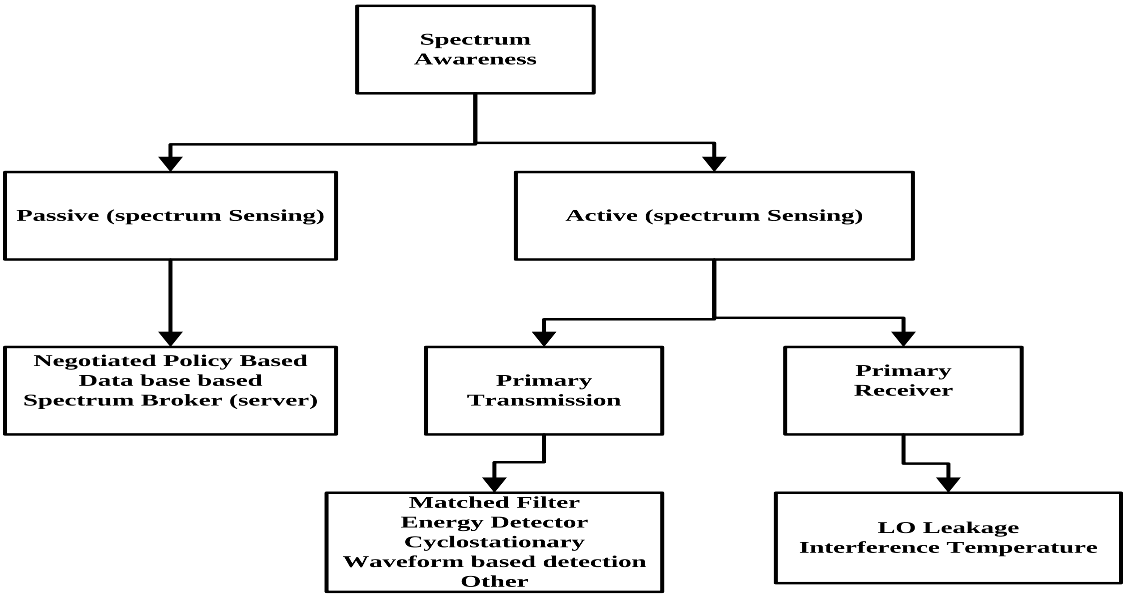

Figure 2.4 Classification of spectrum awareness

2.3.5 Spectrum Decision

Based on the outcome of the spectrum sensed information gathered, cognitive radio estimates the spectrum-hole (idle channel) and makes decision on when to start its operation. The identified idle channels are shared among the SUs to transmit their packets in an opportunistic way without causing interference to the PUs. After spectrum-hole have been known, the services available are then weighed thereafter, the most appropriate spectrum based on the quality of service and user experience are selected. The main reason for this evaluation is to minimize the forced termination and blocking probabilities in the secondary transactions. This has a direct link to the anticipated period of the spectrum opportunity and the packet configuration. Moreover, the patterns of the PUs must be considered in the weighed significance of the spectrum-hole selection. This gives cognitive radio the leverage to utilize information from regulatory and policy database in order to enhance its operations. With proper design of the spectrum-hole methodology, secondary users can select realistic spectrum-holes (TVSW) for packet transmission or quickly handoff transactions to other available spectrum-holes if the PU arrives.

Spectrum estimate and decision algorithms using machine learning is still an open area of investigation for the past decades. However, costing and designing of spectrum sensing policies must be balanced. Using artificial intelligence (AI) algorithm to monitor the spectrum flag, introduces a spectrum forecasting strategy via partially observable Markov decision procedure [53]. The technique studied the channel detection and channel access together as no statistical interchange is needed between the SUs.

Therefore, each SU identifies the spectrum status by its own sensing procedure at its position. With channel modelled in time slot, the choice of spectrum-hole is commonly assumed as a Markovian procedure using POMD sensing output in individually slot. Observing and mastering PU behaviour is strengthening over a long period of time in a self-organising manner. The methodical optimization depends on: the detecting strategy, dependence strategy of sensing vector and exploit strategy. In cognitive radio networks, the spectrum-hole organization in the multi-hop communication is modelled as a distributed optimization problem whiles the mastering procedure taken as a theory [54]. The usefulness of the spectrum-holes is weighed upon the observation at the terminal and by the statistics among the users. The intervals between them are weighed with the value of the information and a model "information cell" is proposed to compute the value of the status of the adjacent users.

2.3.6 Spectrum Sharing

Once the SU has opportunistically accessed the spectrum, and spectrum sensing has been done to ascertain the PU status, the next phase will be how to share the identified spectrum resources among SUs, considering the diversity of SUs traffic request. As several SUs may demand spectrum resources concurrently, the robust spectrum sharing strategy must be in place to manage the concurrent SUs transaction and the same time, prevent undue meddling to the primary users. Spectrum sharing strategy is proposed as a panacea to this problem, and this is similar to the role Media Access Control (MAC) protocol plays in the OSI model of a conventional wireless networks [55].

This have shown that spectrum sharing generally improves the performance of cognitive radio networks precisely, in a densely deployed network as each SU will be adequately catered for irrespective of the traffic type and requirements. Conversely, because of the distinctive features of CRNs which includes spectrum adjustment and PUs tolerance, the resource sharing strategy in CRNs faces several problems. This has been a hot research topic in the present day and with a lot of efforts put in to addressing it. The current proposed spectrum sharing scheme are categorized into four different pair architectures. They are: the infrastructure and infrastructure-less spectrum sharing, collaborative and non-collaborative spectrum sharing, overlapped and underlapped spectrum sharing and intra-network and inter-network spectrum sharing architecture respectively [19, 20]. In infrastructure spectrum sharing architecture, there is a fusion centre otherwise called cognitive base station (CRBS), which collates the statistics about vacant spectrums opportunities, manages the resources allocation and access. In this model, different requirements from different secondary users are better considered and organised by the fusion centre (FC).

However, in infrastructure-less sharing model, spectrum allocation and admission is performed by separate node independently without necessarily reporting to the CRBS. Though, both architectures have their respective drawbacks and advantage over each other when compared. The main difference is that CBRS performs access management and resources allocation in the infrastructure architecture, though the statistic collation and sensing processes are carried out independently by SUs. The CRBS collates the feedback statistics from each SU, based on how the spectrum allocation decision is designed, as shown in Figure 2.5. Another advantage is that optimum scheduling can be realized by the CRBS since it is aware of the traffic of each associate secondary user through exchange of information. In [56], the concept of spectrum broker (server) approach is proposed to allow the co-existence of licensed and unlicensed in mutual environs as shown in Figure 2.5. The central spectrum-broker gets statistics about the interference and environment through measurements from different users and then schedules its operations for optimal spectrum use. In [57], an infrastructure system for managing and organising spectrum access called Dynamic Spectrum Access Protocol (DSAP) was proposed.

This technique allows lease-based dynamic spectrum access through an organising fusion centre and allows effective spectrum sharing and exploitation in wireless environments. The contention for both spectrum resources and clients is taken into account under the regulation of a spectrum strategy server, which reconciles spectrum sharing among communication hardware, and thus monitors the appropriate spectrum. In the infrastructure-less system, SU partakes actively in resource sharing among them. This architecture reduces the intricacies of system implementation with the information exchanges among users occupying significant volume of system resource. Much emphasis has been placed on decentralized spectrum sharing techniques [58], [59], [60]. In [58] a game theory based approach called *price-based* infrastructure-less (decentralized) spectrum sharing scheme, to realize optimum resource utilization was presented. Infrastructure-less multi-channel spectrum sharing system is proposed to attain the optimal stable equilibrium in a multi-channel scenario [59]. The MAC policy with incomplete spectrum information is studied from a game model point of view [60] while [61] proposed an infrastructure-less auction-based spectrum sharing mechanism where the SUs offer to purchase spectrum bands from the licensed user who is the seller, selling vacant spectrum bands to make revenue. They considered a more general and realistic scenario where channels have different qualities and SUs are free to make their choice for each channel independently. That is, each SU submits a tender, one for each channel as shown in Figure 2.6 (a) and (b). However, clear difference between centralized and decentralized architecture can be found in [62], [63], [64], [65], [66] with other open issues.

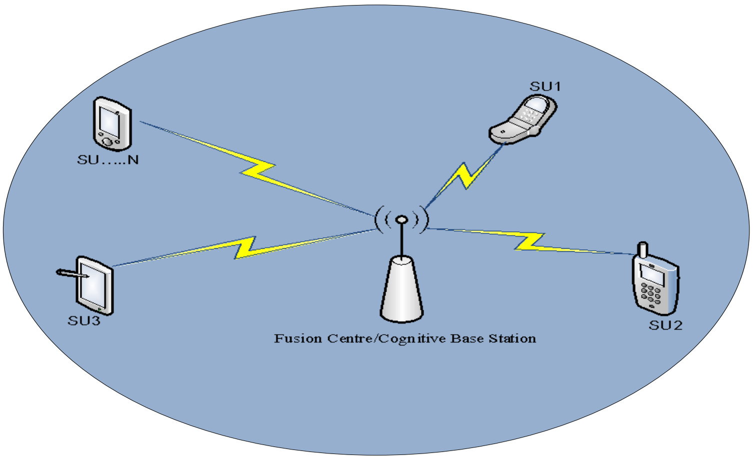

Figure 2.5 Centralized spectrum sharing architecture

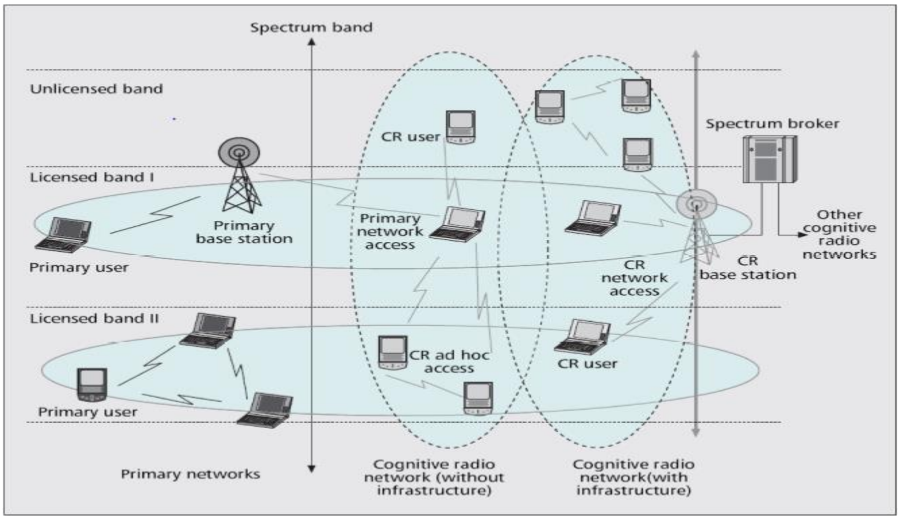

Figure 2.6 (a) A generalized CRN architecture for spectrum sharing [67]

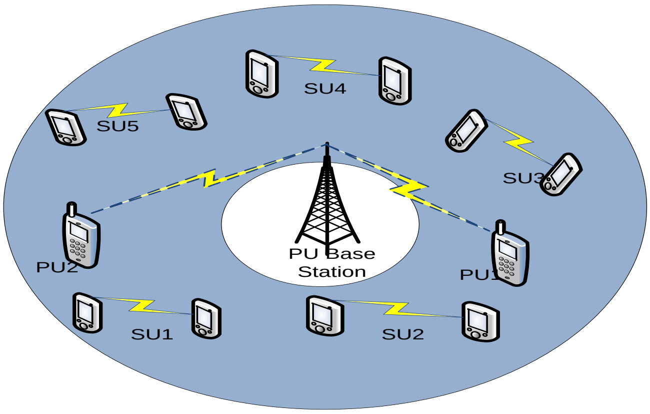

Figure 2.6 (b) Decentralized spectrum sharing architecture

In the case of collaborative and non-collaborative spectrum sharing models, the grouping is done based on the affiliation between SUs. To be precise, the condition is whether they share their spectrum sensing information among themselves or not. On the other hand, non-collaborative spectrum sharing is designed in such a way that, SUs make spectrum access decisions independently without necessarily exchanging information with other SUs. [68] proposed game model for non-collaborative CRN which enables SUs to make choice on spectrum access in non-collaborative manner in order to access several appropriate spectrums. This can be achieved by taking into account different QoS requirements and resource classification. [69] presents a resource sharing problem in a secondary band where outcomes indicate to be tight and quantify the best feasible performance in a non-collaborative situation.

By comparison, collaborative resource sharing has gained popularity over non-collaborative model since the SUs can share extra information about the wireless environment thus improving their performance. [70] proposed installation of agents based on the devices that can be collaborative to improve spectrum utilization. The study demonstrates that multi-agent based collaborative spectrum sharing can achieve up to 87 percent (87%) of the entire utility. In spectrum sharing, there are different design objectives and these objectives are aimed at different metrics, which includes energy efficiency and signal to interference reduction with corresponding techniques to accomplish such goals [71]. Though, coordination has shown to improve performance of spectrum sharing, however at the expense of total coordination delay and overhead [72]. As asserted earlier in overlapped spectrum sharing model, SUs access the TVWS opportunistically and transmits on these channels, only when the PUs are totally absent from the spectrum. As such, conflicting transaction which will cause interference will be minimized and possibly prevented. Statistics about PU’s position and communication is essential which is obtained through deep spectrum sensing. In underlapped spectrum sharing model, both primary and secondary users’ transactions are permitted concurrently. This is leveraged by SUs spreading their signals across the available frequency band. In underlapped spectrum sharing model, the interference caused to PUs can be characterized as wide-band background noise.

As long as the noise level is under an acceptable limit, the primary user link can be secured. Thus, significant study has been carried out on these two sharing models from different points of views. The energy allocation issue is investigated in a combined spectrum overlapped/underlapped fashion in CRNs [73], [74]. [75], [76], [77], considered the combination of energy and rate adaptation strategy while in [78], a rate sharing strategy for an overlapped model is proposed using a hypothetical game approach. In [79], a comparative study to evaluate the performance of different spectrum sharing strategies, together with spreading based underlapped and interference avoidance-based overlapped is investigated via outage probability. System such Multi-Input Multi-Output (MIMO) takes into account overlay and underlay scenarios [80]. The improvements and trade-off between overlapped and underlapped models have been studied in detail in [79], [81], [82], [83]. However, no research can analytically claim that one scheme is better than the other. The choice of one scheme over another is predicated on several factors like mode of coordination, closeness of device/users to each other and the sensing approach adopted.

For intra-network and inter-networks spectrum sharing models, the sharing is simply done within a licensed network and or with other different networks respectively. Nevertheless, after the actual deployment, occasionally one area is covered by a single network, while the other is covered by several networks from different network providers or multi-modal systems owned by the same operator coexisting in the area. The intra-network spectrum sharing is adopted to allot resources while for inter-network policy; it could be used for inter-network spectrum sharing. In [84], an infrastructure intra-network resource sharing is proposed where the systems are evaluated analytically with one optimal model found in terms of fairness and throughput. In [85], a hybrid set-up like the Multi-Carrier Code Division Multiple Access (MC-CDMA) scheme and Direct Sequence Code Division Multiple Access (DS-CDMA) installed in the same cell is taken into account. This has shown that the spectrum utilization can be better improved by spectrum sharing as compared with systems without sharing. Inter-network spectrum sharing for Universal Mobile Telecommunications System (UMTS), cognitive radio system 802.22 standard and International Mobile Telecommunications-Advanced (IMT-Advanced Standard) systems has been studied in details [86], [87], [88].

2.3.7 Spectrum Mobility

After primary user arrives and starts to transmit, secondary users have to halt its operations or departs presently used channel. This can be done by possibly switching to another radio spectrum that is vacant in order to escape interfering with license users. For this to be deployed in real time, secondary users have to constantly probe for possible alternative spectrum holes. These capabilities of cognitive radios are embedded on: its signal processing techniques and software defined radio capability [31], [89], [90], [91], [92], [93]. The purpose of the CRN is to optimize natural resources such as: time, frequency, and energy efficiently. This is done by identifying the surroundings and adapting its communication parameters and same time to avoid interfering with the PUs. However, the requirements for a CRN includes: stable TVWS and PU sensing, precise link prediction between nodes, swift and exact power control. These factors guarantee stable transactions between CR node and enables interference avoidance to PUs. So far, spectrum sensing, decision, sharing and mobility respectively, are all ways that SUs improve its performance in terms of: accurate and timely sensing, appropriate resource allocation and possibly vacation of the spectrum when the PU arrives to avoid inference. For instance, if several spectrum-holes exist and have been accurately sensed, the SU accesses the spectrum opportunistically and begins to transmit its packet using just one of the spectrum holes (channel-slot).

“*One open question is; what happens to the other spectrum holes (channel-slot)”*. It is obvious that those spectrum-holes will still be wasting. Then, the task would be how to organise these wasting and scarce resources for optimal usage for the secondary users considering the fact that there is a limited window period for transmitting SU packets. As a result, the concept of channel assembling strategy (spectrum-hole aggregation techniques) was proposed and implemented for CRN.

2.4 Channel Assembling in Cognitive Radio Networks

Channel assembling (CA) is one of the latest concepts, which cognitive radio network is introducing to support the next generation/5G wireless networks. This implies that the performance of a CRN needs a dynamic channel allocation scheme and one way of achieving such is through channel management, is an adaptive policy which allows combination of multiple scattered channels into a one logical practical chunk. Furthermore, CAS enables SUs to aggregate vacant channels (spectrum-holes) in order to increase the data rate and possibly, complete transmission of its packets before PU arrival. This has shown to enhance SUs performance in terms of throughput, blocking, access/admission and forced termination probabilities of the secondary network [5], [8], [30]. Several of this has been investigated in many studies in an effort to optimally use the scarce but wasting resources. Moreover, CAS can be categorized as fixed and dynamic. In fixed CAS, a SU can assemble a fixed number of primary channels while in dynamic CAS; a SU can assemble variable number of channels depending on availability.

These policies consist of spectrum adjustment which is of two folds [5]: spectrum handover where a SU can combine channels at different spectrums and spectrum adaptation where SU modify upward or downward, the quantity of spectrum resources during communication. In [4], spectrum adaptation is incorporated in CAS. Their study proposed two schemes that adapt channel tenancy of current traffic flows with the assumption that all channels are identical. [5] proposed CAS with adaptation in a heterogeneous traffic flow. The performance of these policies is evaluated using CTMC models. The estimation of this model in the pseudo-stationary scenarios are analysed and the capacity closed form are derived in different settings.

The performance comparisons of CAS were studied in three different cases when channel adaptation is not incorporated. The scenarios are: with a fixed number of assembled channels, without channel-assembling, and aggregating all vacant channels whenever a SU is admitted into the network [30]. In [8], two channel assembling strategies called RBS and IBS in a dynamic wireless link featuring adaptive code and modulation (AMC) were proposed. In the IBS scheme, if a SU cannot assemble the required channel-slots, it is instantly blocked. Similarly, if the PU arrives and randomly selects from of the ongoing SU’s channel-slots, the SU is forced to terminate. RBS scheme is more flexible than the IBS in the sense that if the SU assembles the required number of channel-slot and if PU arrives, instead of instant blocking, the SU will adjust down the number of channel-slots it has aggregated and keep probing for other PU free channels. Finally, both schemes took into account the dynamics of the wireless-link featuring AMC which was not considered in most investigations.

The systematic framework to analyse the performance of the CAS is developed and applied in this research work. In [94], a variable and constant CA scheme were proposed. The performance analysis of both schemes for wideband CRN was evaluated. In the variable scheme, the amount of spectrum resources a SU is assembled depends on probability distribution and the number of the residual channels that are vacant. Studies in [95] extended the investigation considering imperfect sensing for wideband cognitive radio networks. This research [6] therefore develops and compares through simulation study, two channel assembling strategies which are the IBS and RBS in a single class SU traffic on a dynamic wireless link. As [96] investigated CA for elastic data traffic with spectrum adaptation, it proposed two new policies namely, the *Greedy* and *Dynamic* strategies respectively. In the greedy strategy, a SU will continue to aggregate channels up to its upper bound if channels are available at the time it gained access. This will continue as long as channels are available. If PU departs and more channels become vacant, it keeps grasping more until it gets to the upper bound. In the dynamic policy, SU responds in the similar manner as in the greedy policy.

But, if a SU appears and there are inadequate vacant channels, instead of blocking, ongoing SU services will share their occupied channels with the new arrivals as long as it has the minimum channels required to commence and sustain its transmission after sharing as [97] incorporated a queuing technique into CA. In their study, when there are no idle channels available, or the PU interrupts the SU transmission, the SU service is queued instead of blocking instantly or forcibly terminating it. A different and seemly more robust method was proposed in [98], where channel assembling and fragmentation (CAF) strategy was combined. In this strategy, SUs is allowed to adjust the currently used channel-slot with respect to the spectrum opportunity and traffic load. Precisely, if there are low network load and sufficient vacant channel-slot existing, then the SUs will occupy the spectrum and deploy CAS to optimize the throughput (service rate). Else, the channels are split so that, several SUs could benefit. In CAF policy, both CF and CA are implemented adaptively. Whereas CA delivers a high throughput and exploits the spectrum resources optimally, channel fermentation ensures that the blocking and force termination probabilities are kept at minimal. Another approach to channel assembling strategies is the incorporation of a queuing regime.

This is found in [7], [9] [24], [97, 99, 100] . In their work, queue is introduced so that SU traffic that would have been forced to terminate or blocked are queued in a buffer and possibly served later. Therefore [24] proposed and compared three channel assembling strategies in multiclass SU traffic scenarios considering the varying nature of a dynamic wireless link with AMC. This proposed scheme is evaluated through a simulation study without detailed analysis. In [97], the author incorporated queuing technique into channel assembling strategies proposed in [4], [5], [30] models. In their work, the secondary users' traffic is classified as elastic and non-elastic. Higher priority is given to the non-elastic users because of the delay sensitive traffic unlike the elastic traffic with lower priority. However, the non-elastic users access the channel first and will not be fed-back into the queue unlike the elastic user's traffic which has the flexibility of being queued whenever it is interrupted by the PU. This approach improves system performance items of: forced termination, spectrum utilization, network capacity, blocking and access/admission probabilities but at the expense of mean total delay especially for the SU elastic.

In [99], the simulation framework and theoretical model was developed using CTMC introduced queuing technique into CA and fragmentation (CAF) policy for spectrum access. Their work extends the CAF policy of [98], by proposing a second queuing technique. They presented the CAF with queuing policy in which a buffer is assumed to accommodate pre-empted SUs. With the help of the buffer, whenever an SU is pre-empted by PU arrival, it would otherwise wait in a buffer to be served later. In as much as sufficient vacant channels resurface before the waiting time elapse, the SUs could reclaim the transmission opportunity else, the SUs will be dropped-off from the buffer. This has shown to improve the dropping probability of the SU. The impact of CA and CF for SU flows by proposing a channel access strategy which integrates both CF and CA was studied by [101]. Their investigation reaffirms the fact that higher network capacity and throughput could be attained by deploying CA and CF jointly.

2.5 Conclusion

In this chapter, a survey/overview of the research paradigm called cognitive radio networks was presented. In the same vein, what makes it cognitive is embedded in its capabilities to: (1) intelligently sense the primary user's channel to avoid collision (interference) using appropriate sensing techniques; (2) dynamically and opportunistically access the primary user's spectrum before the PU arrives (overlay) or coexist with the PU with limited interference (underlay); (3) make decisions based on both its radio environment and neighboring users; (4) centrally or otherwise share spectrum resources among each other to avoid starvation of weaker users; (5) hop to another free channel/spectrum if it cannot coexist with the PU and (6) assemble/aggregate spectrum resources (white space) across frequency and time domain to improve SU transmissions as shown in Figure 2.7. The essences of cognitive radios are to identify and use PU's resources optimally. But, this identification and reuse of the PU resources is made possible by capitalizing on its erratic ON/OFF behaviours across the spectrum. The next chapter investigates the various assumed or commonly characterized ON/OFF behaviours and it impacts on SU performance in cognitive radio networks.

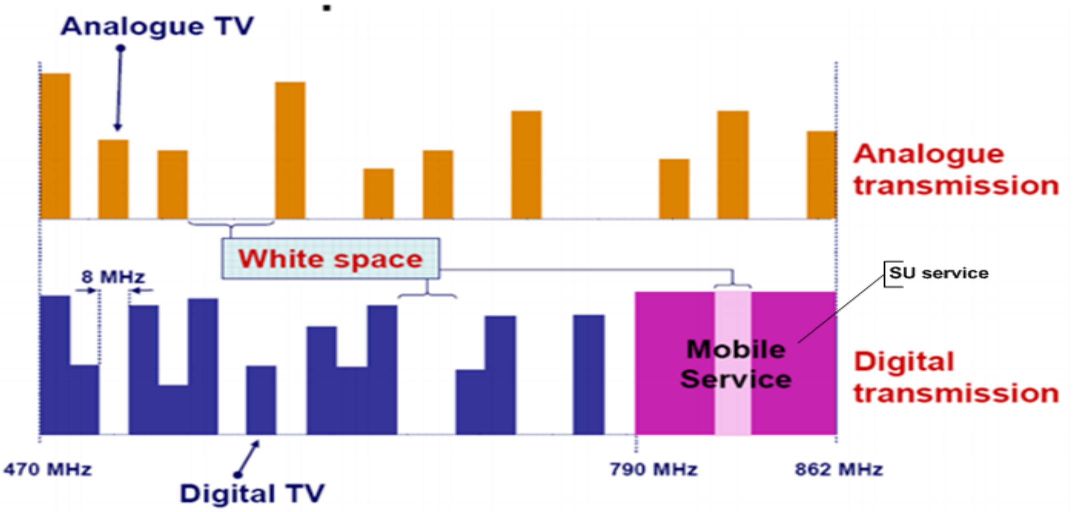

Figure 2.7 Aggregating of TV white space (spectrum holes) for SU services

CHAPTER THREE

Primary Users ON/OFF Behaviour and Its Impact on Secondary User Channels in Cognitive Radio Networks

In the previous chapter, the PU behaviour has been characterized as ON/OFF. This behaviour has resulted in the inefficient usage of the scarce spectrum resources. In this chapter, two important aspects of cognitive radio network will be discussed and thus, this chapter is divided into two parts. The first aspect investigates the primary users ON/OFF behaviours while the second part focused on the interaction impact caused by the PU on the secondary channels in a centralized cognitive radio network using an overlay performance analysis. The first part investigates and compares the commonly assumed ON/OFF behaviours while in the latter part, an analytical approach was proposed to analyze the opportunistic spectrum access strategy (OSAS) with different occupancy statistics [34], [102], [103]. The average service time, throughput and time delay were the metrics used for the performance evaluation.

Part one is organized as follows: In section 3.1, introduction and related works are presented. System description and investigation of the PUs ON/OFF behaviours is described in section 3.2. Three primary users ON/OFF distribution are discussed section 3.3. The simplified flow chat/algorithm of the various primary users ON/OFF behaviours is presented in section 3.4 while numerical results and discussion is found in section 3.5. Part one of this chapter is summarized in section 3.6.

Part two of this chapter is organized as follows: introduction and closely related works are presented in section 3.7 and 3.8 respectively. System/network models and assumptions are presented in section 3.9. System analytical model is found in section 3.10 while performance measures are discussed in section 3.11. System algorithm/flow chart is in section 3.12. Numerical results and discussions are presented in section 3.13 while the investigation is concluded in section 3.14.

3.1 Introduction

Recent research has established that part of the cause of spectrum scarcity is the underutilization of some spectrum bands (licensed band) [104] . However, this is ascribed to PUs ON/OFF behaviours, giving rise to TVWS. In this regard, cognitive radio technology (CRT) was recommended as a model for identifying and utilizing of TVWS across domain. This is made possible through the deployment of a dynamic spectrum access (DSA) scheme which is another promising access strategy for reclaiming some of the licensed spectrum that is not optimally unused [17], [25]. In addition, CRT has been proposed to deploy OFDMA system for spectrum access, while OFDM for resource distribution and interference cancellation/avoidance, sensing that the PU activities are imperative. This is to ensure good performance for both the PUs and the SUs. Thus, understanding and predicting the statistical behaviour of the PUs is also a key to a reliable and effective sensing process. The behaviour of PUs has been modelled as: ON/OFF Markovian, exponential and geometric respectively [37], [105, 106, 107, 108].

This part of this thesis focuses on investigating the PUs activity in relation to these three commonly assumed distributions. Also, to evaluate and establish which of these is/are relatively stable, so as to give the SUs the opportunity to utilize the OFF or idle channel- slots since this is of utmost concern to the SU. Since it has now been established that CRT is an efficient means to maximize bandwidth for next generation networks, coupled with the fact that radio resources are facing scarcity owing to speedy growth in multimedia application and service [105], [109]. Then, there is need to investigate and compare the commonly assumed PUs ON/OFF distributions which this part of the thesis has achieved. The essence is to establish the level of available and stable of spectrum resources in terms of unused/idle channel-slots based on the distributions.

In Markovian process, two factors determine the ON/OFF states. They are: the state probability matrix and the state transition matrix [110]. While the exponential ON/OFF process is a random process which depends on ON/OFF mean time , the mean time determines the ON/OFF duration (how long), thus, serving as input to the function for generating random ON/OFF period thus, depicting a typical PU behaviour [37]. The geometric ON/OFF distribution is a stochastic process which depends on the probabilities of the ON/OFF epoch [108]. The contribution of this research work gives insight into spectrum availability pattern in different ON/OFF activity models (distribution).

3.2 System Description and Investigations

In this investigation, ON/OFF activities of the PUs have been generally assumed in literatures as exponential, Markovian or geometric. However, in this investigative study, we considered various behaviours across a time-slot to evaluate the distribution with the better/stable capacity of OFF slot (resources) which is of importance to the SUs. The three assumed ON/OFF behaviours is chosen because; it is the most common description of PUs behaviour in communication system [108], [111], [112], [113]. Individual channel is structured in slots and as such, slots are created across each channel as shown in Figure 3.1. The PU ON/OFF alternation occurring in these slots are shown in Figure 3.2. The slot state of the m^{th} channel in a time t is given by $\delta_m\,(t) \in 1(idle), 2(busy)$ for all the three (exponential, Markovian process and geometric) processes. In the Markovian process for example, the probability matrix $P(i,j)$ guides the transition of the ON/OFF or idle/busy state.

Where $$P(i,j) = \begin{pmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{pmatrix} \tag{3.1}$$

However, this can be expressed as, $$P(i,j) := Pr\{\delta_m(t) = j | \delta_m(t-1) = i\} \tag{3.2}$$
Then, P being the conditional probability distribution follows that,

$$\sum_{j \in \delta_m} P(i,j) = 1 \tag{3.3}$$

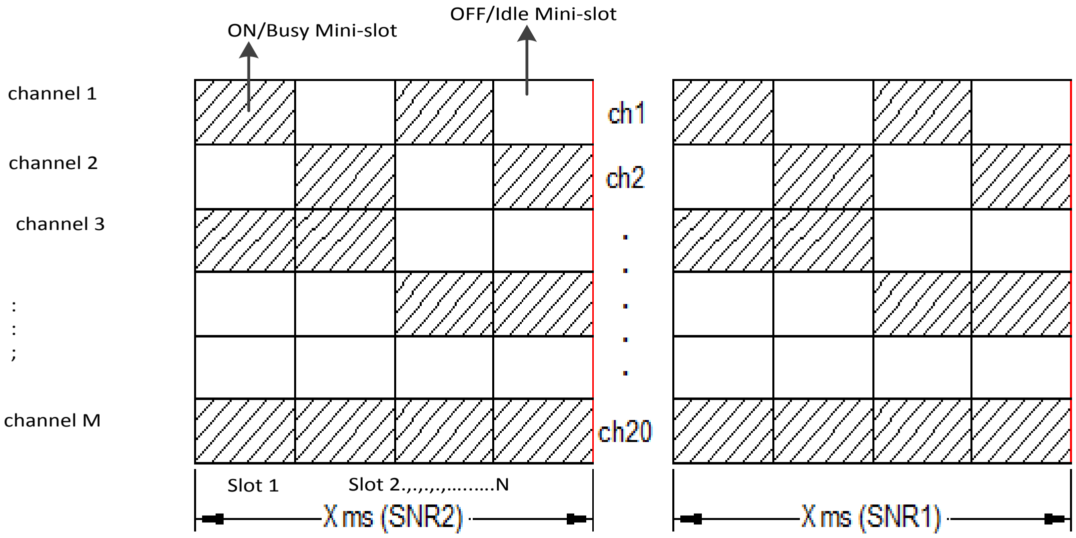

Figure 3.1 An ON/OFF PU frame structures

3.3 Primary Users ON/OFF Processes

Investigations have shown that the incumbent (PU) are often TV band whose activities periods are reported [108], [111], [112], [113]. However, PU activity is modeled as: Busy/Idle Markovian procedure source, interchanging between ON and OFF states. The ON/OFF processes are commonly assumed as ON/OFF Markovian, ON/OFF exponential and ON/OFF geometric. Thus, the ON/OFF channel pattern specifies a time frame in slot that a PU is present or absent. Once mastered, this erratic behaviour of the PU, the SUs can then logically aggregate the idle slots in and used it for transmitting its data within a time frame as shown in Fig 2.3, 2.7, 3.1 [36]. Moreover, the conventional pattern of PUs is not uniformly distributed all the time as commonly assumed since the PUs has diverse choice of channel. For instance, in the IP TV system, while the band of a certain IP TV station is stable, several bands of wireless TV are idle. These idle frequency bands could then be utilized by the SUs.

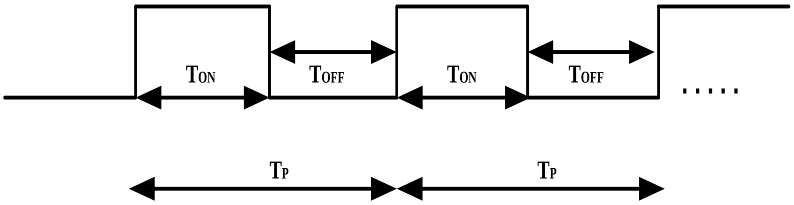

Figure 3.2 A Busy/Idle pattern of PUs

3.3.1 Markovian ON/OFF Process

The Markovian ON/OFF process is guided by two factors which are the state transition matrix and state transition probabilities [107], [108]. Nevertheless, state transition matrix and the state transition probabilities remain constant for the similar distribution however the capacity of ON/OFF slot varies for a particular distribution as observed. Consider a scenario with M wireless channels Figure 3.1, where time is denoted as t and it take values from $(0,1,2\ .\ .\ .N)$. Thus the PU behaviour is modeled as a Busy/Idle, two-state Markovian process with state space 1 and 2 representing a typical discrete time model as shown in Figure 3.1 and Figure 3.2. It is assumed that the state transition takes place at the borders and the transition matrix of the Markovian process is given by [110].

$$P = \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix} \tag{3.4}$$

1 represents OFF/Idle state which means the spectrum is not been occupied while 2 represents ON/Busy state depicting spectrum occupancy. The likelihood of transition from state i to state j is characterized as P_{ij} or $P_{j,i}$ otherwise as shown in Figure 3.3. The CDF of the ON period in equation (3.5) [110] as

$$T_{ON}(n) = \lim_{n \to N} \sum_{\substack{i=n \\ n=\{1,2,\ .\ .N\}}}^{N} P_{21}\, P_{22}{}^{i} \tag{3.5}$$

For n discrete time-slots up to N frames, the function T_{ON}, gives the probability that a PU is Busy for length of n or more. Likewise, the CDF for the idle state interval is (3.6)

$$T_{OFF}(n) = \lim_{n \to N} \sum_{\substack{i=n \\ n=\{1,2,\ ..N\}}}^{N} P_{12}\, {P_{11}}^{j} \tag{3.6}$$

Where P_{12} and P_{21} are the transition probabilities from state 1 to 2 and 2 to 1 respectively, as shown in Figure 3.3. Let $\varphi = (\varphi_1, \varphi_2)$ be stationary probability vector of matrix P.
Then, $\varphi P = \ \Phi$ and $\varphi_1 + \varphi_2 = 1$. Therefore,

$$\varphi_1 = \left(\frac{p_{21}}{p_{21} + p_{12}}\right) \tag{3.7}$$

$$\varphi_2 = \left(\frac{p_{12}}{p_{21} + p_{12}}\right) \tag{3.8}$$

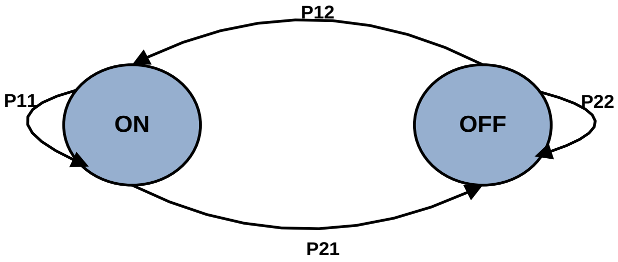

Figure 3.3 ON/OFF transition diagram

3.3.2 Exponential ON/OFF process

When the primary users' activity is described as ON/OFF with exponential distribution, it simply means that the PUs will be ON for a time period and OFF for the remaining time. It furthermore implies that a time t, the PUs will be ON with an average mean ON-time (τ_{ON}) and at other time, it generates the OFF period with an average OFF mean (τ_{OFF}) . To determine the number of resources (mini-slots) in OFF or ON state that SUs have per time slots, we translate the exponentially generated time into time-slots. The duration of an OFF time, when the channel M is available for SUs, is modelled as a random variable T_{OFF}^{M} with PDF $f_{T_{OFF}^{M}}(x) > 0$. Likewise, the PDF of the interval of an ON period, when the channel is busy, is given as $f_{T_{ON}^{M}}(y) > 0$ [36].

$$\begin{cases} f_{T_{OFF}^{M}}(x) = \tau_{T_{OFF}}\, e^{-\tau_{T_{OFF}} x}\,(x) \\ f_{T_{ON}^{M}}(y) = \tau_{T_{ON}}\, e^{-\tau_{T_{ON}} y}(y) \end{cases} \tag{3.9}$$

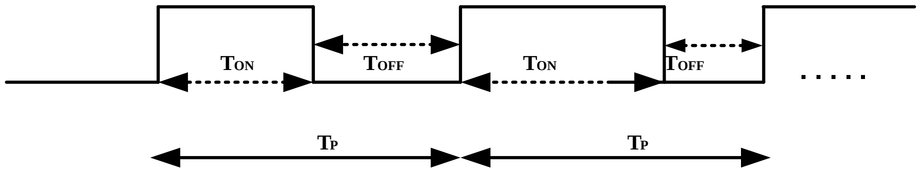

Figure 3.4 Exponential ON/OFF transition diagram

Where $T_{ON} + T_{OFF} = T_P$ represents one complete period of a cyle. Also, $T_{ON} \sim f_{T_{ON}}(y), y > 0$ while $T_{OFF} \sim f_{T_{OFF}}(x), x > 0$. Let the time for OFF (Idle) frame and ON state as generated by the ON distribution in eq.3.10 be T_{OFF} and T_{ON} respectively. The number of mini-slots N_{ON} in ON state can be estimated as,

$$N_{ON} = \frac{\lim_{n \to N} \sum_{n=i}^{N} T_{ON}}{T_B}$$

$$N_{ON} = \frac{\lim_{n \to N} \sum_{n=i}^{N} \{T_F - T_{OFF}\}}{T_B} \tag{3.10}$$

Similarly, if T_{OFF} represents time for OFF frame as generated by the Idle (OFF) CDF in eq.3.11, and T_B denote the duration for ON or OFF slot assuming both to be identical. Then, the number of mini-slots N_{OFF} in Idle (OFF) state can be express as

$$N_{OFF} = \frac{\lim_{n \to N} \sum_{n=i}^{N} T_{OFF}}{T_B}$$

$$N_{OFF} = \frac{\lim_{n \to N} \sum_{n=i}^{N} \{T_F - T_{ON}\}}{T_B} \tag{3.11}$$

3.3.3 Geometric ON/OFF process

In the geometric process, the duration of successive ON and OFF periods is time independent. However, these two periods are determined by their respective probabilities $P_{r(ON)}$ and $P_{r(OFF)}$. This in turn, account for how often each (ON or OFF Period) occurs. Consequently, how far they spread out is captured by their variances which alternatively are accounted for by their standard deviation or the square root of the variance. Moreover, standard deviation is one of the factors used to evaluate the stability of the three commonly assumed PUs ON/OFF activities. Statistically, geometric distribution follows the general notation,

$$\begin{cases} Pr(x,y) = p(1-p)^{x-1} \; general \;\; form \\ \qquad P_{rON}(x) = p(1-p_{OFF})^{x-1} \\ \qquad P_{roFF}(y) = p(1-p_{ON})^{y-1} \end{cases} \tag{3.12}$$

Where $P_{r(ON)}$ and $P_{r(OFF)}$ are probability of ON and OFF respectively.

3.4 System Algorithm/Flow-Chart for the ON/OFF Processes

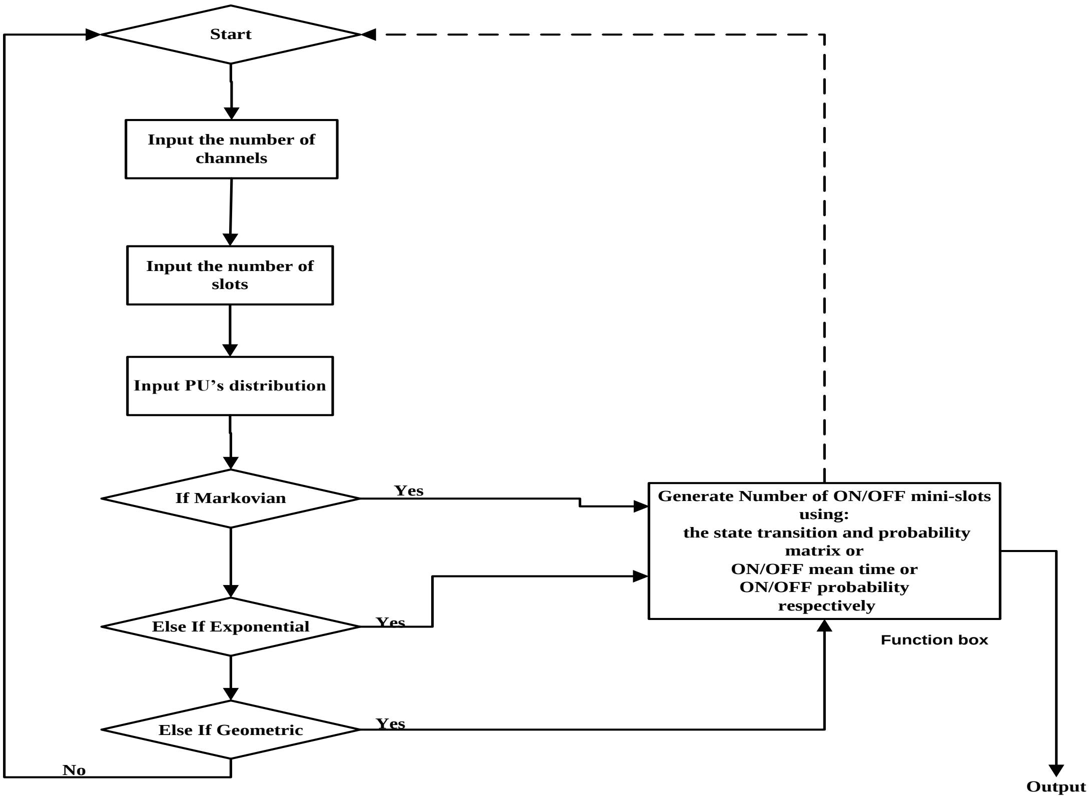

Figure 3.5 System Algorithm/Flow-chart

Figure 3.5 illustrates how the algorithm (simulation set-up) generates this behaviour of the PUs. As stated, the number of sub-channels and time-slot combination form a matric like structure. Figure 3.1 and each representing the ON or OFF mini-slots. The function box generates (output) any of the behaviours after all the basic parameters (number of channels, number of slots and so on) has been inputted. From the output, the results are shown is in the next section.

3.5 Numerical Results and Discussion

The numerical results and discussions are presented in this section. The simulation was ran using Matlab and excels tools. In the simulation, the parameters are configured as follows: state transition matrixes = $[0.8866, 0.1134; 0.5309, 0.4691]$, state probability matrix$=$ $[0.824; 0.176]$, number of channels $=$ 10 , time-slot $=$ 10, number runs $\equiv$ number frames 100, mean ON time = 0.5, mean OFF time = 0.5. Probability for ON-OFF period = [0.5, 0.5]. The results in Figures 3.6, 3.7 and 3.8 show the percentage availability of ON/OFF state in geometric, exponential and Markovian ON/OFF process respectively. Figures 3.6 and 3.7 are similar in behaviour however, in Figure 3.6; the highest ON period is 62% while the highest OFF period is 59% showing that the SU must deploy a robust/intelligent sensing technique to avoid interference with the PU since PUs are busier in the spectrum. In Figure 3.7, the highest ON period is 66% while the highest OFF period is 55% depicting similar scenario in 3.7 and as such, same measure will follow to avoid inference and other factors like packet blocking/dropping. However, Figure 3.6 has more OFF period of 3% higher that Figure 3.7 which is very significant to the SU since it does not own any spectrum of its own. Figure 3.8 shows 27% and 98% ON and OFF period respectively which is quite higher than that in Figure 3.6 and 3.7. In Figure 3.9, the result indicates that the mean OFF/ON time for Markovian process (OFF/ON- time (M)) is a better preference for SUs since it has higher average OFF time than the geometric (OFF/ON- time (G)) and exponential (OFF/ON-time (E)) process respectively. Though, geometric and exponential, OF/ON process are similar with little behavioural deference in mean and standard deviations.

Thus, since what is of utmost important for the SU is the OFF period (OFF time slot) the Markovian process will be better for any cognitive users (SUs) due to wide window period of exploiting the unused/idle PU resources. Markovian process is relatively reliable and stable based on investigation with the following premises:

- It has a standard deviation of 4.6139 which is lesser than geometric and exponential process with 5.6617, 6.1967 respectively at equal runs.
- The investigation agrees with [36], [107] and [110] views about Markovian behaviour.

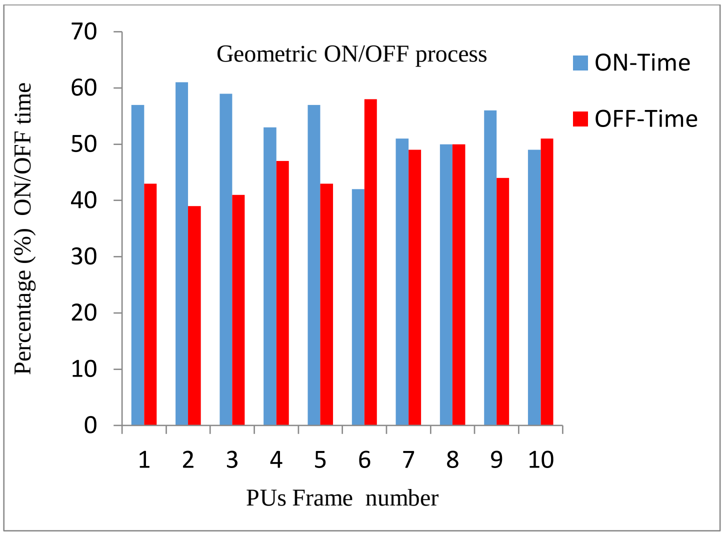

Figure 3.6 Percentage (%) time vs PU frame number

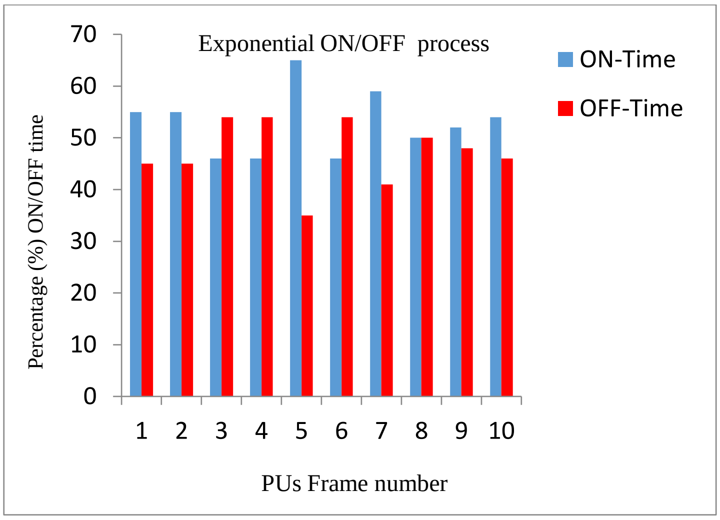

Figure 3.7 Percentage (%) ON/OFF time vs PU frame number

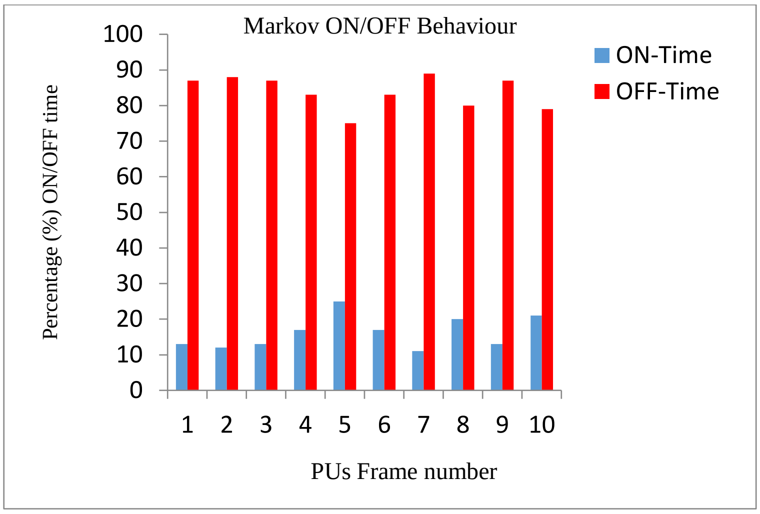

Figure 3.8 Percentage (%) versus Slot number

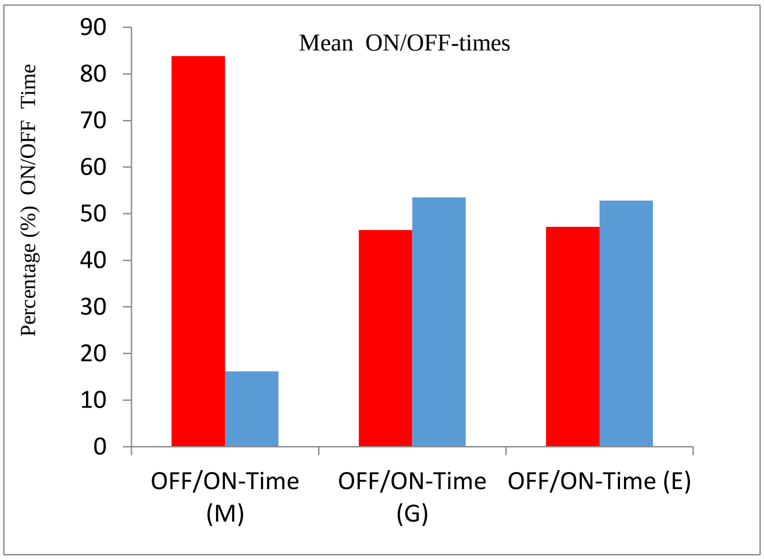

Figure 3.9 Percentage (%) ON/OFF versus Mean Time

3.6 Conclusion

The first part of chapter three investigates, evaluates and compared the commonly used/assumed PUs ON/OFF behaviours/activities illustration the behaviour being relatively stable in terms of OFF period, which is of importance to the SU. Also, it shed more light on the opportunities abound with the OFF duration which is of great importance to the SUs. Thus, it could be optimized by assembling them for improving SU data rate and reducing delays, blocking and forced termination of SU traffic. However, based on the percentage time, it was shown that ON/OFF Markovian process has less than 20% mean ON-time while geometric and exponential have 54% mean ON-time. This means that, more can be achieved when Markovian behaviour is assumed for PUs. If we have assumed a Markovian ON/OFF process/behaviour as the preferred process, the next section will dwell on the investigating the impact of the primary users' activity on secondary user's channels in cognitive radio networks. The second part of this work will focus on the impact of the primary user's behaviour (activities) on the SU's channel in a CRN.

Part II of Chapter Three

3.7 Introduction

CRN is an innovative model for solving the problem of spectrum underutilization associated with PUs. But this can be achieved through a dynamic spectrum access (DSA) scheme. The PU being the licensed owner, has higher priority on the channel while the SU access primary channel opportunistically at the time when the PUs is absent (idle). When the PU arrives and the SU is still transmitting it data, the SU either coexist as long as the interference is minimal or is forced to terminate (dropped). It could also be queued in a buffer if the interference is destructive. Nevertheless, if the PU arrives and enough channels exist, *how does this impact the SU performance in an overlay scenario?* This section investigates and evaluates the impact of the PU on the SU channels. In the first part of this chapter, the motivation for this study is to buttress what literatures have established on the quest for spectrum which has been rapidly on the increase in recent times. Furthermore, the wireless services/applications are rapidly gaining acceptance over the wired counterpart primarily due to their low cost, portability, accessibility and flexibility which in turn has exponentially increased the demand for licensed spectrum [114].

As a nimble and innovative model, CRN has introduced a concept shift that allows the opening up of the spectrum space to simultaneous operating users in a non-intrusive mode**.** Consequently, to make possible spectrum allocation without causing collision or harmful interference to existing traffics, SUs (cognitive users) should possess a minimum of information (ON/OFF statistics or behaviour) of the PUs. Depending on the knowledge that is needed to coexist with the primary network, cognitive radio approaches fall into three classes: Underlay, Overlay and Interweave [115]. Overlay and underlay are the two commonly used techniques in cognitive radio network, in a bid to optimally utilize the limited/scarce spectrum resources. Detailed study confirms that static spectrum sharing policy results to very low exploitation (around 7%) of the primary radio band most of the time [116], [117]. The residual slice of the unlicensed band is used up by these emerging services and application hence resulting to the problem of spectrum scarcity. Therefore, this calls for better spectrum management strategies [61], [117]. In order to better explore and exploit both licensed and unlicensed band, a promising approach which improves spectrum utilization, by dynamically allowing spectrum sharing amongst the SUs is proposed.

The SU uses opportunistic spectrum access (OSA) scheme to exploit the temporary unused spectral resources, by constantly probing the PUs band cooperatively. The sensed information (PU’s ON/OFF statistics) is collated by the fusion center or cognitive radio base station (CRBS) for possible decision based on the channel state and volume if the licensed channels available. Subsequently, managing large volume of unused spectrum resources becomes easier and more effective. The PU being the licensed users, unaware of the presence of the SUs and thus no pre-notice is given before it occupies its channel(s). This raises the question of; how will the SUs react or respond when the PUs arrives? This section investigates and analyzes the interactive effect of PUs on the SU network response in terms of throughput, average service time, delay and packet blocking etc. An extensive simulation with a carefully worked-out model using a simplified discrete time two states Markovian process to analyze the PU/SU spectrum occupancy on the premise of [118] is developed.

3.8 Related Works

The underutilization of spectrum under the current predetermined spectrum management policy has spurred many research works especially on DSA [53]. In [119], two cognitive MAC protocols for SU voice service were proposed. They are the contention free technique and contention based technique. In their study, a systematic model is introduced to find the voice-service capacity of the two techniques. Moreover, the effect of the PUs Busy/Idle pattern is taken into account for independent and correlated channel(s) respectively. [120] proposed an approximated model for un-slotted OSA networks under a non-saturated condition while a decentralized cognitive MAC (Cog-MAC) procedure that efficiently exploits the scarce spectral resources without affecting the features of PUs was proposed by [121]. The use of spectrum opportunities often requires stochastic approaches due to constraint in predicting their appearances. Their study describes Cog-MAC, a distributed MAC procedure that is built on the multi-channel preamble reservation policy.

The strategy adaptively picks a vacant communication spectrum by deploying a decentralized spectrum selection strategy and allows users to be totally asynchronous to one other. [122] extends the investigation of [121] by proposing Cog-MAC+ procedure for a distributed channel system. The idea is based on preamble set-aside system and CSMA standard. It attains akin transmissions for several SUs by allowing them to estimate the interval of channel occupancy of each users. In order to achieve the best sensing schedule, it also allows SUs to dynamically access channels according to the channel occupancy of PUs and other secondary networks. Moreover, Cog-MAC+ uses an adaptive energy detection scheme to dynamically set the energy detection threshold according to the carrier sensing flag, the false positive detection ratio and the predictable noise level. [123] proposed a new cognitive MAC protocol for efficient DSA based on full-duplex CRNs, where SUs are able to perform concurrent spectrum sensing and data transmission owing to full-duplex systems. Precisely, SUs can detect the collision during transmission, so as to reduce the collision time and improve secondary network performance.

In [124], a hidden Markovian system with state estimation for opportunistic channel access in CRNs was proposed. In their study, the primary spectrum structured in a TDMA mode with synchronized time-slots of identical interval and transiting between OFF and ON states respectively thus, the SUs uses them whenever they are vacant via spectrum sensing. Furthermore, their proposed strategies take advantage of state spectrum sensing, estimation and acknowledgments (ACKs) from the receiver for optimum usage. [125] proposed an effective DSA procedure to enhance channel usage and stable communications multi-hop CRN. In their study, the Pareto distribution model was adopted due to the characteristic of PUs behaviour. On this ground, SUs can precisely detect the spectrum-holes. Unlike the outdated access scheme, the acknowledgement information provides the stable delivery of data in multi-hop CRN. Besides, to realize the optimum spectrum usage, the graph model to analyze channel sharing was proposed. In the investigation, the various domain division multiplexing technologies were assumed to support their policies of spectrum distributions and adaptation. [126] proposed a MAC protocol for SUs which enables it to opportunistically utilize the unused PU spectrum.

In this proposal, period is on time slots basis and each time slot is of equal interval. However, the slot structured is in two phases which are the contention phase and the data transmission phase. The first phase selects a SU based on 802.11 standard with RTS/CTS mechanism. In the data transmission phase, the SU is allowed to occupy the time remaining after the contention phase thus, in the case of collision, a dynamic back-off strategy is deployed. [127] proposed DAS as a means to achieve both spectrum and energy efficiencies. In this investigation a secondary user can adaptively select a channel to transmit data when the channel is not occupied by any PUs. Alternatively, the SU can harvest RF energy for packet transmission when the channel is busy. The ideal frequency/channel selection policy of the SU can be obtained by formulating a Markov decision process problem. So far, the OSA has shown to be one of the reliable approaches to optimally utilize/access the PU channel without meddling or collision. In [128], a priority access scheme is proposed amidst the SUs. In their study, SUs are classifies as high and low priority classes respectively.

The high priority SUs are given access first while the low priority SU is buffered. In [118], the author presented a performance analysis for the OSA but did not consider a centralized model where the SUs are coordinated by a fusion center or cognitive base station (central controller) [103]. Delay, packet blocking and throughput as a performance measure were not considered in their performance measures. It is therefore worthy to note that this section of the thesis is an extension of the investigation in [102] with a simplified flow chart/algorithm with well-presented analysis, clearer and more detailed numerical results and discussion.

3.9 System Model and Assumptions

In this section, a centralized CRNs scenario where PUs' channel is sensed by SUs cooperatively is considered and shown in Figure 3.10. The sensed information is sent to the CRBS for decision and spectrum allocation. Based on the channel state information of the PU, the CRBS grants the SU access into the PU channel. However, if the PU is in idle state or not occupying the channel at a particular time, the SU becomes the owner. Based on the overlay system, it is likely to have two simultaneous communications in a given interference area, where normally only one transaction takes place at a given time. However, if the SU inference goes beyond a particular predefined threshold, the SU packet will have to be blocked/dropped to avoid destructive interference and possible collisions among users. The scope of this work did not border much on inference, as investigation on interference has been overemphasised in literature. Future work will possibly study the impact of inference on the SU performance with a comparative evaluation.

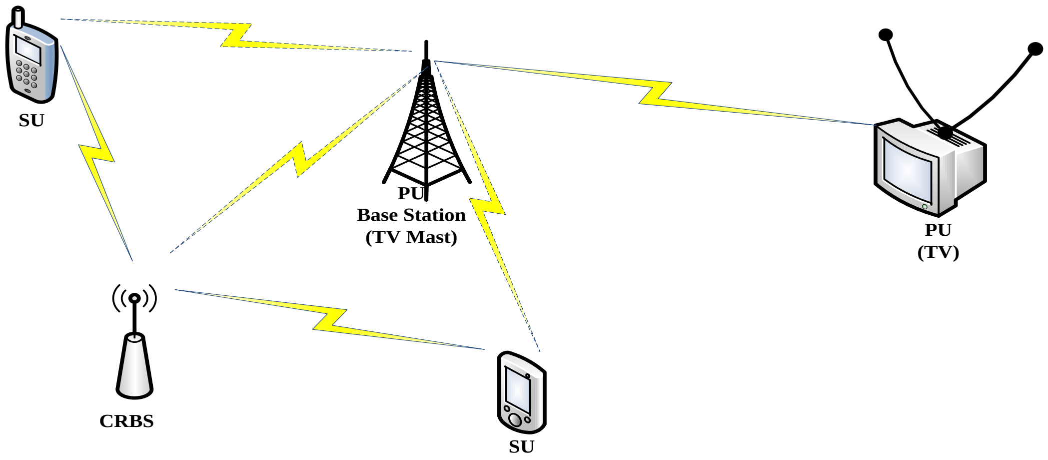

Figure 3.10 Network Model/Architecture

In this model, a single PU and SU channel respectively is assumed. The frame is apportioned in time-slots, and to each time-slot, the PU is either ON (busy) or OFF (idle). The PU is in busy state when it is transmitting and in OFF-state when it is not transmitting packets or when SU is using channel. Note that BUSY/ON and IDLE/OFF are used interchange respectively. The behaviour of the PU on the channel is modelled as a two state discrete Markovian process. A value 1 or 2 is assigned to the channel state if it is in busy or idle state respectively. It alternates from ON-state to OFF-state with probability Θ where $\Theta = P_{12}$ and stays in OFF-state with probability $\tau\ where\ \tau = P_{22}$. Figure 3.11 and 3.12 shows a transition diagram and the SU probing to transmit its packets. Furthermore, since we are investigating a SU scanning for spectrum opportunities in the primary channel, it is however assumed, that prior to sensing and gaining access to the PU channel, the SU initially harmonizes with the slot arrangement of the incumbent channel.

After PU channel is detected to be OFF, the SU can send its packets. However, if the channel-slot is busy, cognitive users are restrained from sending its packet to avoid interference or packet collision. Nevertheless, the cognitive users keep probing the channel-slot by keeping the packet to be sent at the beginning of the queue, and probe the channels again at the next slot, see Figure 3.11. The SU senses the primary channels at an average interval of l, consecutively per time-slot at start of a fixed line for a SU packet and for each slot beginning of the queue, $l \geq 1$ [118]. However, if a secondary user has not sent packet for l successive time slots, it will send in the next time slot to avoid collision.

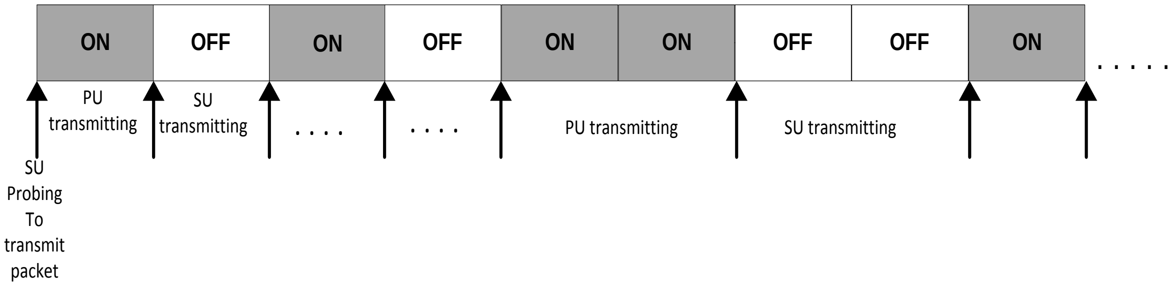

Figure 3.11 ON/OFF slots diagram showing SU probing and transmitting

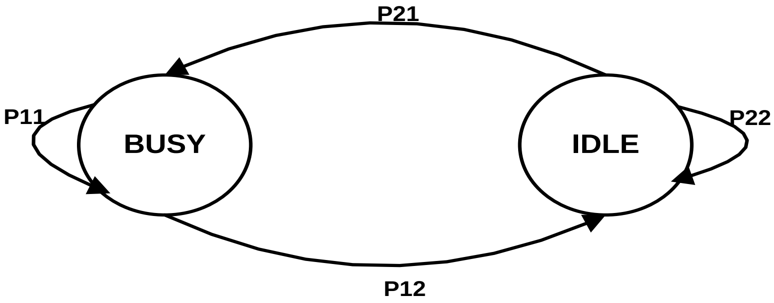

Figure 3.12 Markov transition diagram

The system assumptions are listed as follows:

- Accurate sensing of primary users' channel by the secondary users.
- The cognitive user operates under overload/saturation condition where packet is ready and waiting to be serviced.
- Centralized architecture where the cognitive radio based (CRBS) protocol does the coordination and management.

- The secondary users could be a real time traffic/users (packetized voice calls e.g. Skype, WhatsApp, Viber, etc.) or non-real time traffic (file downloading, browsing and so on).
- The secondary channel is dedicated to the SUs.

3.10 System Analytical Model

The system model is presented, and analysed by using a Hidden Markov Chain (HMC). For simplicity, fixed interval hidden points at the start of the time slot after a packet departs the queue as shown in Figure 3.12. However, to represent the order of hidden points, let $\{\phi_m, m = 1,2,3, \,.....\}$ be the order of the hidden points and $Y(\phi_m)$ represents the primary channel state at the m^{th} hidden point ϕ_m. Therefore,

$$\varphi_m \equiv \phi_{m+1} - \phi_m \tag{3.13}$$

Then, defining the two states as $\left\{\left\{\varphi_{m\,,} Y(\phi_m)\right\}, m = \{1, 2,3, \ldots\}\right\}$ as a birth death process whose behaviour is guided by the partial Markov kernel/transition matrix [118], [120], the generalized transition matrix kernel is expressed as

$$P_{i,j}\,(\psi) \equiv P\{Y(\phi_{m+1}) = j, \varphi_m = \psi |\; Y(\phi_m) = i\} \tag{3.14a}$$

For $i = 1, 2,\; j = 1, 2,$ and $\psi = 1, 2, 3, \;.\;.\;.\;., l, l+1$ the transition matrix kernel is expressed as,

$$P_{i,j} \;= \begin{bmatrix} p_{11} & p_{12} \\ p_{21} & p_{22} \end{bmatrix} \tag{3.14b}$$

Where

$$p_{11}(\psi) = \begin{cases} 1, & \psi = 1 \\ \left[\left(1 - \Theta\right)^{\psi-2} \Theta\,(1-\tau)\right], & \psi = 2, 3,.\;.\;.\,l \\ [\left(1 - \Theta\right)^{l-1} [\left(1 - \Theta\right)^{2} + \Theta\,(1-\tau)], & \psi = \;l+1 \end{cases} \tag{3.15}$$

$$p_{12}(\psi) = \begin{cases} 1, & \psi = 1 \\ \left[\left(1 - \Theta\right)^{\psi-2} (\Theta\,\tau)\right], & \psi = 2, 3,.\;.\;.\,l \\ \left(1 - \Theta\right)^{l-1} [\left(1 - \Theta\right)\Theta + 1 - \Theta\,\tau], & \psi = \;l+1 \end{cases} \tag{3.16}$$

$$p_{21}(\psi) = \begin{cases} 1-\tau, & \psi = 1 \\ 1, & \psi = 2, 3, . \ . \ . l+1 \end{cases} \tag{3.17}$$

$$p_{22}(\psi) = \begin{cases} \tau, & \psi = 1 \\ 1, & \psi = 2, 3, . \ . \ . l+1 \end{cases} \tag{3.18}$$

Hence, the transition probability from state 1 to 2 or $i \; to \; j$ respectively, for the Markov chain $\{ \, Y(\phi_m), m = 1, 2 \; 3. \; . \; \}$ is expressed as

$$p_{i,j} = \sum_{\psi=1}^{\iota+1} P_{i,j}\,(\psi)\,, \qquad i = 1,2, j = 1,2\,, \tag{3.19}$$

$$p_{11} = \left[(1-\tau) - (\Theta - \tau)(1-\Theta)^{l}\right], \tag{3.20}$$

$$p_{12} = \left[\tau + (\Theta - \tau)(1-\Theta)^{l}\right] \tag{3.21}$$

$$p_{21} = (1-\tau) \tag{3.22}$$

$$p_{22} = \tau \tag{3.23}$$

From the problem formulation, a discrete random variable is assumed. However, the conditional probability mass function (CPFM),

$$\delta_i(\psi) \equiv P\{\varphi_m = \psi | \; Y(\phi_m) = i\} \tag{3.24}$$

$i = 1,2, \;\; \psi = 1,2,3, \; . \; . \;\; l+1,$

For φ_m, given that $Y(\phi_m) = i$, it is expressed as,

$$\delta_1(\psi) = \begin{cases} 1, & \psi = 1 \\ (1-\Theta)^{\psi-2} . \, \Theta, & \psi = 2, 3, . \ . \ . l \\ (1-\Theta)^{\iota-2}, & \psi = \; l+1 \end{cases} \tag{3.25}$$

$$\delta_2(\psi) = \begin{cases} 2, & \psi = 1, \\ 1, & \psi = 1,2,3,\ \ldots\ \ l+1 \end{cases} \tag{3.26}$$

3.11 Performance Measures

Since the quality of service (QoS) is of concern, the performance metrics are defined as follows:

a) The Service Time

The service time is the duration required for a SU data to be effectively sent after been placed at the beginning of the queue at the inception. However, it is a function of the channel state as it moves to the beginning of the queue as shown in Figure 3.11. Let the state probability be π and the probability of the channel in state i will be π_i where $i = 1,2,$ then, the state of the PU channel when a SU packet moves to the head-of-line of the queue is expressed as

$$\pi_1 = \frac{p_{21}}{p_{12+}p_{21}} = \frac{[1-\tau]}{\left[1 + (\Theta - \tau)(1 - \Theta)^l\right]} \tag{3.27}$$

$$\pi_2 = \frac{p_{12}}{p_{12+}p_{21}} = \frac{\tau + (\Theta - \tau)(1 - \Theta)}{1 + (\Theta - \tau)(1 - \Theta)^l} \tag{3.28}$$

Having established that the state of the channel is $i(1)$ when the SU packet moves to the head-of-line position of the queue, the conditional probability that the service time of the packet ψ is precisely the same as the probability of $\delta_i(\psi)$. However, conditioning the state of the primary channel, the probability distribution can be determined for the service time μ of the SU packets. The probability $P\{\mu = \psi\}$ of the service time of a secondary user packet is expressed as:

$$P\{\mu = \psi\} = \pi_1\delta_1(\psi) + \pi_2\delta_2(\psi) \tag{3.29}$$

$$P\{\mu=\psi\}=\begin{cases}\dfrac{\tau+(\Theta-\tau)(1-\Theta)^{l}}{1+(\Theta-\tau)(1-\Theta)^{l}} & \psi=1\\[2ex] \dfrac{(1-\tau)(1-\Theta)^{\psi-2}}{1+(\Theta-\tau)(1-\Theta)^{l}} & \psi=1,2,3,..l,\\[2ex] \dfrac{(1-\tau)(1-\Theta)^{l-1}}{1+(\Theta-\tau)(1-\Theta)^{l}} & \psi=l+1\end{cases} \tag{3.30}$$

The average service time of the SU packet is expressed as

$$Z[\mu]=1+\frac{1}{\Theta}\cdot\left[\frac{(1-\tau)\left[1-(1-\Theta)^{l}\right]}{1+\left[(\Theta-\tau)(1-\Theta)^{l}\right]}\right] \tag{3.31}$$

b) Saturated Throughputs (T_p & T_s)

The saturated throughput T_p of the SU over the primary channel is defined as the number of secondary packets (data) successfully transmitted on the primary channel per time-slot. While the saturated throughput T_s of the primary users over the secondary channel is defined as the number of primary packets (data) successfully transmitted on the secondary channel per time-slot. Thus, the saturated (overload) throughputs T_p and T_s respectively can be expressed as,

$$T_p=\frac{1-P\{\mu=\psi+1\}}{Z[\mu]} \tag{3.32}$$

$$T_p=\left[\frac{\left[1+(\Theta-\tau)(1-\Theta)^{l}-(1-\tau)(1-\Theta)^{l-1}\right]}{\left[1+(\Theta-\tau)(1-\Theta)^{l}+(1-\Theta)^{\frac{1-(1-\Theta)^{l}}{\Theta}}\right]}\right] \tag{3.33}$$

$$T_s=\frac{P\{\mu=\psi+1\}}{Z[\mu]} \tag{3.34}$$

$$T_s = \left[\frac{\left[(1-\tau)(1-\Theta)^{\iota-1}\right]}{\left[1+(\Theta-\tau)(1-\Theta)^{\iota}+(1-\Theta)^{\frac{1-(1-\Theta)^{\iota}}{\Theta}}\right]}\right] \tag{3.35}$$

The secondary user total throughput $T,$ is defined as the number of secondary user packet successfully sent per slot, is expressed as,

$$T = T_p + T_s \tag{3.36}$$

$$= \left[\frac{\left[1+(\Theta-\tau)(1-\Theta)^{\iota}-(1-\tau)(1-\Theta)^{\iota-1}\right]}{\left[1+(\Theta-\tau)(1-\Theta)^{\iota}+(1-\Theta)^{\frac{1-(1-\Theta)^{\iota}}{\Theta}}\right]}+\frac{\left[(1-\tau)(1-\Theta)^{\iota-1}\right]}{\left[1+(\Theta-\tau)(1-\Theta)^{\iota}+(1-\Theta)^{\frac{1-(1-\Theta)^{\iota}}{\Theta}}\right]}\right]$$

$$= \left[\frac{\left[1+(\Theta-\tau)(1-\Theta)^{\iota}-(1-\tau)(1-\Theta)^{\iota-1}\right]+\left[(1-\tau)(1-\Theta)^{\iota-1}\right]}{\left[1+(\Theta-\tau)(1-\Theta)^{\iota}+(1-\Theta)^{\frac{1-(1-\Theta)^{\iota}}{\Theta}}\right]}\right]$$

$$T = \left[\frac{\left[1+(\Theta-\tau)(1-\Theta)^{\iota}\right]}{\left[1+(\Theta-\tau)(1-\Theta)^{\iota}+(1-\Theta)^{\frac{1-(1-\Theta)^{\iota}}{\Theta}}\right]}\right] \tag{3.37}$$

c) The Time delay

In this work, the delay is the interval between the time the SU packet is waiting at the head of line position to be served and the time the PU's channel turns OFF (transitions from ON state to OFF state). Though, the delay is obtained from our extensive system simulations.

d) Packet Blocking (ζ)

It is assumed that the SU packets can be blocked or dropped based on some conditions: when a PU arrives and there is no available slot for it or when a SU packet over stayed on the queue (head-of-line of the queue) waiting for time-slot to transmit its packet. Hence, can be expressed as the reverse of throughput,

$$\zeta = (1 - T) \tag{3.38}$$

$$\zeta = \left[1 - \left[\frac{1 + (\Theta - \tau)(1 - \Theta)^{\iota}}{\left[1 + (\Theta - \tau)(1 - \Theta)^{\iota} + (1 - \Theta)^{\frac{1-(1-\Theta)^{\iota}}{\Theta}} \right]} \right] \right] \tag{3.39}$$

3.12 System Algorithm/Flow Chart for the OSA Scheme

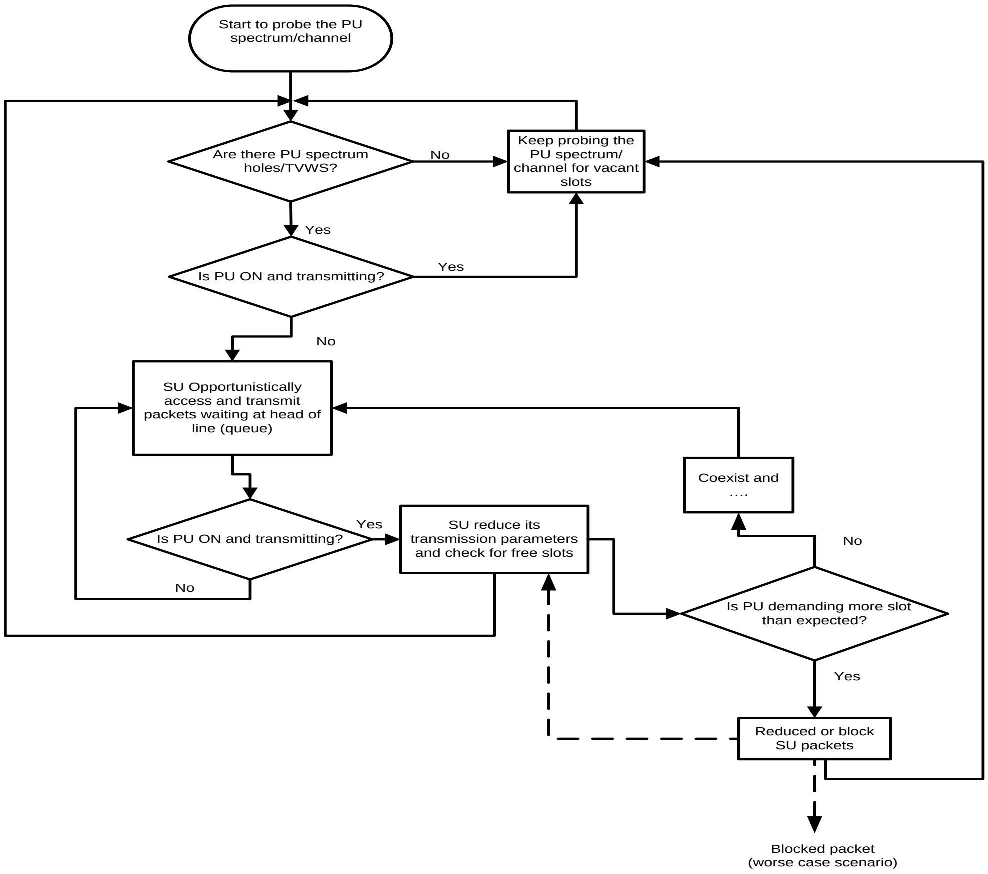

Figure 3.13 System algorithm/Flow chart

This section presents simplified system algorithm/flow chart of the system analytical model in section 3.9 and 3.10. The SU probes the PU's channel and file its packets at the beginning (head-of-line position) of the PUs' slot is shown in Figure 3.13. The adjustment and synchronization of the SU with the channel allows and ensures smooth transaction between the SU and the PU for opportunistic spectrum access. However, worst case scenario could occur which leads to packet dropping.

3.13 Numerical Results and Discussion

The section presents the numerical results and corresponding discussion to explicate the system performance. The results are built on hypothetical analysis and were validated with extensive simulations. Figure 3.14 shows the average service time under different statistics of the PU channels. With a high probability of 0.8 (the probability of the state remaining in the OFF/IDLE state), there are likelihood that there will be more time-slots in OFF state than ON state and as such, the average service completion time will reduce as compared to 0.5 and 0.2 respectively, which have relatively higher ON-state probability. It also implies that; SU packet transmission (service) will take more time to complete when fewer slots are OFF/IDLE and when many slots are ON/BUSY. However, a probability of 0.8 showed better performance than 0.5 and 0.2 as the time slot l varies from 1 to 20. Also, different traffic statistics of the primary channels have different performances, but saturate after a point along l. As l increases, the average service time of the SU packet increases and at a point remains constant which confirms the SU harmonization with the PU channel structure as previously indicated in the system model.

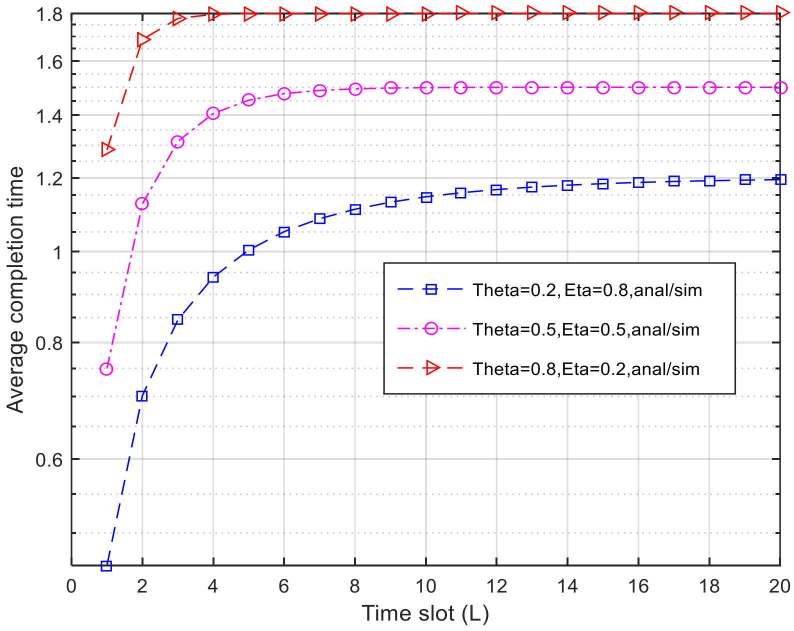

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Figure 3.14 Average Throughput vs time-slot

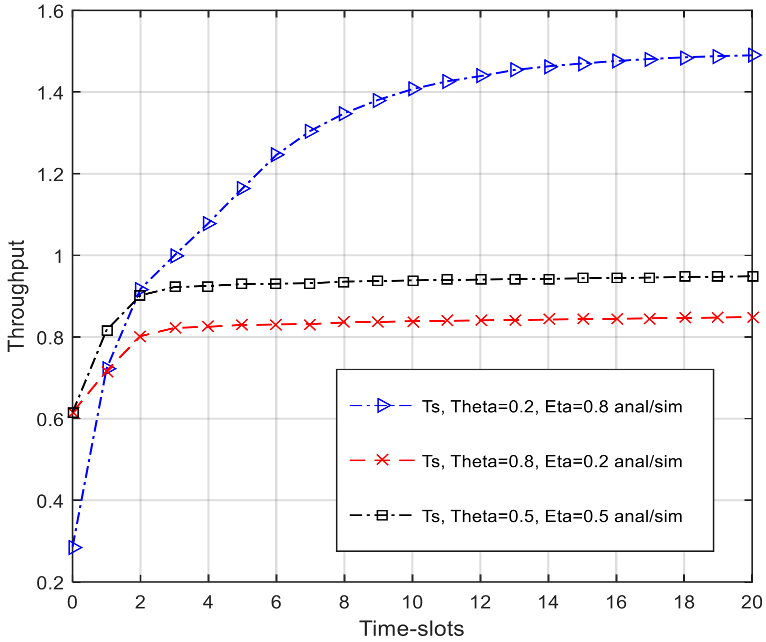

Figure 3.15 SU Throughput vs time-slot

In Figure 3.15, the throughput T_s of the primary users over the secondary channel shows that as l increases, the throughput (number of successful packet transmitted) increases irrespective of the occupancy statistics; though a probability of 0.8 implies that more packets were sent due to more slots being available for the PUs over the secondary channel. Closely followed in performance are 0.5 and 0.2 respectively. Nevertheless, the throughputs over secondary channel T_s get to saturation point as the timeslot further increases.

At a glance, the results presented in Figure 3.15, 3.16 and 3.17 respectively, demonstrates similar behaviours. This is due to emphasis on a metric (throughput) which is discussed in details but in different case study. The result in Figure 3.16 shows that the throughput T_p of the SUs over the primary channel increases irrespective of the occupancy statistics as previously stated. As T_p increases, time slot increases implying that, more time slots are available for more packets to be transmitted. However, a probability of 0.5 has a higher throughput than 0.8 and 0.2 respectively. This is due to the equal number of ON/OFF distribution depicting a relative stability or equal sharing of the time slots among the primary and secondary users respectively.

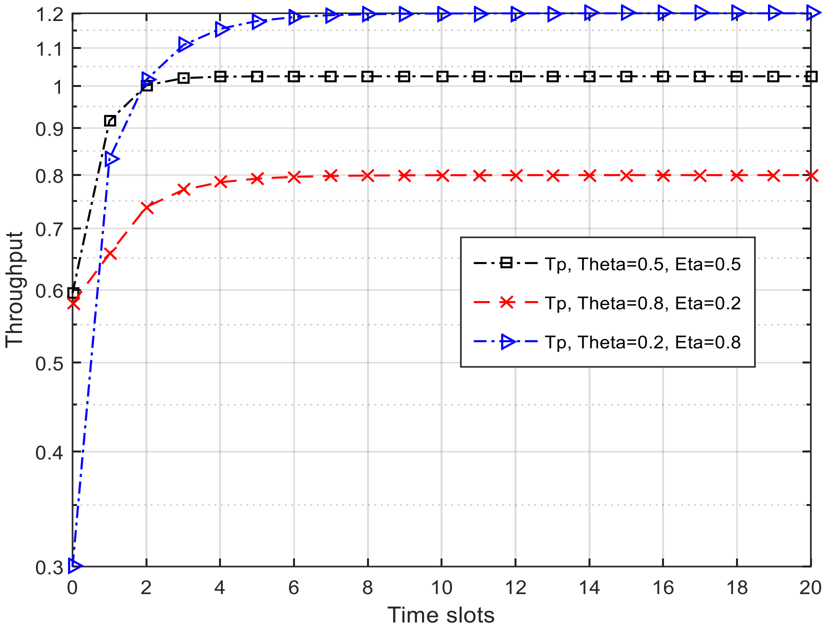

Figure 3.16 SU throughput Tp vs time-slot

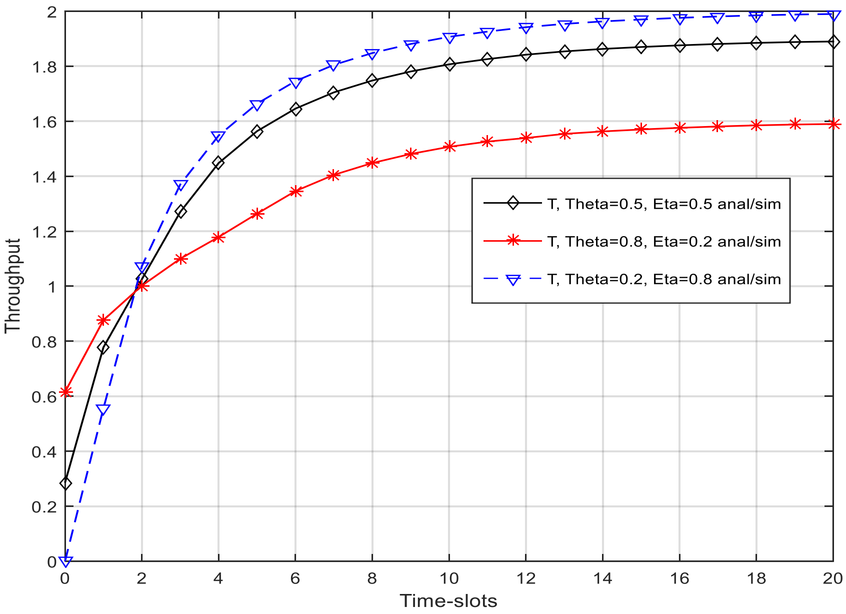

Figure 3.17 Total (PU/SU) Throughput vs Time-slot

In Figure 3.17, the result of the total throughput T which is a summation of the throughput of PU over the secondary channel and the SU over the primary channel respectively shows that as l increases, the total throughput (total number of successful packet transmitted) increases irrespective of the occupancy statistics. However, as estimated, a probability of 0.8 implies that more packets were sent due to more slots existing for the primary users over the secondary channel. Just as in Figure 3.15, closely followed in performance are 0.5 and 0.2 respectively due to established statistical facts.

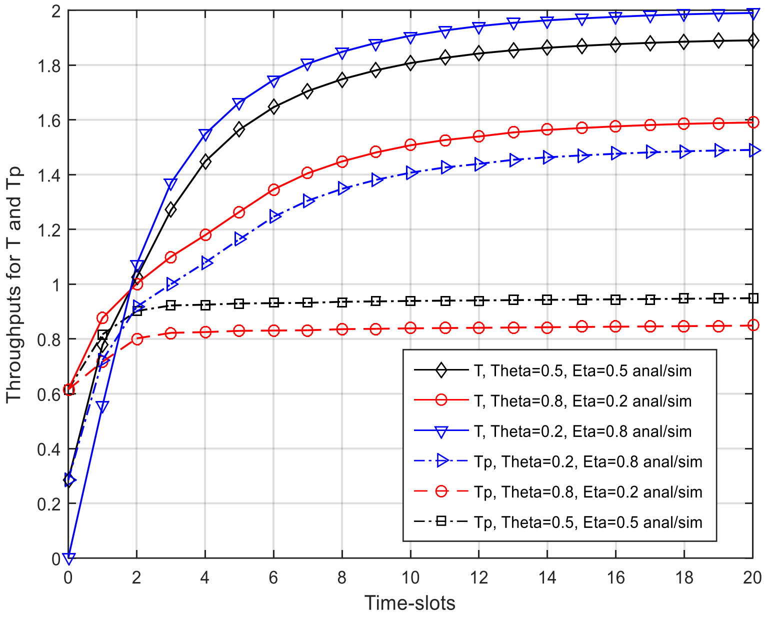

Figure 3.18 Throughputs (T and T_p) vs time-slot

Figure 3.18 is a partial comparison between the total throughputs T and that of the SUs over the PU channel. Since T is the summation of the respective throughputs T_p and T_s respectively, it is expected that the total throughput be higher than each individual throughput. For each of the occupancy statistics, T outperformed the other two (T_p and T_s). Similarly, the same goes for Figure 3.19 which compares the entire throughputs of the system i.e. T, T_p and T_s . The reason for this comparison is to have a clearer representation of the performance of the respective throughputs and also shows how the occupancy statistics has impacted on the system performance at a glance.

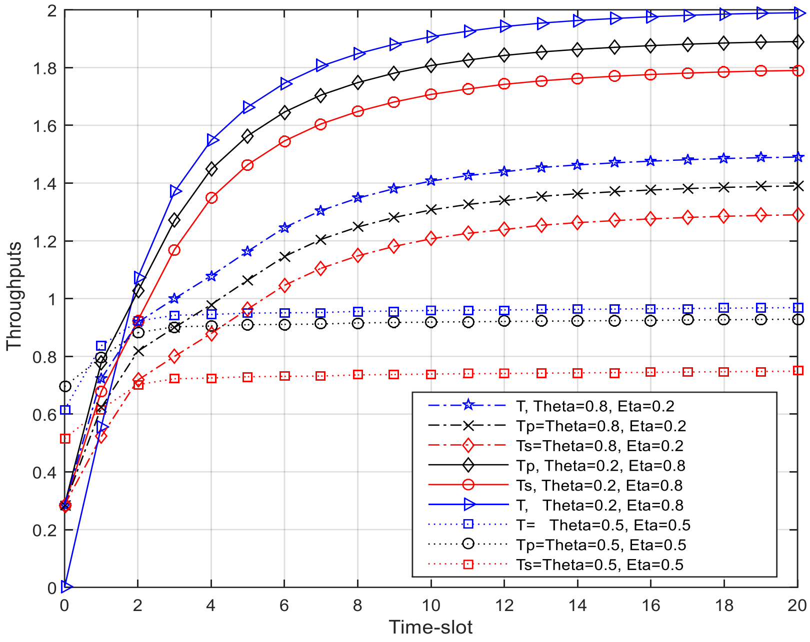

Figure 3.19 Throughputs (T, T_p and T_s) vs Time-slot

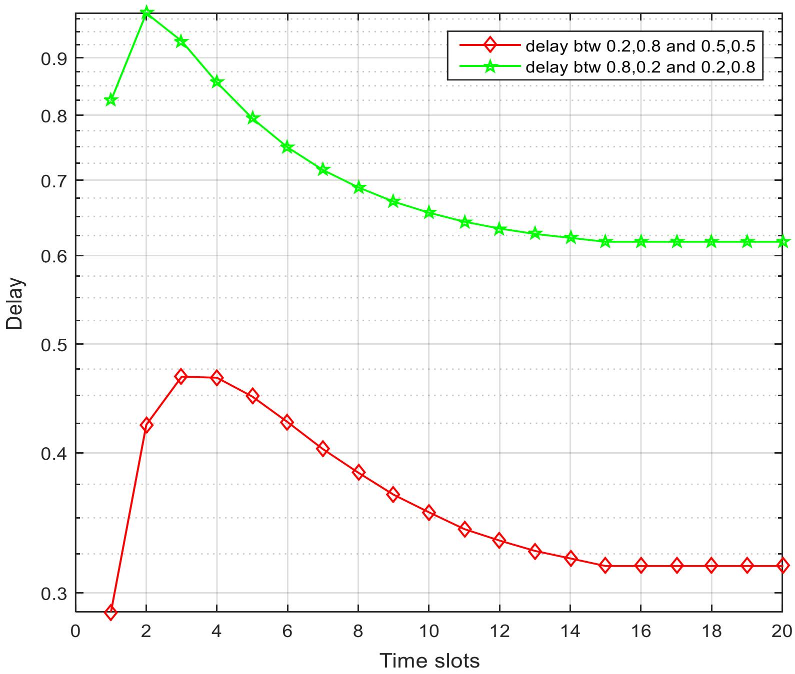

Figure 3.20 Time delay vs time-slot

Figure 3.20 shows the delays for each of the occupancy statistics as it transits from one state to another. From result, the delay increase to a point and after the synchronisation with the channel structure, it begins to reduce as more slots are available for the SU packets. A 0.2, 0.8 and 0.5, 0.5 (20% ON-slot, 80% OFF slot and 50% ON-slot, 50% OFF slot) occupancy statistics indicates that more OFF slots than ON slots are available. This implies that enough window periods exist for a secondary user to transmit its packet before a primary user arrives and as such, blocking/dropping of the secondary user's packet will be reduced at the same time. On the other hand, a 0.8, 0.2 and 0.2, 0.8 (80% ON-slot, 20% OFF slot and 20% ON-slot, 80% OFF slot) occupancy statistics indicates that, equal number of OFF slots and ON slots exist. However, in comparison, the first case shows lower delay statistics compared to the second occupancy statistics.

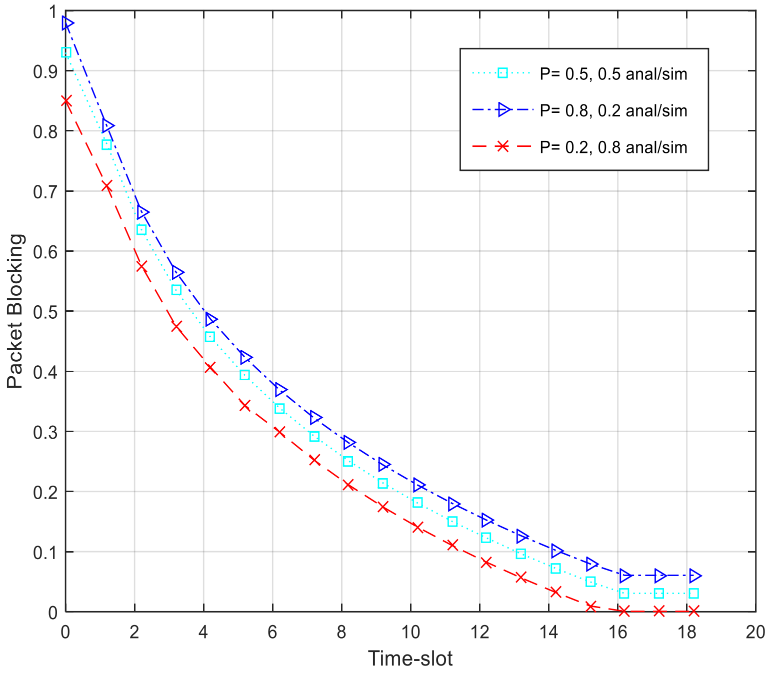

Figure 3.21 Packet blocking vs time-slot

Figure 3.21 shows the packet blocking for each of the occupancy statistics. A 0.2, 0.8 (20% ON-slot, 80% OFF slot) occupancy statistics indicates that, more OFF slots than ON slots exist. Therefore, a secondary user would transmit more packets before a primary user arrives and as such, blocking of the secondary user's packet will be reduced significantly. Conversely, a 0.8, 0.2 (80% ON-slot, 20% OFF slot) occupancy rate indicates that more ON slot that than OFF slots exist while a 0.5, 0.5 (50% ON-slot, 50% OFF slot) occupancy statistics shows that equal number of ON and OFF slots exist. However, the packet blocking reduced as more slots were made available. But by evaluation, 0.2, 0.8 statistics will create more opportunities for SU packet than 0.5, 0.5 and 0.8, 0.2 statistics respectively.

3.14 Conclusion

This section investigates the interaction-effect between the primary and secondary users on their respective channels through their ON/OFF statistics. The average service time, packet blocking, and throughput (T, T_p and T_s) were the basic metrics used for the performance measures of the OSA strategy. An analytical approach is proposed and developed to evaluate the performance of the spectrum access policy using different occupancy statistics. The analytical model was validated by extensive system simulations and both shows the enormous benefits of OSA strategy to SUs. The next chapter focuses on employing spectrum access/allocation strategies to ensure that the spectrum hole/TVWS (OFF channel-slot) that is identified across frequency and time domain are optimally used and reused by assembling/aggregation them for diverse users in cognitive radio networks.

CHAPTER FOUR

Performance Evaluation of Channel Assembling Policies with Single and Multi-Class Users in Cognitive Radio Networks

Since TVWS (spectrum-holes) are scattered across spectrum, it would be appropriate to employ spectrum allocation/coordinating strategies to ensure that these spectrum holes (OFF channel-slot) are organized for optimal usage by SUs. This chapter therefore investigates, proposes, develops and evaluates spectrum allocation strategies otherwise called channel assembling strategies (CAS). It is divided into two parts. The first part presents an evaluation of two channel assembling strategies with a single class SUs in CRN [6], while the second part extends the work done in the first part by the evaluation of the CAS with multi-class SUs in CRN [24].

The first part is organized as follows: In Sections 4.1 and 4.2, introduction and related works are presented respectively. System model and assumptions are formulated in Section 4.3 with two channel assembling strategies in Section 4.4. System model performance measures are described in Section 4.5 while numerical results and discussion are presented in Section 4.6. The first part of this chapter is summarized in Section 4.7. In the second part of this chapter, Sections 4.8 presents introduction while Section 4.9 discusses related works. System model is described in Section 4.10, and then three CAS are presented in Section 4.1. Performance measures are found in section 4.12. Numerical results and discussion are presented in Section 4.13 while the second part of this chapter is summarized in Section 4.14.

4.1 Introduction

CAS which allows several PU idle or unused channel-slots to be aggregated into combinations of usable SU channels has been deployed in CRN. Nevertheless, many of these schemes have been implemented without considering the varying nature of a wireless link that incorporates AMC in a CRN. Specifically, the essence of channel assembling in CRN is to maximize the scarce spectrum resources (spectrum holes) through a well-coordinated strategy and optimize SUs' throughput such that, before the PUs arrives, the SUs would have completed their ongoing transmission. Over time, research has established that frequency spectrums are the greatest assets in wireless communication systems. This is based on the fact that the existing licensed band are almost exhausted as a result of exponential growth in wireless applications and services both in multimedia and voice services [116], [129]. Studies have also shown that busty PU behaviour has been characterized as ON/OFF (utilizing and non-utilizing), given rise to unused spectrum holes in time and spatial domain.

In a radio network comprising of PU and SU, the PUs have high priority to use their spectrum while SU periodically probe to identify unused channels [130]. Based on the sensing outcome, SU tune their transceivers to communicate among themselves without interfering with the PU. However, the unused PU channel-slots need some organization to meet the demand of the SUs hence, the need for channel assembling. An efficient CAS must consider the PU performance models and quite a few of them were investigated in [34], [36]. Network traffic has evolved from simple to more complex scenarios such that, each SU requires different QoS at different SNRs. Hence, the need to assemble PU unused channel to improve SU throughput and capacity considering the varying wireless link. This section of the thesis develops and compares two channel assembling strategies (IBS and RBS) which incorporate the dynamics of a wireless link with adaptive modulation and coding (AMC) against No-assembling strategy (NA) in a homogeneous SU traffic. For emphasis, the amount channel-slot to be aggregated for a specific SU is a function of the SNR.

4.2 Related Works

Significant research works on CAS has been proposed in literature and they are aimed at developing novel schemes that exploits the scarce spectrum resources. In [4], CAS with various spectrum adaptation policies were proposed. The investigation proposed and develop two schemes which adaptively adjusts the number channel aggregated for ongoing SU traffic. In [94], two CAS for wide-band CRN which are: the variable and constant channel aggregation (VCA and CCA) schemes. In the VCA strategy, the number of channels a SU aggregates is a function of two factors which are: the probability distribution and or the number of the residual channels of the PU. In [5], a flexible CAS designed for non-homogeneous traffic environment was proposed. In their study, channel sharing and channel assignment occurs among real time and non-real time SUs. In [97], the authors introduced priority queuing in CA such that both real time SU and non-real SU are queued if no resources are available and served later. However, the essence of the priority queue is to ensure that real time SU are served first before non-real time SU.

More importantly, instant blocking of service resulting from non-availability of resources or forced termination of service resulting from PU arrivals will be reduced. Combined queuing based CA and channel fragmentation is proposed in [98], [99]. The protocol work in such a way that in any event of batch arrival of new SU, an already admitted SU with more channels can be split with its channel and share among other SUs. This is to accommodate other SUs which cannot tolerate delay. However, none of these strategies discussed so far considered the varying nature of a wireless link incorporating AMC. This work develops and compares through a performance evaluation, two channel assembling strategies which are: the immediate Blocking Strategy (IBS) and Readjustment Based Strategy (RBS) with single-class SU traffic on a dynamic wireless link.

4.3 System Model and Assumptions

In this section, an infrastructure based network architecture was considered comprising of a PU base-station (TV mast), CRBS and other SUs of similar classes using the same spectrum-band as illustrated in Figure 4.1. The licensed user (PU) has higher priority to use the channel and can interrupt the unlicensed users (SUs) at will regardless of the users using it as long as it not a licensed user. In this system model, it is assumed that all secondary users are identical and managed by the last in last out (LILO) protocol domiciled in the CRBS. The first SU*i* has higher priority than SU*j* in terms of spectrum access and thus can interrupt its fellow users if so necessary especially doing urgent network off-loading. This is to avoid network congestion and total collapse of the secondary network. Moreover, the licensed user (SU) utilizes the PU channels opportunistically through the deployment of any of the proposed schemes.

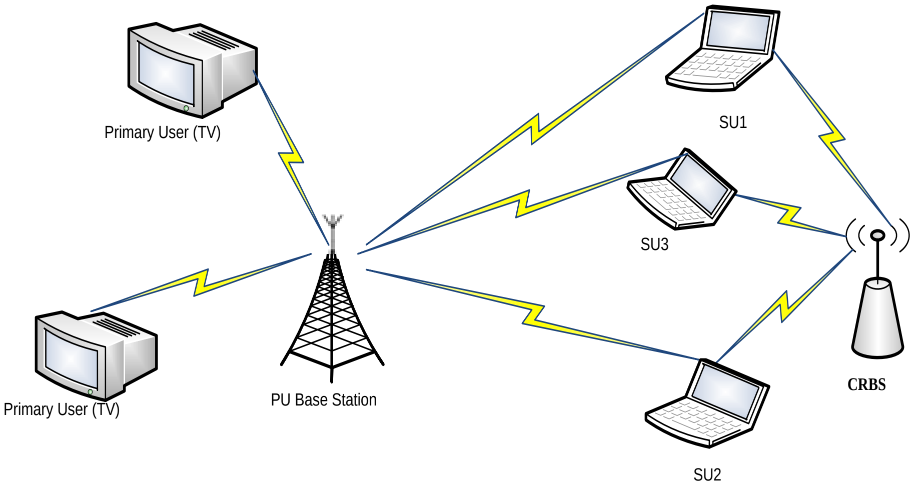

Figure 4.1 Network architecture/model with first come first serve regime

The primary network is made up of M channels however; each of the licensed channels is structured in frames with each consisting of β slots therefore making channel usage on a slot basis. The licensed user uses one channel per time whereas the unlicensed user intelligently aggregates several neighbouring or adjacent channel-slots in all spectrum domains. The wireless frame occupancy for PU Busy/Idle activities is illustrated in Figure 4.2. This dynamics of SU frame translates into a “heterogeneous system” with varying capacities hence requires a precise number of channel-slot and transmission rate pair. The CRBS makes the decision whether to block, drop or admit, the SU on the bases of resource availability as initiated by CAS. However, the SU capacity is a function of the wireless link conditions (SNR).

4.3.1 Wireless Channel Model and AMC

To depict dynamics of the wireless link, a more versatile channel model called “Nakagami- m channel model” was adopted. This is due to its ability to capture a wide range of fading characteristics of the wireless link. [6], [131].

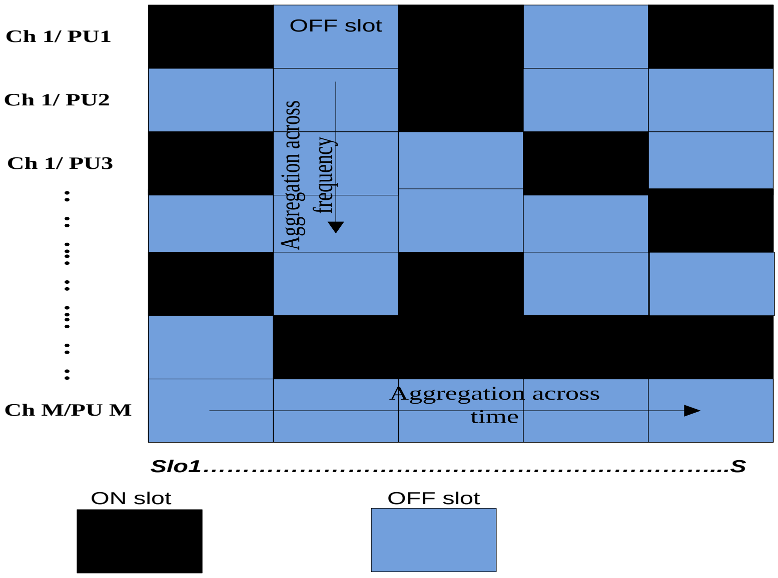

Figure 4.2. SU Wireless frame utilization schemes

The different conditions of the wireless link are characterized using a finite state Markovian process whose investigation and evaluation for fading is detailed in [132], [133]. However, the signal to noise ratio is sectioned “partitioned” bad, moderate and good link quality respectively as illustrated in Figure 4.3. Conversely, the modulation schemes for the IEEE 802.22 standardization was adopted from [23]. The transition matrix of the finite state Markovian process T_{Δ} is given by [133].

$$T_{\Delta} = [T_{ij}]_{(\kappa+1)\times(\kappa+1)} \tag{4.1}$$

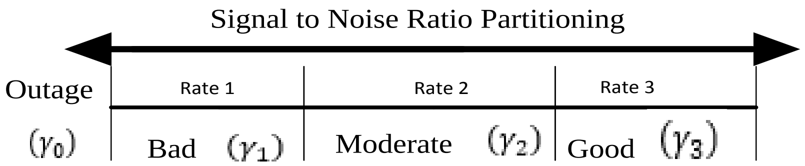

Figure 4.3 Partitioned SNR corresponding to different rate/mode pair

The essence of the AMC is to optimize data rate with respect to the conditions of the channel and same time keeping packet error rate (PER) as low as possible [131]. The quantities "number" of channel slots a secondary user assembles in order to commence service reduces as SNR becomes better since high data rate can be achieved. For instance, at 64-QAM few slot(s) will be aggregated due to high rate and while at 16-QAM more slots will be needed and so on. Thus, Mode 1, Mode 2, Mode 3 corresponds to QPSK, 16-QAM and 64-QAM representing bad, moderate and good SNR/Mode pair respectively.

4.3.2 Channel Slot Capacity

Let $\emptyset$ and R_n represents the message size in bits and the number of bit per symbol mode respectively. Where n is the transmission mode and ranges from $1 \leq n \leq N$ and N been the highest mode. The quantity of channel slot (s) in a static frame S depends on changing signal to noise ratio (γ). Thus in a coherence time interval the S can be estimated as [6],

$$S = \left(\frac{\emptyset}{R_s \varepsilon_s R_n}\right) . R_N \tag{4.2}$$

Where ε_s, R_s and R_N are the channel constant in symbol rate per second, symbol rate per second and highest transmission rate/mode pair [134]. As the channel is utilized in ON/OFF pattern, then it is characterised by two state Markovian process as presented in Figure 4.4 and as earlier discussed in the previous chapter of this thesis. Since the PU usage in ON/OFF manner, it will be necessary to estimate the amount of resources it has captured. Following the transition, let α_i and β_i represents the transitional probability from ON state to OFF state and from the OFF state to the ON state for a i^{th} channel.

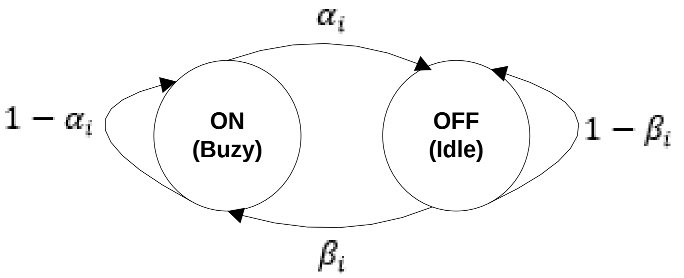

Figure 4.4 The PU ON/OFF channel usage pattern

Then the PU's channel slot capacity θ_{pu}, on arrival and based on the utilization ratio is given as;

$$\theta_{Pu} = S.\sum_{i=1}^{M}\left(\frac{\beta_i}{\beta_i+\alpha_i}\right) \tag{4.3}$$

The overall capacity of the system is given by $(M * S)$ where $\delta_i = \beta_i/(\beta_i+\alpha_i)$ is the channel utilization ratio. Therefore,

$$\theta_{Pu} = S.\sum_{i=1}^{M}(\delta_i) \tag{4.4}$$

Thus, SU channel slot capacity θ_{su} is given as,

$$\theta_{su} = (M * S) - \theta_{Pu} \tag{4.5}$$

4.4 Channel Assembling Strategies

This section presents and discusses the two channel assembling strategies which are: the Immediate Blocking and the Readjustment Based strategies. Subsequently, a corresponding algorithm that governs the policies is highlighted.

4.4.1 Immediate Blocking Strategy $(\boldsymbol{\theta_{pu}}, \boldsymbol{\theta_{su}}, \boldsymbol{\theta_n})$

In this policy, if there are insufficient or no capacity (channel slot) upon secondary user demand for spectrum resources, the secondary user is instantly blocked from accessing the networks. However, a

SU that arrives first is given higher priority than the SU that arrives last. Nevertheless, all secondary users are interrupted by PU arrival. Let V_n be the total number secondary user on the network and resource requests for first SU_i be θ_i while subsequent SU_j be θ_j respectively [24]. Since θ_n is the number of slot(s) secondary users can combine (assembled) in a given mode *n*/SNR pair. Then, the assembly procedure is shown in algorithm 1:

Algorithm I *for the CA using IBS*

```
CRBS check wireless channel SNR $(\gamma)$ ;// CRBS checks the signal to noise ratio.
    CRBS check $\boldsymbol{\theta_{su}}$;// CRBS checks for available resources for SUs
  If ($\overbrace{\boldsymbol{\theta_{su}} \geq \sum_{i,j=1}^{V_n} \boldsymbol{\theta_{n_{i,j}}}}^{Access\ condition}$); // channel aggregation test for SUs.
      $\boldsymbol{SU_{i,j}}$_Admit = True; // accept $SU_s$ however admit $SU_i$ first and aggregate channel slot for it.
  Else
      $\boldsymbol{SU_{i,j}}$_Admit=False; //block the $SU_s$ from gaining access
  If [($\boldsymbol{\theta_{su}} < \sum_{i,j=1}^{V_n} \boldsymbol{\theta_{n_{i,j}}}$)]; // reduction in SU requirement due to PU arrival, interrupts $SU_i$
     $\boldsymbol{SU_{i,j}}$_Forced-Termination =True;//drop ongoing  $SU_s$ service
End if ;// end if no event
  Repeat;//go to start
```

4.4.2 Readjustment Based Strategy ($\boldsymbol{\theta_{pu}}, \boldsymbol{\theta_{su}}, \boldsymbol{\theta_n^{min}}, \boldsymbol{\theta_n^{max}}$)

In this RBS scheme, both users SU_i and SU_j respectively demands a minimum of $\theta_n^{min}(\theta_{ni}^{min}, \theta_{nj}^{min})$ and maximum of $\theta_n^{max}(\theta_{ni}^{max}, \theta_{nj}^{max})$ number of channel-slots to commence services or stop assembling respectively. When a SU_i request for service, the assembling algorithm domiciled in the CRBS checks for resource accessibility in a similar way as the IBS system. If the resources (channel slot) are available and adequate, the secondary user is admitted else, the readjustment algorithm II is executed which enables the SU with the maximum number of channel to denote to starving or new arrivals respectively. However, because the system is designed in FCFS model, SU_i given preferential treatment before SU_j.

Algorithm II *for the CA using RBS*

```
 CRBS check wireless link $\boldsymbol{\gamma}$ ;// CRBS checks for SNR
     CRBS check $\boldsymbol{\theta_{su}}$;// CRBS checks available resources for SUs
If ($\overbrace{\boldsymbol{\theta_{su} \geq \sum_{i,j=1}^{V_n} \theta_{i,j}^{min}}}^{\boldsymbol{condition\ for\ access}}$); ); // channel aggregation test for SUs.
        $\boldsymbol{SU_{i\_}}$Admit = True; // accept $SU_i$
Else
     $\left.\begin{array}{c} \textbf{If}\ (\sum_{i=1}^{V_n} \boldsymbol{\theta_{i,j}^{min}}) < \ \boldsymbol{\theta_{i,j,new}^{min}}) \\ \boldsymbol{or} \\ (\boldsymbol{\theta_{su}} < \sum_{i=1}^{V_n} \boldsymbol{\theta_{i,j}^{min}}) \end{array}\right]$ ;// test for new SU or PU arrivals
Do $\left(\boldsymbol{\theta_{i,j}^{max}} - 1\right)$, ++ j:// readjust and iterate over $i, j^{max}$ user resources
   $\boldsymbol{SU_{i,j\_}}$Admit = True; // accept $SU_{i,j}$ and aggregate for both users
     Else
          $\boldsymbol{SU_{i,j\_}}$Admit =False; //block new $SU_{i,j}$ no-free slot or insufficient
   Else
If the conditions cannot be meet
Then
        $\boldsymbol{SU_{i,j\_}\ FT}$=True;// force-terminate on going $SU_{i,j}$
End if; // start the process.
```

4.4.3 No-Assembling strategy (NAS)

This scheme implies the traditional wireless communication network were users communicate with each other without application of any special scheme or techniques that will employ any form of spectrum reused or management. However, even when enough idle channels (spectrum hole) exists and are available, it is wasted due to the inability of current radio system to sense, access, make decision, and opportunistically utilized wasting spectrum.

4.5 System Model Performance Measures

In the performnce measures, Let λ_p, λ_s be the arrival rates of the primary and secondary user respectively. The service time is distributed exponentially while the service rates is defined as μ_p , μ_s for the primary and secondary user respectively. The total rate for a secondary user is the product of the user channel slot service rate and the number of aggregated channel-slot(s) $\theta_i \mu_s$ and $\theta_j \mu_s$ respectively.

a) The blocking probability P_b of the secondary user traffic-class is the likelihood that the newly arrived secondary user is not admitted into the spectrum once it cannot meet the condition in the algorithm. If total SU blocked and arrived are Ω_{Ts} and λ_{Ts} respectively, then, it can be expressed as,

$$P_b = \frac{Total\ \ SU\ blocked}{Total\ SU\ arrivals} = \frac{\Omega_{Ts}}{\lambda_{Ts}} \tag{4.6}$$

b) The forced termination probability P_f of the secondary user traffic-class is the probability that an ongoing SU service is obstructed by the primary user appearance nevertheless, in this thesis; the forced termination probability denotes the ratio of the forced terminated SU services over the total admitted/accepted SU connections. If total SU forced terminated and admitted are η_{Ts} and ζ_{Ts} respectively, then, it is expressed as,

$$P_f = \frac{Total\ SU\ forced\ terminated}{Total\ \ admitted\ SUconnections} = \frac{\eta_{Ts}}{\zeta_{Ts}} \tag{4.7}$$

c) Throughput T_v is the ratio of SUs packet that successfully delivered over the total number of packets that was transmitted (average service completion upon primary user appearance) after meeting the necessary conditions in the algorithm. However, in this section, it can be expressed as “not-blocked” which can also be expressed as,

$$T_v = (1 - P_b) \tag{4.8}$$

d) The capacity ρ_{su} of a homogeneous SU network is the mean number of SUs services completed per time. Thus, the capacity ρ_{su} of admitted secondary users at a given time depends on the signal to noise ration and modes pair. It can be expressed as,

$$\rho_{su} = \frac{Average\ number\ of\ SUs\ service\ completion}{Time(seconds)}$$

$$\rho_{su} = \left[\frac{(T_P = (1 - P_b\ ))}{T_n}\right] \qquad (4.9)$$

4.6 Numerical Results and Discussions

To evaluate the responses of the proposed CAS with AMC, the numerical results based on simulation are presented in this section for a homogeneous SU traffic. The parameters are configured as, $\lambda_p = 0.5$, $\lambda_s = 1.5$ $\mu_s = 0.85, \mu_s = 0.6$, $P_b = 0.55$ $P_f = 0.65$, $T_P = 2.5, \rho_{su} = 2.2$ $\theta_i = 4, \theta_{i,j}^{min} \leq 4$, $\theta_{i,j}^{max} \geq 4$. Matlab code was developed and used for the simulations in each of the policies. However, comparing both policies, it can be argued that substantial improvement was shown by the RBS scheme over the IBS owing to its adaptability. Specifically, the RBS scheme performed better than the IBS scheme in terms of SU blocking, forced termination, throughput and capacity respectively.

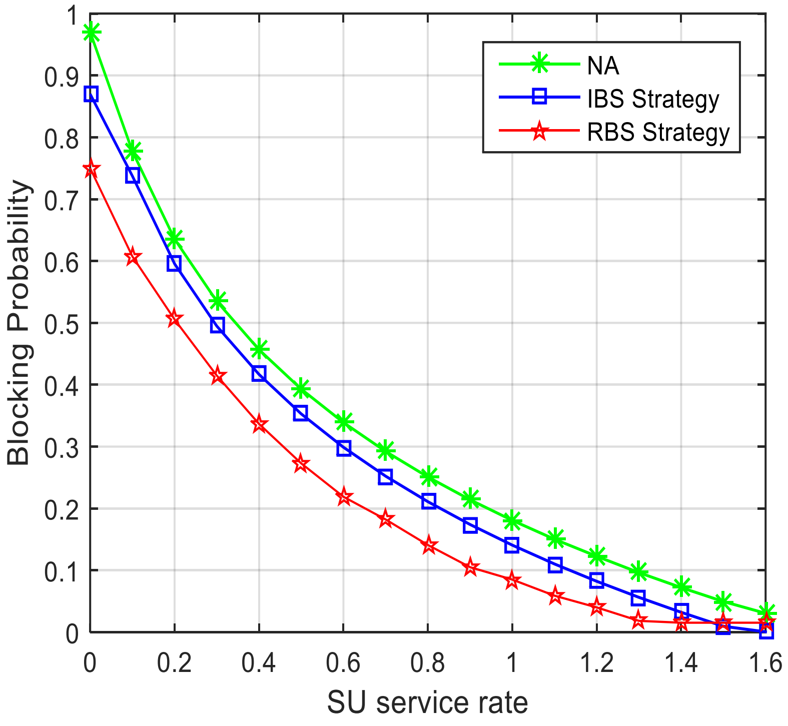

Figure 4.5(a) Blocking Probability P_b vs SU service rate μ_s

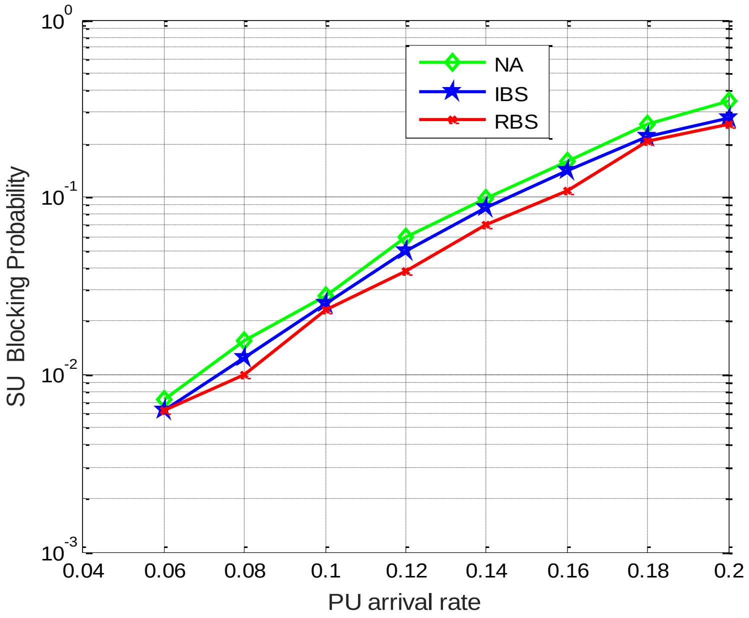

Figure 4.5 (b) Blocking probability of SU as a function of λ_p

Figure 4.5 (a) shows that when the service rate μ_s rises due to good channel condition, the blocking probability drops because more secondary users would be serviced faster. This will in turn give opportunity for other SUs. However, in both cases (Figure 4.5 (a) and Figure 4.5(b)), RBS scheme has a lower blocking probability as compared to the IBS while the NAS scheme has a highest blocking probability. Moreover, in Figure 4.5(b), as more primary users arrive, vacant channel slots will be occupied therefore, more secondary users will not be given access to make use of the resources.

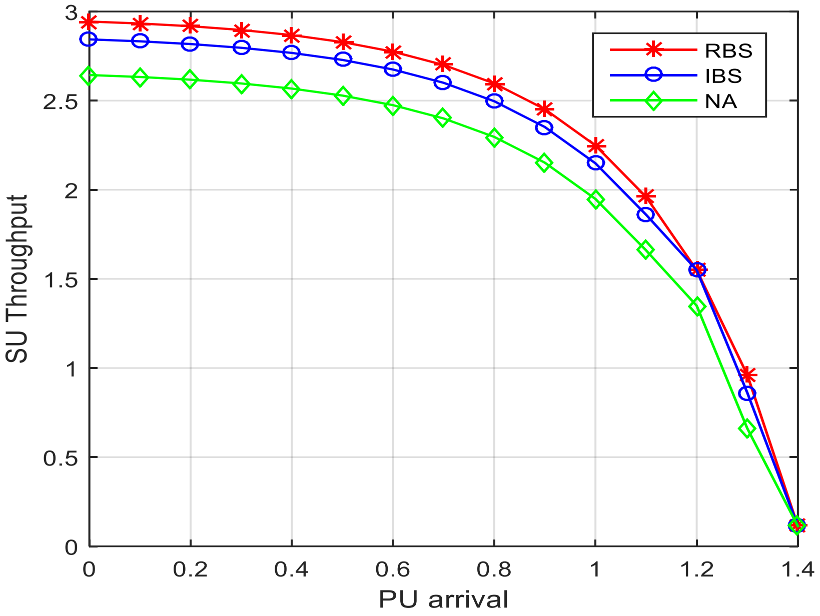

Figure 4.6(a) Throughput of SU as a function of λ_p

In the course of “batch” arrival of the primary users, the secondary users will experience drop in throughput since few or no resources would be accessible by the secondary users. This implies that not so much will be sent by the secondary user as shown in Figure 4.6(a). Similarly, Figure 4.6(b), throughput is improved when the primary users departs because, channel-slots would be available for use by the secondary users. This also implies that the SU will grab free channel-slot thus, service rate will be higher. Nonetheless, the RBS still showed a better performance as compared to the two other strategies (IBS and NA) due to its adaptability with respect to primary users’ arrival and departures.

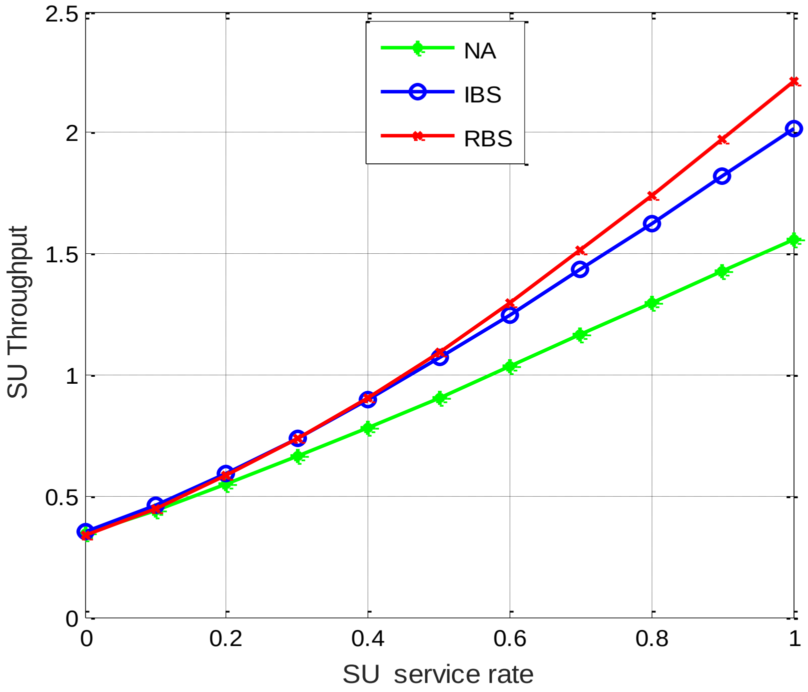

Figure 4.6(b) Throughput vs μ_{su}

Regardless of the policy deployed in Figures 4.7(a) and Figure 4.7(b), both illustrate gradual increase in SU capacity with respect to the service rate and SNR respectively. However, integrating AMC into CAS enhances service completion since more packets will be sent and delivered. It also buttresses the point made earlier that in the proposed model that more secondary users will be served because more packets would be sent at a higher rate thereby making a SU's complete service possibly before a primary user arrives hence giving opportunity for new SU arrivals. In both results, the RBS shows a better characteristic due to its flexibility as compared to IBS and NA respectively. In Figure 4.8(a), the secondary users' activity has significantly affected the behaviour of the primary users in terms of when to aggregate channel resources and when to drop already aggregated channels. If primary users arrive individually or in group, an ongoing secondary user's service must be forced to terminate its ongoing services if vacant channel is not available within the system. Similarly, in Figure 4.8(b), when a secondary user appears and sufficient channels are available, then, it is served. This result to decrease in termination probability. Overall, the RBS scheme emerge as a better scheme than the IBS and the NA respectively as shown in the results.

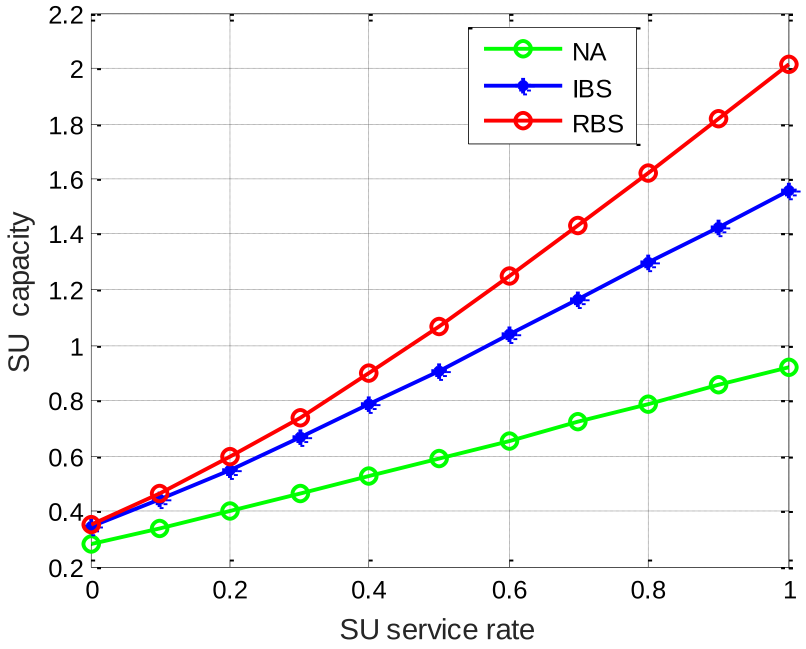

Figure 4.7(a) SU capacity vs μ_s

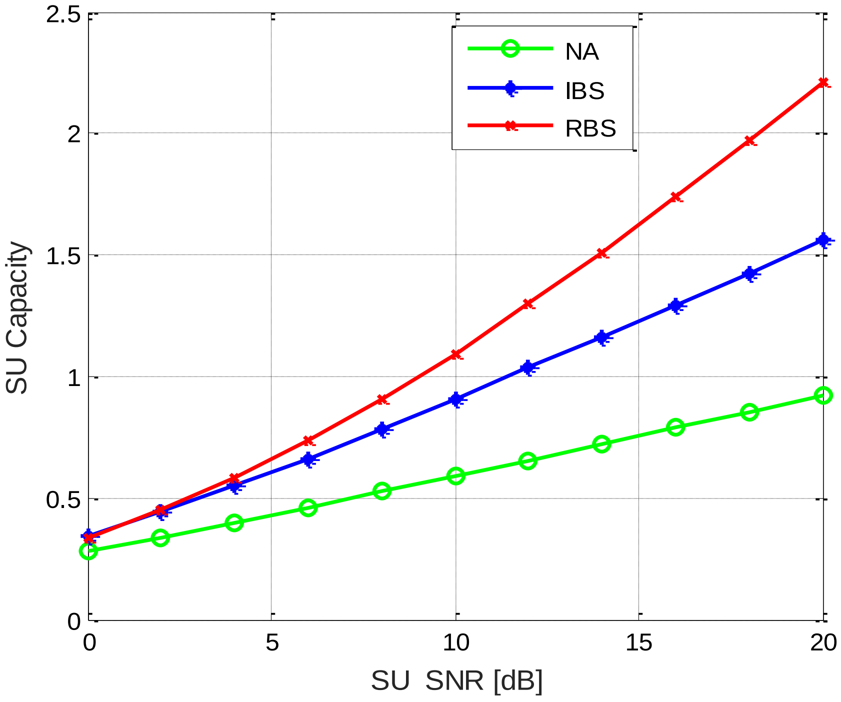

Figure 4.7(b) SU capacity vs SNR [dB]

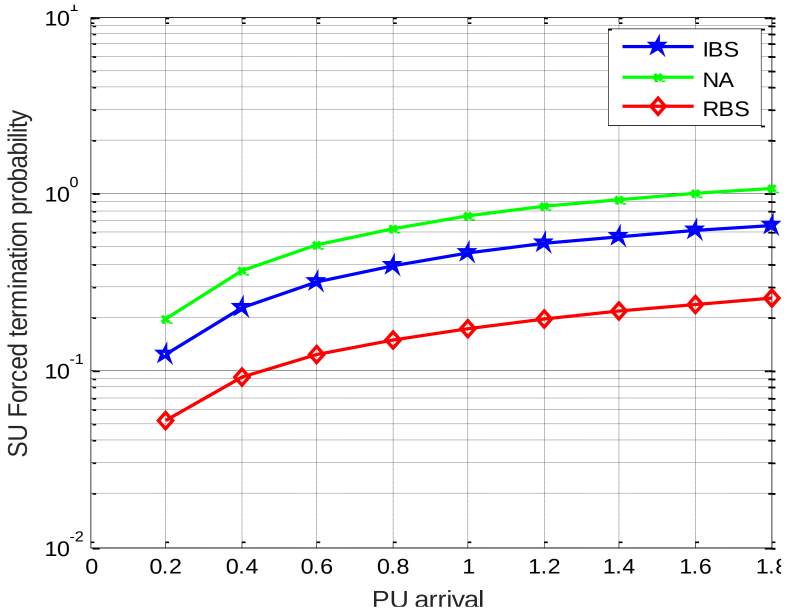

Figure 4.8(a) SU FT vs λ_p

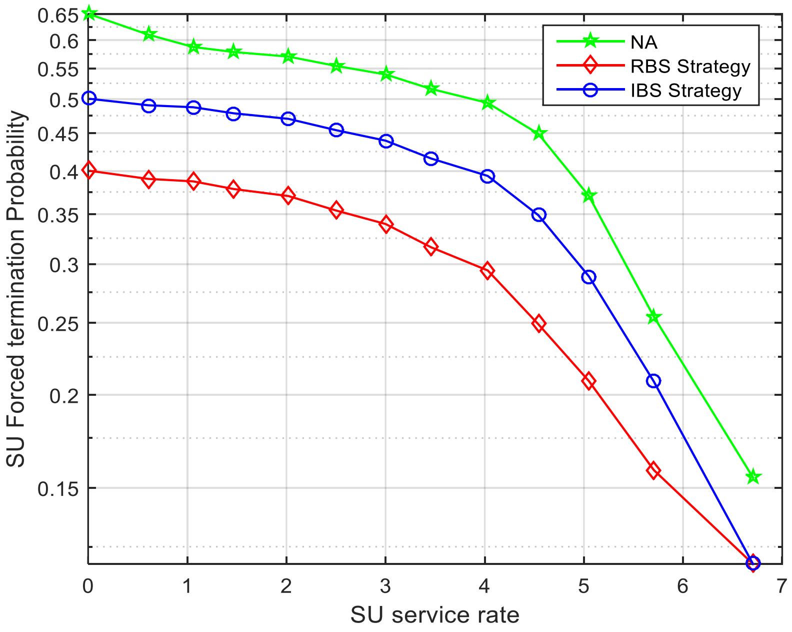

Figure 4.8(b) SU FT vs μ_s

4.7 Conclusion

The first part of chapter four has compared through a simulation frame work, the performance of two channel assembling techniques for CRN featuring AMC against No-assembling strategy. The result obtained from the simulation results indicates that, the RBS techniques perform better than the IBS and the NA techniques because it showed lower force termination and blocking probabilities respectively. Moreover, it shows that the AMC is a robust approach in enhancing spectrum assembling policies if incorporated. As mentioned in the preliminary of this chapter, the second part of this chapter will extend the scope by evaluating the performance of three CAS with a multi class secondary user's traffic in CRN.

Part II of Chapter Four

4.8 Introduction

In order to properly evaluate and analyse the performance of the SUs in a CRN, classifying them according to traffic delay tolerance is very key. The reason is that while some SU class appears generous, other could be greedy thus, classification is fundamental to help the network designer develop a robust system. A practical CAS needs to take into account the traffic classes and its impact on the assembling policies in terms of throughput, blocking, SU network capacity and forced termination. The CAS should also take into account the dynamics of the wireless channel and a mitigating technique like AMC. These research efforts and recommendations are due to the emerging broadband applications and services on the present wireless communications systems. This has led to radio resources scarcity but yet not optimally used. Motivated to improving the spectrum utilization, CRN was recommended as a way upon which secondary users can utilise the spectrum resources of primary users according to spectrum policies [129], [135].

Studies have shown that licensed spectrums are not optimally used due to reasons stated earlier in this work [34], [136]. On the one hand, the left over slice of the secondary spectrum is stretched by emerging wireless applications and multimedia services hence, resulting to the spectrum scarcity [117], [137]. Several research works have been carried out to find the policy that proficiently exploits the underutilized primary bands. In order to optimally use the primary spectrum, channel assembling was introduced to enhance spectrum utilization by giving opportunity to unlicensed users to use and reuse the scares spectrum resources. In a network consisting of two users, the primary and secondary respectively, the primary user has the sole right to use the spectrum at any time while secondary users cooperatively and opportunistically use the unused spectrum resources based on the availability [107], [130]. Sometimes, these unutilized PU channels that are scattered across slice of spectrum are not sufficient for some classes of SUs due to the nature of their traffic demand hence, the need to assemble/aggregate these unused spectrum to meet the user experience for multiclass user (real time or non-real time) traffics.

The reasons for assembling/aggregation of channel-slot is to improve the SU throughput so that, their packets (data) transmission would have been completed at the shortest possible time before the PU arrives. However, since network traffic has progressed from simple to multifaceted traffic classes, with individual class demanding different QoS guarantees in terms of blocking, delay and throughput, just to mention a few, this study developed and compared three CAS in a multi-user traffic scenarios. They are: the IBS and RBS which has been introduced previously and the Queuing Based Strategies (QBS). The amount of resources (channel-slot) to be aggregated for a specific CAS is a function of the secondary users signal to noise ratio and other factors. Similarly, the policies considered the activities of the primary user in terms of spectrum usage pattern [34]. The reason for incorporating AMC is to make the scheme more robust by transmitting at a higher rate depending on the channel conditions.

4.9 Related Works

Remarkable research works have been done in the area CAS. In [4], CAS with diverse spectrum adaptation schemes were investigated. The study proposed spectrum adaptation together with two policies which adaptively adjust the number channels an ongoing SU is using. The performance of these policies is evaluated using a Markovian chain models. [5], proposed a robust CA policy designed for non-homogeneous (heterogeneous) traffic scenario together with adaptation. In this study, channel allocation is carried out among real time and non-real time users. In [94], two aggregation strategies for wideband cognitive radio network were proposed. They are: the adjustable channel aggregation technique and the fixed channel aggregation scheme. In the adjustable channel aggregation technique, the spectrum resources of the primary users are aggregated with a probability distribution or aggregated based on the number of the left over channels while fixed channel aggregates scheme aggregates a fixed number of channels. In [97], a queuing technique is incorporated into CAS. In their work, if there are no resources, a secondary user's service is queued instead of instant blocking, or force to termination [98], [99]; ccombined queuing based CA and channel fragmentation such that, channel can be split in order to meet the demand of SUs and the same time given the opportunity for new SU to transmit their data. However, none of these considered the dynamics of the wireless link. Hence, this investigation extends the previous work by developing and comparing three CAS in multi-class SU traffic scenarios and considering the varying nature of a heterogeneous wireless channel with AMC.

4.10 System Model

In this section, an infrastructure based network architecture comprising of a PU base-station (TV mast), CRBS and other SUs of different classes (class1 and class 2) using the same spectrum-band as illustrated in Figure 4.9 was considered. Class-1 SUs (SU_1) are real-time while class 2 (SU_2) are non-real time SUs respectively. Among the SUs, higher priority and privileges are given to class 1 SU due to its traffic constrains. The licensed (PU) is class 0 hence has higher priority to use the channel and can interrupt the unlicensed users (SUs) at will regardless of the users using it as long as it not a licensed user. In this system model, class 1user traffic has more privilege in terms of spectrum access than class 2 traffic. A class 1 SU traffic can interrupt class 2 traffic for two reasons: firstly, they carry delay sensitive traffic and secondly, help during urgent network off-loading. This is to avoid network congestion and overall collapse of the secondary network. Moreover, the unlicensed user (SU) utilizes the PU channels opportunistically through the deployment any of the proposed schemes. The CRBs schedule and initiate spectrum utilization with overall transactions amongst the SU of the diverse classes.

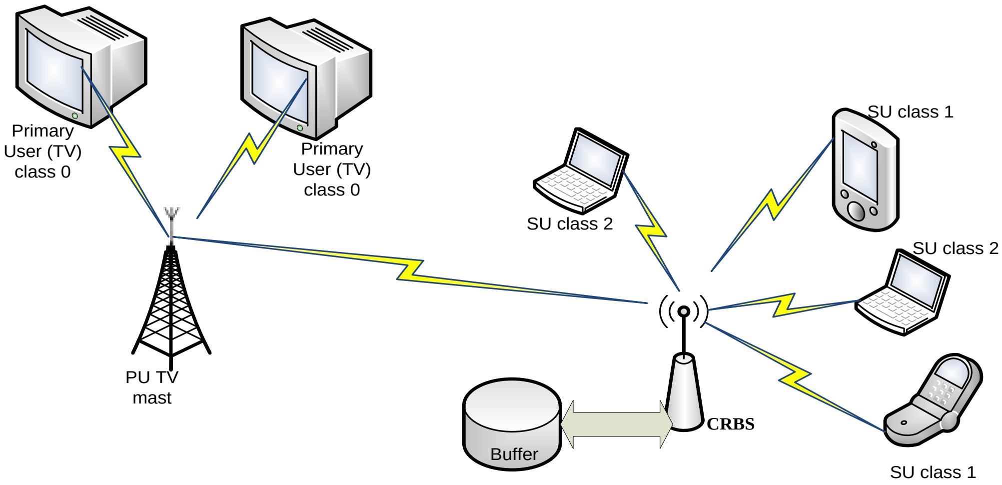

Figure 4.9 Network architecture

The incumbent (PU) network is made up of M channels, each of the licensed channel is structured in frames with each consisting of β slots therefore making channel usage on a slot basis. The licensed user uses one channel per time whereas the unlicensed user can intelligently combine several neighbouring and adjacent channel-slots in all spectrum domains. The wireless frame occupancy for PU Busy/Idle activities is illustrated in Figure 4.2 and [6, 24]. This dynamics of SU frame translate into a "heterogeneous system" with varying capacities hence, SU multi-user traffic class rrequires a precise number of channel-slot and transmission rate pair. As stated previously, the CRBS makes the decision whether to block, drop or admit, a particular SU traffic class on the bases of resource availability as initiated by CAS. Nevertheless, the SU capacity is function of the wireless link conditions (SNR).

4.10.1 Wireless Channel Model and AMC

In two studies of this thesis [6, 24], there was a representation of the dynamics of the wireless link, a more versatile model "Nakagami- m channel model" which was adopted. This is due to its ability to capture a wide range of fading characteristics of the wireless link. [6], [131]. Also, the different conditions of the wireless link were characterized using a finite state Markovian process, whose investigation and evaluation for fading is detailed in [132], [133]. In the study, the SNR is “partitioned” into bad, moderate and good link quality respectively as illustrated in Figure 4.3 and [6]. Conversely, the modulation schemes for the IEEE 802.22 standard was adopted from [27]. The transition matrix of the finite state Markovian process T_Δ is given by [6, 24], [133]. The significance of the AMC is to adjust the data rate with respect to the channel state thereby maintaining a target [131]. All other assumptions remain the same as adopted from part one of this chapter.

4.10.2 Channel Slot Capacity

To estimate channel slot capacity, similar procedure is adopted from one of the studies that forms part one of this chapter. All other assumptions, figures, equation, constants, variables and symbols clearly defined take same denotation. Where α_i, β_i, i^{th}, θ_{pu},$(M * S)$, δ_i and θ_{su} are all well defined in section 4.3.2, equation (4.3- 4.5), [6] and [24].

4.11 Channel Assembling Strategies

In this section, three CAS are presented although, two have been previously mentioned which are: the IBS scheme in which a SU is immediately blocked if there are no or insufficient spectrum resources to utilize respectively. The RBS scheme in which channel adjustment (upward or downward) is implemented to accommodate new SUs and also maintain ongoing SU service upon PU arrival. The QBS where some users are queued in a buffer to avoid or reduce blocking or dropping of SU services.

4.11.1 Immediate Blocking Strategy $(\boldsymbol{\theta_{pu}}, \boldsymbol{\theta_{su}}, \boldsymbol{\theta_{n_i}}, \boldsymbol{\theta_{n_j}})$

In this strategy, when there is no capacity (channel slot) upon secondary user demand for spectrum resources, the secondary user is instantly blocked from accessing the networks similar to previous study. However, two classes of SU traffic are considered in this scenario. The class 1 (SU_1) SU traffic is given higher primacy over the class 2 (SU_2) SU traffic. Although, both classes of SU are interrupted by the PU arrival. Let K and L be total number of secondary users (class 1 and class 2) on the network and resource requirements of SU_1 and SU_2 denotes θ_i and θ_j respectively [24]. The assembling procedure is shown as Algorithm III.

Algorithm III for the CA using IBS

```
CRBS check wireless link $\gamma$ ;// CRBS checks the signal to noise ratio
    CRBs check $\theta_{su}$;// CRBS checks available resources for SUs
     If ($\theta_{su} \geq \sum_{i=1}^{K} \theta_{n_i}$ ); // test for $SU_i$ resources
     $SU_1$_Admit = True; // admit $SU_1$
Else
     $SU_1$_Admit =false; // block  $SU_1$
if [($\theta_{su} < \sum_{i=1}^{K} \theta_{n_i}$) ]; // PU arrival, interrupts $SU_1$
   $SU_1$_Drop = True; // drop transmitting $SU_1$
       Else
 if [($\theta_{su} - \sum_{i=1}^{K} \theta_{n_i}$) ≥ ($\sum_{j=1}^{L} \theta_{n_j}$ )]  ;// enough resources exist
          $SU_2$_Admit = True: // admit $SU_2$
    Else
          $SU_2$_Admit = False; // block  $SU_2$
if [[($\theta_{su} - \sum_{i=1}^{K} \theta_{n_i}$) < $\sum_{j=1}^{L} \theta_{n_j}$ ]]; // no sufficient resources for $SU_2$
         $SU_2$_Drop = true; // dropp $SU_2$
   end if
Go to start
```

4.11.2 Readjustment based strategy $(\boldsymbol{\theta_{pu}}, \boldsymbol{\theta_{su}}, \boldsymbol{\theta_{n_{i,j}}^{min}}, \boldsymbol{\theta_{n_{i,j}}^{max}})$

In this RBS scheme, both users SU_i and SU_j respectively, demands a minimum of $\theta_{i,j}^{min}(\theta_{ni}^{min}, \theta_{nj}^{min})$ and maximum of $\theta_{i,j}^{max}(\theta_{ni}^{max}, \theta_{nj}^{max})$ number of channel-slots to commence services or stop assembling respectively. When a SU_1 user i requests for service, the assembling algorithm domiciled in the CRBS checks for resource accessibility similar to the IBS scheme. If the resources (channel slot) are available and adequate, SU_1 is admitted else, the readjustment algorithm is executed. This prompt SU_j with the maximum number of channels to denote channel to SU_i whom desperately needs it. Thus this is to avoid SU_i from been dropped or blocked. The assembling procedure is shown as Algorithm IV.

Algorithm IV *for the RBS scheme*

```
CRBs check wireless link $\gamma$ ;// CRBS checks for SNR
    CRBs check $\theta_{su}$;// CRBS checks available resource for SUs
If ($\theta_{su} \geq \sum_{i=1}^{K} \theta_{n_i}^{min}$ ); // test for $SU_1$ resources
          $SU_i$_Admit = True; // admit $SU_i$
```

```
    else
        If$(\sum_{i=1}^{K} \theta_{n_i}^{min}) < \theta_{n_{inew}}^{min})$
                  or                                              ;// test for new arrival or PU arrival
          $( \theta_{su} < \sum_{i=1}^{K} \theta_{n_i}^{min})$
     Do $\left(\theta_j^{max} - 1\right)$, ++ j: // readjusting and iterate over j user with maximum resources
            $SU_{i,j}$_Admit = True: // admit $SU_{i,j}$
        Else
            $SU_{i,j}$_Admit = false; // block $SU_{i,j}$
    If $(\theta_{su} - \sum_{i=1}^{K} \theta_{n_i}^{min}) \geq \sum_{j=1}^{L} \theta_{n_j}^{min}$ ); // enough resources exist
        $SU_2$_Admit = True; // admit $SU_2$
Else
    go step 5:// for readjustment
If [[$(\theta_{su} - \sum_{i=1}^{K} \theta_{n_i}^{min}) < (\sum_{j=1}^{L} \theta_{n_j}^{min})$ ]]; // no sufficient resources for $SU_2$
        if all conditions are not meet
    $SU_{,j}$_terminate = True; // dropp $SU_j$
       end if
    Go to start
```

4.11.3 Queuing Based Strategy (QBS)

In the QBS scheme, instead of instant blocking of SU traffic due to insufficient spectrum resources, the SU traffic are queued in the buffer and served later. However, incorporating a queuing regime is to further enhance the system. This will hence reduce the dropping and blocking when compared other CAS. Dropping/forced termination occurs when PU arrives and the resources are not there for it to use or the SU in the queue over stayed while blocking follows whenever the queues are filled. Let Q_{su_1} and Q_{su_2} denotes the queues for the two traffic classes (SU$_1$ and SU$_2$) respectively. When the buffer is unable entertain any more request at that pointing time, and vacant channels are busy with PUs activities or transmitting SUs (old SU), then it will be blocked. However, dropping/forced termination occurs when the delays $\partial_{su_1}$and ∂_{su_2} of the SUs respectively, in the queue exceeds the system delay $\partial_{tsu_1}$and ∂_{tsu_2} set by the CRBS. This strategy can be combined into the two other CA strategies of [7]. The assembling procedure is shown as Algorithm V.

```
  Algorithm V for the QBS scheme
CRBS check wireless link $\gamma$ ;// CRBS checks for SNR
   CRBS check $\theta_{su}$;// CRBS checks available resources for SUs
  If ($\theta_{su} \geq \sum_{i=1}^{K} \theta_{n_i}^{min}$ ); // test for $SU_{s1}$ resources
     $SU_1$_admit = true; // admit class 1 SUs
  Else
     if ( $K < Q_{su_1}$)
        $SU_1$_Admit_Queue = True :// (queue not full)
     Else
        $SU_{s1}$_Admit = False:// (queue full)

   If [($\theta_{su} - \sum_{i=1}^{K} \theta_{n_i}^{min}$) $\geq$ ($\sum_{j=1}^{L} \theta_{n_j}^{min}$ )]; // enough resources exist
     $SU_{s2}$_Admit = True; // admit class 1 SUs
  Else
     if ( $L < Q_{su2}$)
        $SU_2$_Admit_Queue = True :// (queue not full)
     else
        $SU_2$_Admit = False :// (queue full)

If ( $\partial_{su_1} > \partial_{tsu_1}$)
        $SU_1$_Forced terminate _Queue = True:// dropped/forced terminate $SU_1$ from the queue
  If ( $\partial_{su_2} > \partial_{tsu_2}$)
        $SU_2$_ Forced terminate _Queue = True :// dropped/forced terminate$SU_2$ from the queue
  End if
```

4.12 System Model Performance Measures

The performnce measures of thus section is similar to the study in the first part of this chapter. The only deviation is the that λ_{s1} and λ_{s2} which denotes the arrival rates of the SU class 1 and class 2 traffic respectively and the service rates μ_{s1}, and μ_{s2} for the two traffic class. All other assumptions, symbols, constants remain the same as adopted from part one of this chapter [24].

a) The blocking probability $P_b^{i,j}$ of the secondary user's traffic-classes is the likelihood that a newly arrived secondary user is not accessing the spectrum since it cannot meet the condition in the algorithm. Thus, if total SUs of class 1 and 2 are blocked and arrived are $\Omega_{T_{s1,2}}$ and $\lambda_{T_{s1,2}}$ respectively, it can be expressed as;

$$P_b^{i(1)} = \frac{Sum\ of\ \ Secondary\ users\ class\ 1\ blocked}{Total\ \ Secondary\ users\ class\ 1\ arrival} = \frac{\Omega_{T_{s1}}}{\lambda_{T_{s1}}} \tag{4.10}$$

$$P_b^{j(2)} = \frac{Sum\ of\ \ Secondary\ users\ class\ 2\ blocked}{Total\ \ Secondary\ users\ class\ 2\ arrival} = \frac{\Omega_{T_{s2}}}{\lambda_{T_{s2}}} \tag{4.11}$$

b) The forced termination probability $P_f^{i,j}$ of the secondary user’s traffic-classes is the probability ongoing SU of class 1 or 2 being pre-empted by a primary users’ arrival however, in this thesis, forced termination probability represents the fraction of the forced commenced SU services. If total SU of class 1 and 2 forced terminated and admitted are $\eta_{T_{s1,2}}$ and $\zeta_{T_{s1,2}}$ respectively, then, it is expressed as,

$$P_f^{i(1)} = \frac{Total\ SU_1(class1) forced\ terminated}{Total\ \ admitted\ SU_1\ connections} = \frac{\eta_{T_{s1}}}{\zeta_{T_{s1}}} \tag{4.12}$$

$$P_f^{j(2)} = \frac{Total\ SU_2\ (class\ 2)\ forced\ terminated}{Total\ \ admitted\ SU_2\ connections} = \frac{\eta_{T_{s2}}}{\zeta_{T_{s2}}} \tag{4.13}$$

a) Throughput $T_v^{i.j}$ is the fraction of SUs of class 1 or 2 packet that successfully transported over the total number of packet that was transmitted after meeting the necessary conditions in the algorithm. However, in this section, it can be expressed as “not-blocked” which can be expressed as;

$$T_v^{i.j} = (1 - P_b^{i,j}) \tag{4.14}$$

c) The capacity $\rho_{su}^{i,j}$ of a heterogeneous multi-class network is the mean number of SUs (class 1 and 2) services completed per time. Thus, the capacity $\rho_{su}^{i,j}$of admitted secondary users at a given time is dependent on the signal to noise ration and modes pair [6], [24]. It can be expressed as;

$$\rho_{su}^{i,j} = \frac{Average\ number\ of\ SUs\ (class\ 1\ and\ 2)\ service\ completion}{Time(seconds)} \tag{4.15}$$

$$\rho_{su}^{i,j} = \left[\frac{(T_v^{i.j} = (1 - P_b^{i,j}))}{T_n}\right] \tag{4.16}$$

4.13 Numerical Results and Discussion

This section presents the numerical results with corresponding discussion. MATLAB tool was used to demonstrate the performance of the three CAS in multiclass SU scenarios. The results of SUs (class 1 and 2) blocking probability against the PU arrival time is illustrated in Figures 4.10(a) and 4.10(b). The result indicates that as PU arrives more, the blocking probability shows a corresponding growth. This is anticipated because the SUs are not the original owner of the spectrum. PU interrupts any users using its channel and this causes blocking of the SUs service irrespectively of the class. Nevertheless, the QBS policy showed a lower blocking probability than IBS and RBS due to its inbuilt buffer system. The essence of the queue regime is to ensure that SU are not just dropped out of the spectrum but, kept so that it could be given another opportunity for spectrum allocation which is an edge over the RBS. For the RBS, since it has the adaptive capability to adjust the spectrum resources upwards or downwards depending on the amount of channels the PU has grabbed or the amount of spectrum resources left, it would obviously outperform the IBS which is not as flexible like the two other strategies mentioned.

Nevertheless, IBS will be of the same performance like the QBS and RBS if spectrum resources are sufficiently available. Last but not least, it shows that class 1 SUs has a lower blocking probability compared to class 2 SUs which points to the privileges given to it in terms of priority queuing and resources reallocation.

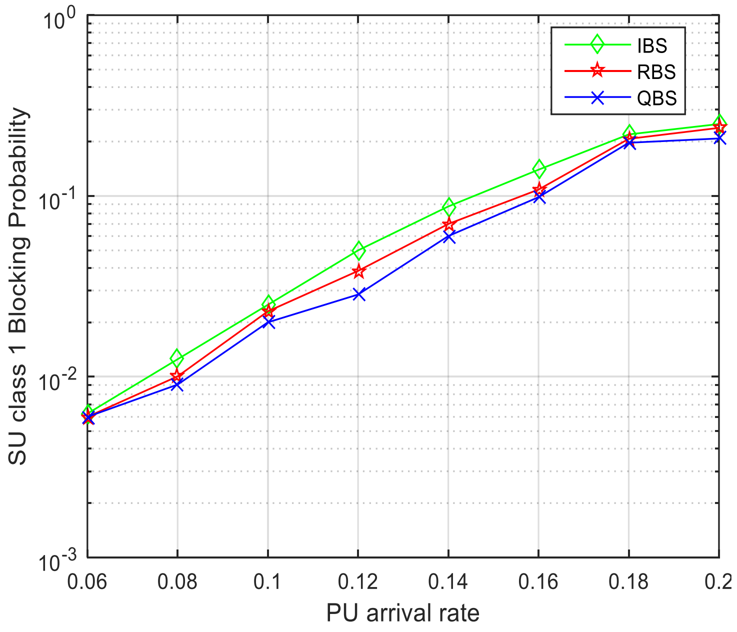

Figure 4.10 (a) Blocking probability of SU class 1 vs PU arrival rate

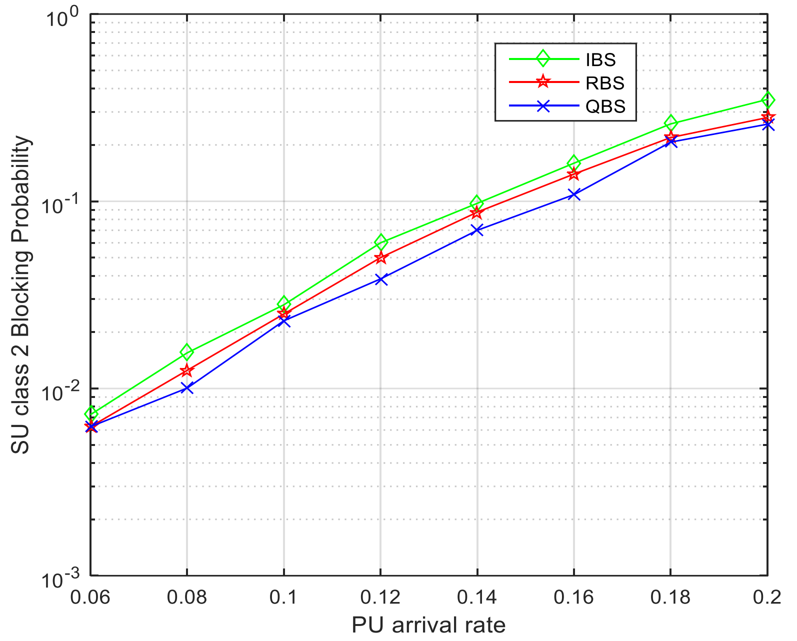

Figure 4.10 (b) Blocking probability of SU class 1 vs PU arrival rate

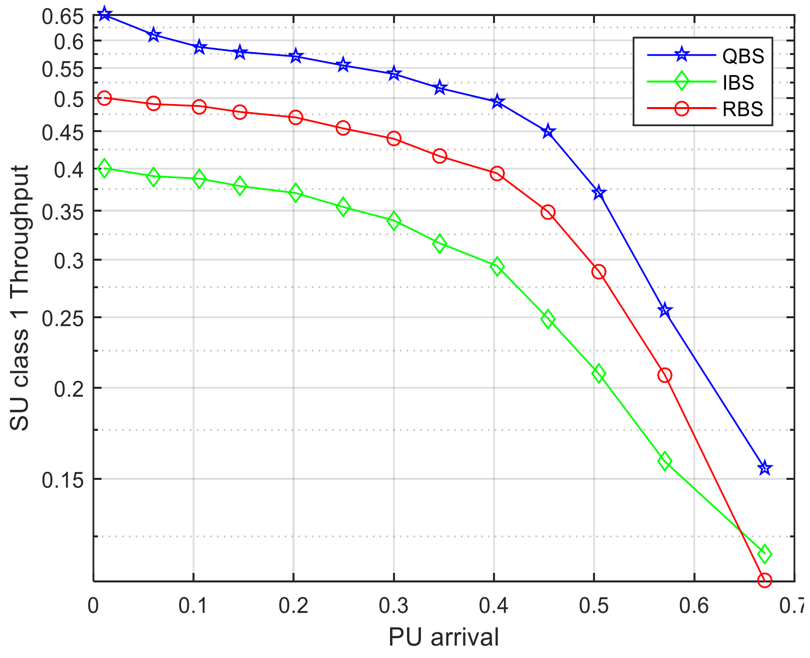

Figure 4.11 (a) Throughput of SU class 1 vs PU arrival rate

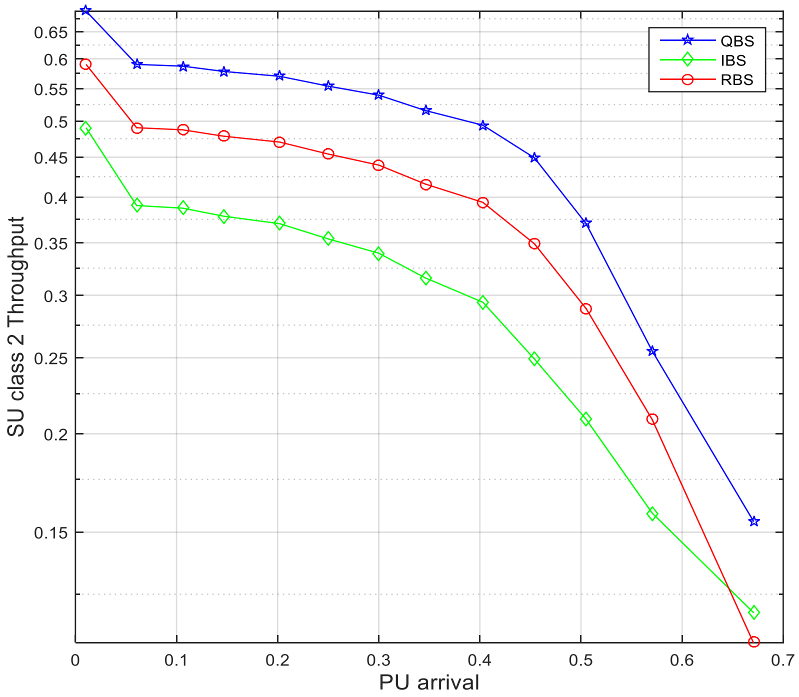

Figure 4.11 (b) Throughput of SU class 2 vs PU arrival rate

Figures 4.11(a) and (b) respectively, present throughput which responds to PU arrival. From the result, it is obvious that the SU's throughputs reduce as the PU arrival rate increases in all cases (QBS, RBS and IBS). The SU experiences low throughput due to PU(s) individual arrival or in batches. This implies that SU will hands-off the spectrum because they are not the licensed owners. This possibly results to blocking, forced termination or queued SU service depending on the severity of PU behaviour. These interruptions (blocking, forced termination) cause throughput to decrease as a result of PU arrival. However, the QBS performed better than other the two (RBS and IBS) policies all points owing to it robustness. Closely followed is the RBS scheme which can readjust its slot occupancy amidst PU sporadic behaviour. The last is the IBS scheme which is more of a direct or blind strategy without much flexibility except when resources are much more available. However, when the PUs are absent, class 1 SU traffic achieves greater throughput than class 2 SUs traffic. This is because of the superiority and privileges given to class 1 by the CRBS due their traffic type.

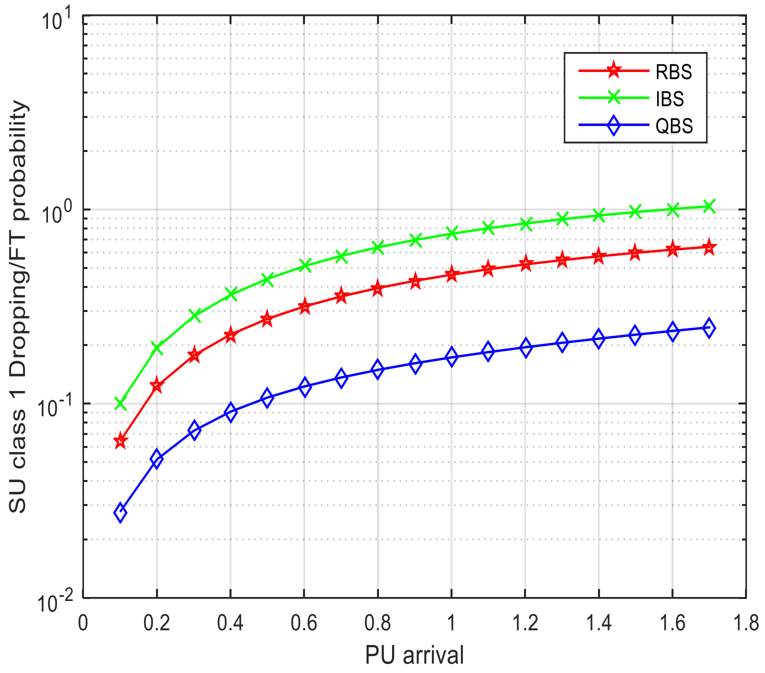

Figure 4.12 (a) Forced termination probability of SU class 1 vs PU arrival rate

One of the aims of channel assembling is to ensure that dropping/forced termination is kept low as possible. Also, it is to ensure that spectrum reuses are made possible and practicable. However, the response of the forced termination probability as a result of primary user arrival is shown in Figures 4.12 (a) and (b) respectively. As anticipated, SU will experience forced termination in all the schemes due to PU arrival. But, the performance of the QBS scheme is far better than the IBS and RBS schemes at all instances. This is due to its adaptive capabilities and the robust queuing regime it has. Due to the preferential treatment given to class 1 secondary users, the lower forced termination is experienced compared to class 2 traffic. Moreover, when the primary users depart, the forced termination of the entire scheme drops significantly, meaning that more channel-slots would be made available for the SUs.

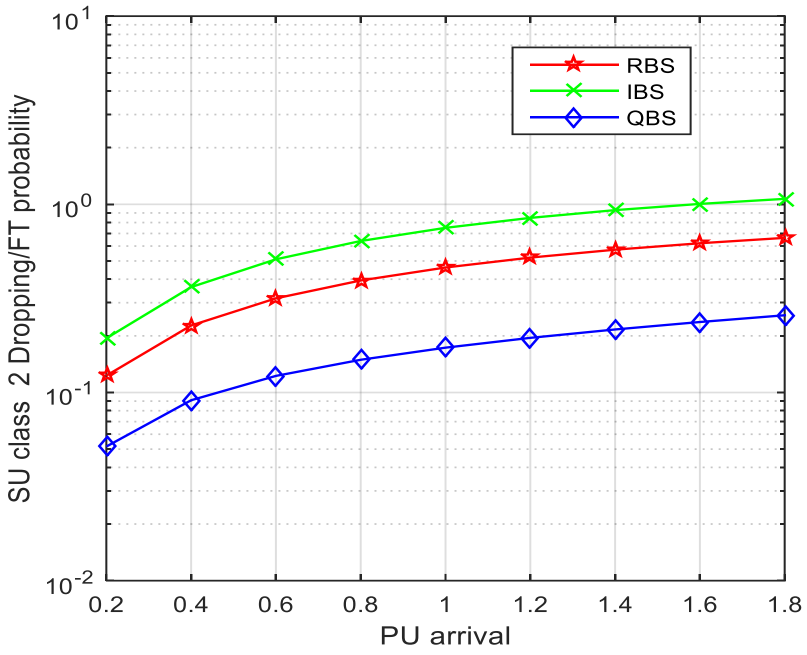

Figure 4.12 (b) Forced termination probability of SU class 2 vs PU arrival rate

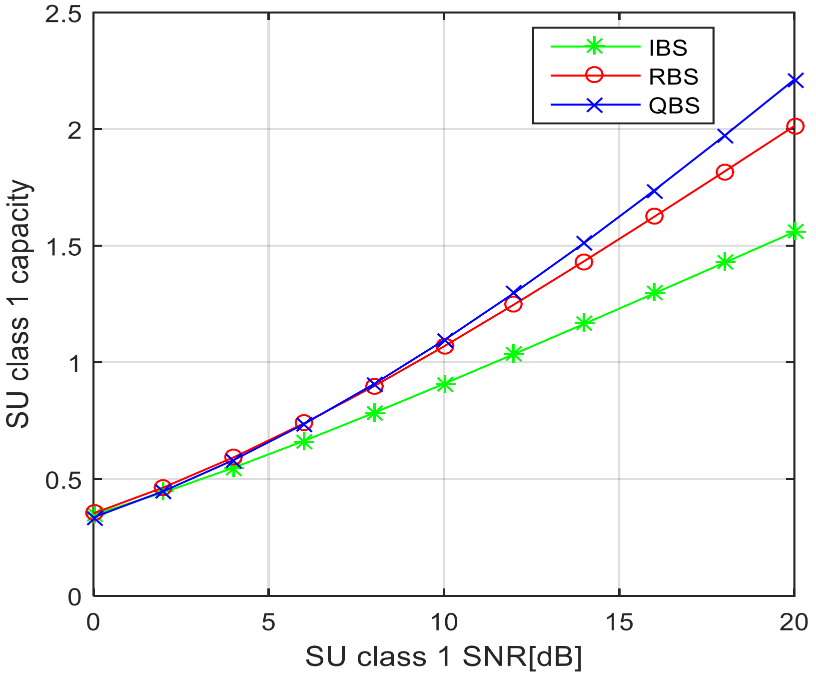

Figure 4.13 (a) SU_1 capacity vs SNR [dB]

The results of Figures 4.13 (a) and (b) respectively, show gradual increase in capacity as a function of the signal to noise ratio for class 1 and 2 regardless of the policy deployed. Integrating AMC technique into CAS enhances service completion time. This is because within the shortest window period, more packets (data) would be delivered at good SNR. Nonetheless, incorporating queuing regime is a design strategy for developing more robust policy hence, this is where the QBS show off its superiority over the other two schemes. RBS and IBS are excellent strategies for a network that is not too busy or congested. Besides, because priority is given to class 1 secondary user, more capacity is achievable as compared to secondary user of class 2 traffic.

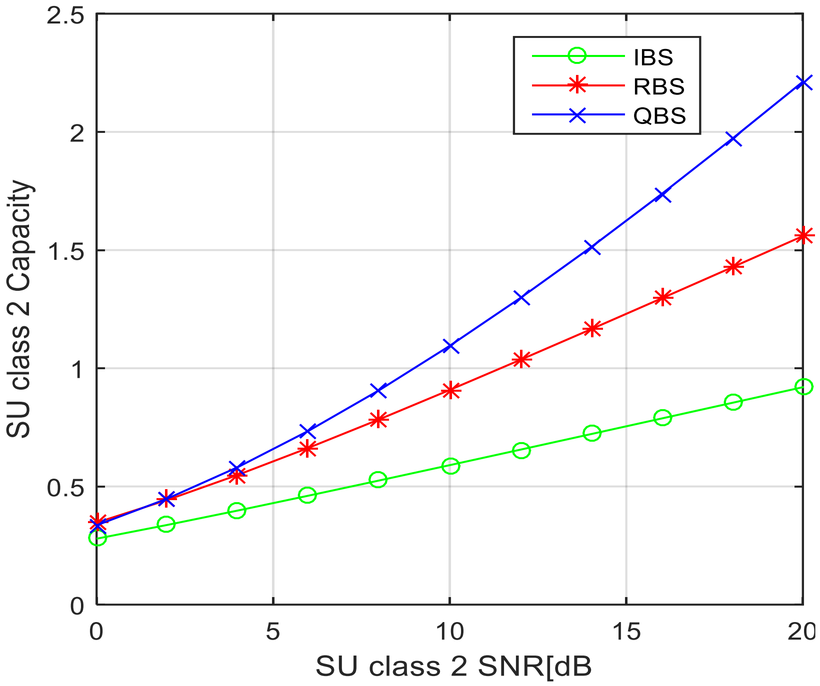

Figure 4.13 (b) SU_2 capacity vs SNR [dB]

4.14 Conclusion

The performance of the three channel assembling strategies for CRN have been evaluated considering the varying nature of the wireless link featuring AMC in a multiuser secondary user traffic classes. From the results of study, it shows that SUs of dissimilar class respond differently with substantial effect on the CAS with respect to capacity, blocking probability, throughput and forced termination probability. It also demonstrates that the QBS technique performed better that IBS and RBS scheme respectively, when tested within a network with multi-class traffic owing to its robustness. Furthermore, it showed relatively lower force termination and blocking probabilities respectively when compared with other polices. Lastly, it affirms that AMC together with “queueing regime” is a more dynamic approach in enhancing channel aggregation policies. Though, detailed performance analysis with the system analytical models were not discussed. It forms the basis for the extension of this work which focuses on analyzing the performance of the heterogeneous CAS in CRN. Specifically, this extension is based on our proposal in part one of this chapter and is presented in the next chapter of this thesis.

CHAPTER FIVE

Performance Analysis of Heterogeneous Channel Assembling Policies in Cognitive Radio Networks

This chapter presents an analytical evaluation of the two proposed CAS (IBS and RBS) in CRN. Precisely, a detailed analysis of the models used and the assumptions made to extend earlier work of this thesis [6, 24] in part one of chapter four. This chapter is organized as follows: introduction is presented in section 5.1. Sections 5.2 covers related works while system model and resources utilization are found in Section 5.3. Wireless resource capacity modeling and analysis are presented in Section 5.4 then the proposed channel assembling strategies is discussed in Section 5.5. System analytical model was developed in Section 5.6 while numerical results are discussed in Section 5.7. The concluding part of the study is found Section 5.8.

5.1 Introduction

To maximize the TVWS, a flexible channel allocation policy featuring the aggregation several primary user idle resources (TVWS) into groups of useable secondary channels has been studied in literatures. Nevertheless, for it to be applied in real world, the CAS must take into consideration the factors/parameters that have direct impact on the capacity and quality of the accessible/available spectrum resources (channels). This comprises but not limited to the signal to noise ratio, dynamics of the wireless link, traffic classes and enabling technique like AMC thus making the strategies robust and non-homogeneous "*heterogeneous*". Furthermore, the flexible allocation of the TVWS across frequency and time can only be made possible via an intelligent radio system (CRN). CRN is promising research model that supports dynamic allocation and flexible spectrum access [105], [138]. However, cognitive radio is intelligent enough to adaptively and autonomously alter its communication parameters and thus learn from past events in an attempt to optimally use and reuse the PU channels effectively [10], [107], [139].

Though, the channels used by the SUs belong to the PU, traditional owner/authorised users. An unlicensed user "SU" ingeniously uses the primary spectrum that are vacant and depart once the true owners "PU" appears to avoid meddling therefore, taking advantage of the erratic behaviour of the primary users in frequency and time domain respectively. The scattered idle spectrum needs coordination to meet the quality of service experience of the secondary users hence, the need for channel assembling. CAS allows secondary users to aggregate several vacant channels into one useful chunk in order to improve its throughputs. This has proven to enhance secondary performance metrics such as blocking probability, high data rate, spectrum utilization and forced termination probability of the secondary network [4], [5]. However, CAS enhances the overall system performance particularly if spectrum adaptation is applied with accurate parameters [5], [98], [140].

Since fifth generation networks (5G) would support different applications and services with diverse capacity requirements, a dynamic CAS is key in CRN so as to enhance SU performance. Furthermore, the quantity of channel aggregated for a specific policy is a function of some factors which includes: the user traffic class, the PU behaviour and the modulation scheme (AMC). Moreover, aggregating channel is possible and convenient under certain PU activity patterns with most of which modelled as Markovian process. Though, other model exist but vary in their ON/OFF distribution [34], [141].

For CAS to be effective and implementable, it must consider PU behavioural pattern as studied in [37].Therefore, with the understanding of the PU behavioural patterns, the resource utilization planning and signal to noise ratio per frame, channel aggregation/assembling can be successfully implemented. These factors mentioned in turn determines the bit error rate (BER) and number of channels available. A real-world scenario of the wireless link could be characterized by a number of finite states [142]. For instance, a three state wireless link conditions could be of bad, medium, or good quality respectively. This represents a more practical scenario of the wireless link conditions which is in contrast to the novel "homogeneous" case in[4], [5]. Therefore, a realistic CAS must consider the varying nature of the wireless link and this builds part of the basics of the current study.

Diverse techniques have been proposed to alleviate several deficiencies of the wireless networks. Adaptive modulation and coding "AMC" is one of such that have substantially enhanced spectrum utilization via the classification the spectral efficiency, SNR, code rate and coding scheme [132]. Also, AMC improves the rate at which packets are sent and deliver with minimized error rate [143]. The varying channel conditions (varying SNR) introduces a multi-rate capacity of wireless channel in terms of the amount of channel slot(s) used which is in contrast to the constant "*homogeneous*" single-rate system [4]. Motivated by this, two CAS that considered the dynamic wireless link, the effect of signal to noise ratio, the diversity of the traffic class and the enabling technique like AMC were proposed. In addition, the study develops a systematic framework to analyse the performance of these proposed schemes (IBS and RBS) used in this study thus, extending previous work in part one of chapter four.

5.2 Related Works

To improve the performance of CRN, several CAS have been proposed in literature. Majority of them could be categorized as dynamic or static. In the dynamic CAS, an unlicensed user (SU) aggregates a flexible chunk of spectrum resources depending on the availability while in the static regime, the number of channel aggregated is defined, fixed and cannot be altered. These policies can be implemented jointly with adaptation in two ways [5]. Firstly, spectrum adaptation where a secondary user adjusts upward or downward the quantity of channels assembled during communication. Secondly, spectrum handover which enables secondary users assemble channels at different frequency. [5] developed an analytical model for CRN with spectrum adaptation. In their study, two channel aggregation policies that take into account spectrum adaptation in a heterogeneous traffic scenario were proposed. A CTMC model was used to evaluate the performance of these policies. In [140], a close-form for the hypothetical capacity upper limit of a secondary network with channel assembling was proposed. This investigation shows that the incumbent (PU) arrives intermittently with its services on the channel lengthier than the SU services.

In [30]], the performance of three channel assembling strategies was compared without incorporating spectrum adaptation. The three scenarios considered were: assembling all idle channels when SU access the spectrum (greedy user), without channel assembling and assembling fixed number of channels. In [96], an adaptive channel assembling strategy for non-real time user were proposed depending on channel accessibility and other secondary events. To extend the body of knowledge, [4] and [5] implemented a robust CAS for heterogeneous traffic. The adaptive features enable channel handover and sharing respectively. In these studies, the authors assumed that the unlicensed users will experience stable services without channel variation (fading) with the help a sophisticated physical layer procedure. But, parameter such as varying SNR and AMC which has significant effect on the performance of any given CAS in CRN were not did not considered in their studies.

Spectrum access strategies have been proposed in literatures with the drawback of frequent blocking and dropping of SU services. Consequently, the queuing-based strategies have attained importance due to its robustness to mitigate against these draw backs. [97] Incorporated a queuing regime into the strategy proposed in [5]. In the study, when there are insufficient or no spectrum resources, like an open network model (lossy system), where a new secondary user request is pre-empted and the interrupted secondary services are dropped or forced to terminate, it is queued and served later. This minimizes the rate at which secondary services are blocked and dropped thus improving spectrum utilization and secondary network capacity. In [99], channel assembling and fragmentation (CAF) were jointly proposed in CRN. In the investigation, the authors assumed that secondary users can adaptively split their presently occupied channel(s) to smaller granules so as to accommodate more SU arrivals.

In [100], the performance evaluation of two channel assembling polices with imperfect sensing for wideband CRN were proposed just like in [94]. Specifically, missed detection and false alarm (imperfect sensing) were carefully taken into account in their analysis. Moreover, pre-empted SU are accommodated in a queue to wait for channels availability and same time, the maximum waiting time is set by the CRBS so that when the SU queue waiting time expires, the SU service would be dropped to avoid starvation of other SUs which needs to be queued. The finite queue regime saves blocking SU request and forces termination of ongoing SU services. In spite of the tremendous research on channel assembling in cognitive radio, previous investigations did not take into account the varying nature of the wireless link especially a three state scenarios and the effect of a robust technique like AMC on CA which this current study took into account. This chapter provides more insight on the performance of CAS in a cognitive wireless networks. However, the key contributions of this chapter includes:

- Proposed two channel assembling strategies for a multi-rate wireless link together with AMC as a mitigating approach.
- Developed an analytical framework to evaluate the performance of the proposed channel assembling strategies used in this chapter.

5.3 System Model and Resource Utilization

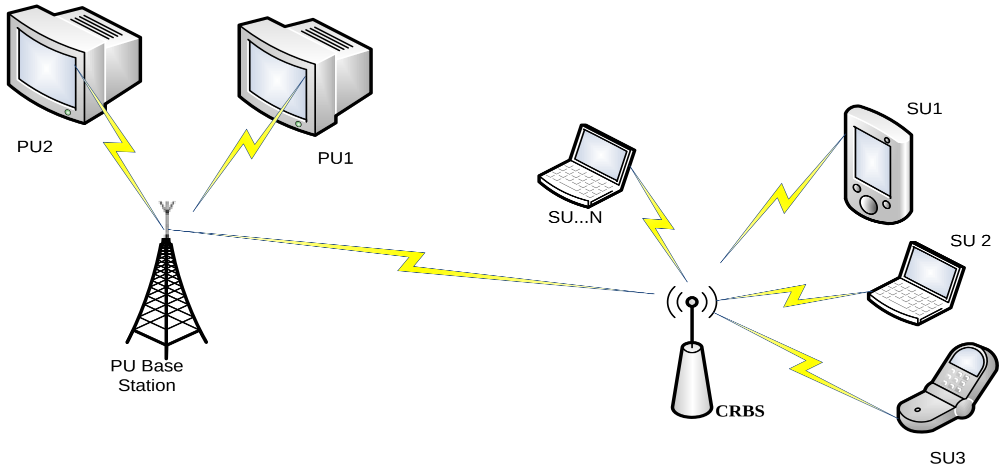

Figure 5.1 Network Architecture

The system model is an infrastructure based network architecture comprised of a primary owner base-station (TV mast), a secondary controller (CRBS) and other opportunistic users using the same spectrum-band as illustrated in Figure 5.1. The licensed owner (PU) is privileged to use the channel anytime and can interject the opportunistic users (SUs) at will irrespective of the users using it as long as it not a licensed user. In this model, that all secondary services that are managed by the last in last out (LILO) protocol embedded in the CRBS were assumed first. Second, the licensed user uses one channel-slot(s) per time in an ON/OFF pattern while the unlicensed user intelligently assembles several neighbouring or non-adjacent channel-slot(s) across spectrum domains using the OFDMA access scheme within a coherent time interval. Moreover, the licensed user (SU) utilizes the PU channels opportunistically through the deployment of any of the proposed schemes. The primary network is made up of M channels however; each of the licensed channels is structured in frames with each consisting of S slots thereby making channel usage on a slot basis. The wireless frame occupancy for PU Busy/Idle activities is illustrated in Figure 4.2 and 4.4 respectively, with α_i, β_i and other parameters remaining identical. This dynamics of SU frame translates into a “heterogeneous system” with varying capacities hence requiring a precise number of channel-slot and transmission rate pair. The CRBS makes the decision whether to block, drop or admit, the SUs on the basics of resource accessibility is initiated by CAS, however, the SU capacity is a function of the wireless link conditions (SNR).

5.4 Wireless Resource Capacity Modelling and AMC

This section focuses on the wireless channel modelling, the slot/frame configurations together with the AMC system. However, emphasis would not be on the wireless channel and AMC since it has been discussed in previous chapter.

5.4.1 SU wireless channel model and AMC

The “Nakagami-m channel model” is adopted since it spans a wide range of fading channels [131], [133]. All other parameters and assumptions used in previous work remains same. In addition, the received signal to noise ratio γ is a random variable with a gamma probability density function $\vartheta_\gamma(\gamma)$ whose analysis is well known [143], [144].

$$\vartheta_\gamma(\gamma) = \frac{m^m \gamma^{m-1}}{\bar{\gamma}^m \Pi(m)} exp\left(-\frac{m\gamma}{\bar{\gamma}}\right) \tag{5.1}$$

Where the mean received, SNR $\bar{\gamma} = E\{\gamma\}$, the Gamma functions is $\Pi(m)$, and m represents the Nakagami fading parameter.

$$\Pi(m) = \int_0^\infty t^{m-1}\ exp(-t)dt \tag{5.2}$$

The essence of the AMC is to optimize data rate with respect to the conditions of the channel and same time keeping packet error rate (PER) as low as possible [131]. The quantities “number” of channel slots a secondary user assemble in order to commence service reduces as SNR becomes better since high data rate can be achieved. For instance, at 64-QAM, few slot(s) will be aggregated due to high rate and while at 16-QAM more slots will be needed and so on. Thus, Mode 1, Mode 2, Mode 3 corresponds to QPSK, 16-QAM and 64-QAM representing bad, moderate and good SNR/mode pair respectively, as depicted in Figure 5.2.

5.4.2 AMC and SU frame configuration

As stated in subsection, $\emptyset$ and R_n represents the message size in bits and the number of bit per symbol mode respectively. Where n is the transmission mode and ranges from $1 \leq n \leq N$ and N been the highest mode. The quantity of channel slot (s) in a static frame S depends on varying signal to noise ratio (γ). Thus, in a coherence time interval S can be estimated. Where α_i, β_i, i^{th}, θ_{pu},$(M * S)$, δ_i and θ_{su} and all other parameters respectively, are well defined in section 4.3.2, equations (4.3- 4.5), [6], [24].

5.4.3 SU channel-slot configuration

The number of channel-slot(s) aggregated by the CRBS for a secondary user decreases as the SNR improves and vice visa as captured in Table I. θ_n is the number of channel-slot(s) a SU assembles in a given mode and SNR pair. In the notations, n denotes the n^{th} mode while N denotes the highest mode. From Table I, θ_n can be estimated for good, moderate or bad channel conditions respectively as;

$$\theta_n = \begin{cases} \underbrace{\begin{matrix} \frac{R_N}{R_n} = 1 & n = N \\ 0 & n = 1, \ . \ . N - 1 \end{matrix}}_{number\ of\ slots\ allocated\ in\ \ good\ SNR} \\ \underbrace{\begin{matrix} 0 & n = N \\ \frac{R_N}{R_n} & n = 1, \ . \ . N - 1 \end{matrix}}_{number\ of\ slots\ for\ moderate,bad\ channel\ state} \end{cases} \tag{5.3}$$

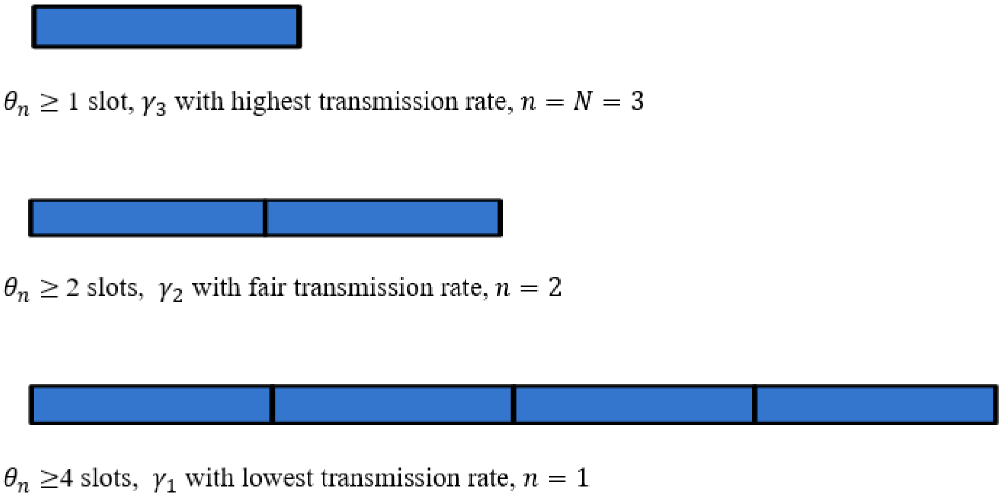

Figure 5.2 Channel-slot configuration which depends on SNR/mode pair.

Table 5.1

Transmission Modes with Convolutional Coded Modulation [8], [21], [22], [23]

AMC mode (n)	Modulation Scheme	Capacity (Mbps)	Spectral Eff. (R) bit/s/Hz	SNR (γ) [dB]	Code Rate (r)
1	QPSK	3.741	0.6241	4.31	1/2
2	16-QAM	7.491	1.2481	10.21	3/4
3	64-QAM	14.981	2.4961	18.31	2/3

The distinctiveness of this policies is such that, at the highest mode where $n = N$ (good channel quality) the SUs will assemble few slots. This ensures that more SUs are admitted into the network since service completion time will be reduced. However, as the channel quality deteriorates, more slots will be required to meet the QoS requirements of the SU as illustrated in Figure 5.2. It therefore means that the rates differ in as much as such that mode 3 rate is higher than mode 2 which is represented as;

$$R_N > R_{N-1} > R_{N-2} \ or \ R_{N-2} < R_{N-1} < R_N$$

Where R is defined in Table I. The PU channel utilization is characterised by two-state Markovian process of Figure 4.4 while α_i, β_i remaining the same. The PU channel-slot(s) capacity θ_{pu}, is given as in Equations 4.3 and 4.4 whereas the SU channel slot capacity θ_{su} and the total capacity of the system $(M * S)$ is given as in Equation (4.5). All other assumptions and notations remain unchanged.

5.5 Proposed Channel Assembling Strategies

Two CAS were proposed. They are the IBS and RBS respectively. On like the previous work in chapter four which focused on evaluation via system simulation, this chapter gives an analytical detail in the subsections following.

5.5.1 Immediate blocking strategy $(\boldsymbol{\omega}, \boldsymbol{\theta_{su}}, \boldsymbol{\theta_n})$

In this strategy, if there are insufficient or no capacity (channel slot) upon secondary user demand for spectrum resources, the secondary user is instantly blocked from accessing the networks irrespective of the SNR. This indicates that for a link conditions (bad, good or moderate), a specific number of spectrum resources is aggregated for the secondary user. Nevertheless, whenever a primary user arrives and picks from the assigned resources, and there are inadequate vacant channel slots to complement for the reduction, then, the SU is "forced to terminate" [6], [8], [24] . Just like in the previous chapter, the total number of SU in the system is V_n while the resource requirement is θ_n. Therefore, a SU will be granted access/admission into the network if the condition in equation (5.4) is satisfied.

$$\theta_{su} \geq \sum_{i=1}^{V_n} \theta_{n_i}, \quad \forall\, z(\phi) < M * S \tag{5.4}$$

Else, the SU is blocked if it satisfies Equation (5.5) which is the reverse of (5.4).

$$\theta_{su} \leq \sum_{i=1}^{V_n} \theta_{n_i}, \forall\{\, M * S - z(\phi)\} < \ \theta_{ni} \tag{5.5}$$

An SU could be forced to terminate if an arriving PU finds the SU using its channel-slot (resources) and there are no vacant slot(s) thus, satisfying equation (5.6). Note the criteria for blocking and forced termination is similar however, the only difference is that, in forced termination (dropping), the SU would have been granted access/admission into the spectrum. It can be can be expressed as;

$$\theta_{su} < \sum_{i=1}^{V_n} \theta_{n_i}\,, \ \ \forall\{\, M * S = z(\phi)\} \tag{5.6}$$

This indicates a reduction/inadequacy of the amount of SU resources (channel-slot). Likewise, an arriving PU could be blocked if condition in equation (5.7) is satisfied.

$$\omega \geq M \tag{5.7}$$

Nonetheless, since PU blocking is not taken into account, emphasis will not be placed on this particular condition because it is not part of the focus of this study. Though, it is possible among greedy PUs of different classes. The algorithm VI is similar to algorithm I but with details of events (arrival/departure).

```
Algorithm VI for the CA using IBS
// SU arrival
CRBS check wireless link $\gamma_{su}$ // CRBS checks wireless link state (SNR) for SUs.
    CRBS check $\theta_{su}$;// CRBS checks available recourse for SUs
If ($\theta_{su} \geq \sum_{i=1}^{V_n} \theta_{n_i}$ ); // resource assembly test as a function of SNR/mode pair.
    $SU_i$_Admit = True;//accept  $SU_i$ and aggregate resources
Else
     $SU_i$_Admit=False;//block the $SU_s$
Else
    End if ;// terminate if no event
// PU arrival
CRBS check wireless link $\gamma_{su}$;//CRBS checks wireless link state (SNR) for SUs.
If [($\theta_{su} < \sum_{i=1}^{V_n} \theta_{n_i}$) ]; // PU arrival pick some SU resources
    $SU_i$_Drop =true;// forced-terminate of ongoing  $SU_s$
  Else
If ($\omega \geq M$);//PU arrives and are more than the available channels
     $PU_i$_FT=true;// SU dropped due to PU arrival
    Else
    $PU_i$_admit=true;// admission PU
End if ;// terminate if no event

// PU departure
```

```
  CRBS check wireless link $\gamma_{su}$ //CRBS checks wireless link for PU absence
If $PU_{i\_}$Channel-slots=Idle (free); // free PU slots
    $SU_i$_Admit = true;// admit new $SU_s$
End
Go to start.
```

5.5.2 Readjustment based strategy ($\omega, \theta_{su}, \theta_n^{min}, \theta_n^{max}$)

In this strategy, secondary user needs a minimum of θ_n^{min} and maximum of θ_n^{max} resources to commence service and stop assembling respectively. When a secondary user requests for service, the assembling protocol domiciled in the CRBS checks for resource accessibility in a similar manner like the IBS scheme. Else, if otherwise as a consequent of PU appearance, the readjustment algorithm VII is executed which enables the SU with the maximum assembled channel denote to starving or new arriving SUs respectively.All other symbols, assumption remain same as in the IBS case [6], [8], [24].

```
Algorithm VII for the CA using RBS
//SU arrival
CRBS check wireless link $\gamma_{su}$; // CRBS checks wireless link state (SNR) for SUs.
  CRBS check $\theta_{su}$;// CRBS checks available recourse for SU
If ($\theta_{su} \geq \sum_{i=1}^{V_n} \theta_{n_i}^{min}$); // test for $SU_i$ resources
      $SU_i$_Admit = True; // accept $SU_i$ and aggregate resources.
Else
if ($\sum_{i=1}^{V_n} \theta_{n_i}^{min}) < \theta_{n,new}^{min})]$ ;// test for new SU arrival due to PU arrival
Go to Do procedure;// Next three step below
// PU arrival
```

```
CRBS check wireless link $\gamma_{su}$ // cognitive radio base station checks wireless link state (SNR) for SUs.
if ( $\theta_{su} < \sum_{i=1}^{V_n} \theta_{n_i}^{min}$);// PU arrives and pick some SU resources
Do $(\theta_j^{max} - 1)$, ++ j; // SU with max. channel, donate and iterate over j user resources
  $SU_{i,j}$, _Admit = True; // admit $SU_{i,j}$ and assemble for both users
    Else
        $SU_i$_Admit =False; // block new $SU_i$due to no-free slot or insufficient
   Else
      If ($\omega \geq M$);// PU arrives and are more than the available M channels
    $PU_i$_FT=True;// SU dropped due to batch PU arrivals
Else
    $PU_i$_Admit=True;// admission PU
    If all conditions cannot be met
      $SU_i$_ FT =True;// force-terminate on going $SU_i$
End if; // start the process.
```

```
// PU departure
```

```
  CRBS check wireless link $\gamma_{su}$ // CRBS checks wireless link for PU absence
If $PU_i$_channel-slots=Idle;// free channel slot exists
  $SU_i$_Admit = True;// admit $SU_s$ admit $SU_i$ and assemble
     Do $(\theta_j^{min} + 1)$;// SU with min channel adjust upward
End
Go to start.
```

5.6 System Analytical Models

The analytical model comprises of dynamic and static SU traffic that employs the CAS of section 4.4 and 5.5. As earlier stated, the resource requirements for the static traffic is (θ_n) while that of the dynamic ranges between $\theta_n^{min} \leq \theta_n^{max}$. Where n could be bad, good, moderate wireless link for user *i* or *j*. The arrival rate for the PUs and SUs follows a Poisson distribution with parameters λ_p and λ_s for PUs and SUs respectively. The service times are exponentially distributed with the service rates μ_p and μ_s for the PUs and SUs respectively. The total service for a user is assumed as the product of the user service rate and the number of accessible channel-slot $\theta_{su}\mu_{su}$. Thus, the system is modelled as a CTMC with state represented by $\phi = \{\omega, V_g, V_m, V_b\}$. where ω is the number of PUs, V_b, V_m, and V_g are the numbers of SUs in a bad, moderate and good conditions respectively. The utilization is expressed as $z(\phi) = \omega + (\theta_g V_g + \theta_m V_m + \theta_b V_b)$, where θ_g, θ_m, and θ_b are the number of channel-slots assembled by the CRBS for its associate SUs with respective to the SNR. The state transition diagram is shown in Figure. 5.3. Note: crossing of state (good to bad or vice versa) is not allowed since we are considering slow fading.

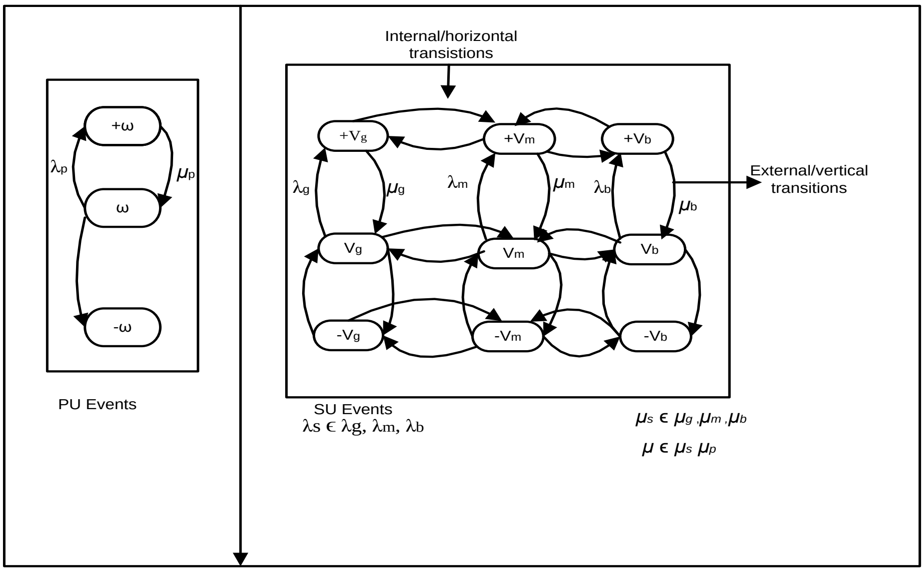

Figure 5.3 Summarized System Transition Diagram [8]

In Figure 5.3, the transitions can be characterized as *Internal/horizontal* and *external/vertical.* The internal transitions occur among SUs within the system (admitted) and their transitions is a function of the varying wireless link (channel condition) while the external transitions occur as a result of arrival of new PU/SU into the system and departure out of the system. Moreover, admission or blocking occurs at the point of entrance into the system, while forced termination occurs for already admitted/accepted SUs as earlier mentioned.

5.6.1 CTMC Analysis for IBS

The possible feasible state of the strategy is expressed as ɋ $= \{\phi \mid \omega, V_g, V_m, V_b) \geq 0;\ z(\phi)\ \leq M * S\}$. Subsequently, we describe all the possible state transition of the system.

5.6.2 Transition Table from Present State (ω, V_g, V_m, V_b) to Other States

For simplicity, the PU is assumed either departing/arriving($\omega - 1 or\ \omega + 1$) hence, the transition table reflects more the SUs state events which is our utmost concern.

Table 5.2

Transition state for the IBS Strategy $(\omega, \theta_{su},\ \theta_n\ )$ [8]

No.	Present State	Next state	Possible State Events	Transition Rate
	(ω, V_g, V_m, V_b)		PU **departs/arrival**	
(1)		$(\omega - 1, V_g, V_m, V_b)$	PU **departs** from the system.	$\omega\mu_p$
(2)		$(\omega + 1, V_g, V_m, V_b)$	PU **arrives** into the system.	λ_p
		SU **departs/arrival**		
(3)		$(V_g - 1, V_m, V_b)$ (external)	SU in good state **departs** from the system after service completion.	$[\mu_s V_g]$
(4)		$(V_g - 1, V_m + 1, V_b)$	SU transits from good to moderate state.	$\left[\frac{\theta_m V_m}{z(\phi)}\right]\lambda_s$
			SU in moderate state **departs** after service completion.	$[\mu_s V_m]$
			SU in moderate state **FT** due to PU arrival. equation (5.6)	$\left[\frac{\theta_m V_m}{z(\phi) - \omega}\right]\lambda_p$
(5)		$(V_g + 1, V_m, V_b)$ (external)	SU arrives into the system in good state with the likelihood of being **admitted/accepted**, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation $(\sum_{i=1}^{V_g} \theta_{g_i}\ )$ of the channel slot required by the V_g, i.e. If $\theta_{su} \geq \sum_{i=1}^{V_g} \theta_{g_i}\ , \forall\ z(\phi) < M * S$ as in equation (5.4)	$\left[\frac{\theta_g V_g}{z(\phi)}\right]\lambda_s$
			Otherwise, it is **blocked** which denotes **NOT accepted** i.e. if $\theta_{su} \leq \sum_{i=1}^{V_g} \theta_{g_i}\ ,\ \forall\{M * S - z(\phi)\} <\ \ \theta_{g_i}$ as in equation (5.5)	
			No **FT** occurred in this event i.e. FT = 0 (PU absent)	FT = 0
(6)		$(V_g + 1, V_m - 1, V_b)$ (internal)	SU transits from moderate to good state.	$\left[\frac{\theta_g V_g}{z(\phi)}\right]\lambda_s$
			SU in good state **departs** after service completion.	$[\mu_s V_g]$
			SU in good state **FT** due to PU arrival with rate. equation (5.6)	$\left[\frac{\theta_g V_g}{z(\phi) - \omega}\right]\lambda_p$
(7)		$(V_g, V_m, V_b - 1)$ (external)	SU in bad state **depart** from the system.	$[\mu_s V_b]$
(8)		$(V_g, V_m + 1, V_b - 1)$ (internal)	SU transits from bad to moderate state.	Same as (4)
			SU in moderate state **departs** after service completion.	Same as (4)
			SU in moderate state **FT** due to PU arrival equation (5.6)	Same as (4)
(9)		$(V_g, V_m, V_b + 1)$ (external)	SU arrives into the system in bad state with the likelihood of being **admitted/accepted**, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation $(\sum_{i=1}^{V_b} \theta_b\ )$ of the channel slot required by	$\left[\frac{\theta_b V_b}{z(\phi)}\right]\lambda_s$

			the V_b, i.e. If $\theta_{su} \geq \sum_{i=1}^{V_b} \theta_{b_i}$,$\forall\, z(\phi) < M * S$ as in equation (5.4)	
			Otherwise, it is **blocked** which denotes **NOT accepted** i.e. if $\theta_{su} < \sum_{i=1}^{V_b} \theta_{b_i}$, $\forall\{ M * S - z(\phi)\} < \theta_{b_i}$ as in equation (5.5)	
			No **FT** occurs in this event i.e. FT $= 0$	FT $= 0$
(10)		$(V_g, V_m - 1, V_b + 1)$ (internal)	SU transits from moderate to bad state.	$\left[\frac{\theta_b V_b}{z(\phi)}\right] \lambda_s$
			SU in moderate state **depart** after service completion.	$[\mu_s V_b]$
			SU in moderate state FT due to PU as in equation (5.6)	$\left[\frac{\theta_b V_b}{z(\phi) - \omega}\right] \lambda_p$
(11)		$(V_g, V_m - 1,\ V_b)$ (external)	SU in moderate state **depart** from the system.	$[\mu_s V_m]$
(12)		$(V_g, V_m + 1, V_b)$ (external)	SU arrives into the system in moderate state with the likelihood of being **admitted/accepted**, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation ($\sum_{i=1}^{V_m} \theta_m$) of the channel slot required by the V_b, i.e. if $\theta_{su} \geq \sum_{i=1}^{V_m} \theta_{m_i}$, $\forall\, z(\phi) < M * S$ as in equation (5.4)	$\left[\frac{\theta_m V_m}{z(\phi)}\right] \lambda_s$
			Otherwise, it is **blocked** which denotes **NOT accepted** i.e. if $\theta_{su} < \sum_{i=1}^{V_m} \theta_{m_i}$, $\forall\{ M * S - z(\phi)\} < \theta_{m_i}$ as in equation (5.5)	
			No **FT** occurs in this event i.e. FT $= 0$ (PU absent)	FT $= 0$

5.6.3 Performance Measures

The derivations are on the premise of [4], [5]. However, in this study, three channel conditions were considered for the SUs. The blocking, forced termination, and admission/acceptance probabilities respectively, are also considered with respect to the varying channel conditions.

5.6.4 Immediate Blocking Strategy IBS

The state transitions are summarized in Table II. Based on the transition rates for the three channel condition, the normalized and balance equation are established in equation (5.7) respectively. $\boldsymbol{\psi}$ is the transition rate matrix whereas the state probabilities are denoted by $\pi(\phi)$ hence, ϕ can be obtained. Given the state probabilities $\pi(\phi)$, the system performance can be developed as follows:

$$\pi\,\boldsymbol{\psi} = 0, \qquad \sum_{\phi \in \text{ȼ}} \pi(\phi) = 1 \tag{5.7}$$

a) The Blocking Probability P_b^n

The blocking probability is expressed in rates. However, the blocking probability P_b^n at a particular channel state (good, moderate or bad) is the sum of all probabilities of states that cannot admit/accept SU into the system. The arriving SU will be blocked if the sum of the available idle channels/slots is less than the required as stated in Table II. It can be expressed as;

$$P_b^n = \frac{Total\ \ SU\ blocking\ rate\ at\ a\ particular\ channel\ state}{SU\ arrival\ rate\ at\ a\ particular\ channel\ state} \tag{5.8}$$

Where *n* depicts the wireless link condition i.e. (good, moderate or bad).

$$P_b^g = \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \le \sum_{i=1}^{V_g} \theta_{g_i}, \\ M*S-Z(\phi) < \theta_{g_i}}} \frac{\theta_g V_g}{Z(\phi)}\, \pi(\phi) \right] \Bigg/ \lambda_s = \frac{1}{\lambda_s} \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \le \sum_{i=1}^{V_g} \theta_{g_i}, \\ M*S-Z(\phi) < \theta_{g_i}}} \frac{\theta_g V_g}{Z(\phi)}\, \pi(\phi) \right] \tag{5.9}$$

Where P_b^g is the blocking probability when the wireless link is in good state.

$$P_b^m = \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \le \sum_{i=1}^{V_m} \theta_{m_i}, \\ M*S-Z(\phi) < \theta_{m_i}}} \frac{\theta_m V_m}{Z(\phi)}\, \pi(\phi) \right] \Bigg/ \lambda_s = \frac{1}{\lambda_s} \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \le \sum_{i=1}^{V_m} \theta_{m_i}, \\ M*S-Z(\phi) < \theta_{m_i}}} \frac{\theta_m V_m}{Z(\phi)}\, \pi(\phi) \right] \tag{5.10}$$

P_b^m is the blocking probability when the wireless link is in moderate state.

$$P_b^b = \left[\sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} \leq \sum_{i=1}^{V_b} \theta_{b_{i,}} \\ M*S-Z(\phi) < \theta_{b_i}}} \frac{\theta_b V_b}{Z(\phi)} \pi(\phi) \right] \Big/ \lambda_s = \frac{1}{\lambda_s} \left[\sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} \leq \sum_{i=1}^{V_b} \theta_{b_i} \\ M*S-Z(\phi) < \theta_{b_i}}} \frac{\theta_b V_b}{Z(\phi)} \pi(\phi) \right] \tag{5.11}$$

P_b^b is the blocking probability when the wireless link is in bad state.

b) The forced termination probability (P_{ft}^n)

The forced termination occurs whenever an ongoing SU service is interrupted by a PU arrival irrespective of the wireless channel state, and the SU and cannot hands-off to an idle slots/channels. In this study, forced termination probability denotes the total forced termination rate divided by the total admitted/accepted SU rate. It can be expressed as,

$$P_{ft}^n = \frac{Total\ SU\ forecd\ termination\ rate\ at\ a\ particular\ channel\ state}{SU\ connections(rate\ of\ commensed\ SU\ service)} \tag{5.12}$$

However, SU connections rate (rate of commenced SU service) indicates that, admission has been granted which can be expressed as $(1 - P_b^n)\lambda_s$. Thus,

$$P_{ft}^g = \left[\lambda_p \sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} < \sum_{i=1}^{V_g} \theta_{g_i}, \\ M*S=Z(\phi)}} \frac{\theta_g V_g}{Z(\phi)-\omega} \pi(\phi) \right] \Big/ (1 - P_b^g)\lambda_s = \frac{\lambda_p}{(1-P_b^g)\lambda_s} \left[\sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} < \sum_{i=1}^{V_g} \theta_{g_i}, \\ M*S=Z(\phi)}} \frac{\theta_g V_g}{Z(\phi)-\omega} \pi(\phi) \right] \tag{5.13}$$

Where P_{ft}^g is the FT probability when the wireless link is in good state.

$$P_{ft}^m = \left[\lambda_p \sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} < \sum_{i=1}^{V_m} \theta_{m_i}, \\ M*S=Z(\phi)}} \frac{\theta_m V_m}{Z(\phi)-\omega} \pi(\phi) \right] \Big/ (1 - P_b^m)\lambda_s = \frac{\lambda_p}{(1-P_b^m)\lambda_s} \left[\sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} < \sum_{i=1}^{V_m} \theta_{m_i}, \\ M*S=Z(\phi)}} \frac{\theta_m V_m}{Z(\phi)-\omega} \pi(\phi) \right] \tag{5.14}$$

P_{ft}^m is the FT probability when the wireless link is in moderate state.

$$P_{ft}^b = \left[\lambda_p \sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} < \sum_{i=1}^{V_b} \theta_{b_i}, \\ M*S=Z(\phi)}} \frac{\theta_b V_b}{Z(\phi) - \omega} \pi(\phi) \right] \Big/ (1 - P_b^b)\lambda_s = \frac{\lambda_p}{(1 - P_b^b)\lambda_s} \left[\sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} < \sum_{i=1}^{V_b} \theta_{b_i}, \\ M*S=Z(\phi)}} \frac{\theta_b V_b}{Z(\phi) - \omega} \pi(\phi) \right] \tag{5.15}$$

$P_{ft}^{b}$is the FT probability when the wireless link is in bad state.

c) Acceptance/Admission probability (P_a^n)

The acceptance/admission probability is the probability that enough resources exists for the SU when it arrives or the resources (channel/slots) remaining is after PU occupancy, is greater than or equal to the resources required by the SU. It can be expressed as the rate of *Not Blocking* with respect to the wireless link.

$$P_a^n = (1 - P_b^n) \tag{5.16}$$

Therefore, for each respective wireless link condition, it can be expressed respectively as fellows,

$$P_a^g = \left(1 - P_b^g\right) \tag{5.17}$$

$$P_a^g = \left(1 - \left[\sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} \leq \sum_{i=1}^{V_g} \theta_{g_i}, \\ M*S - Z(\phi) < \theta_{g_i}}} \frac{\theta_g V_g}{Z(\phi)} \pi(\phi) \right] \right) \tag{5.18}$$

Where P_a^g is the acceptance/admission probability when the wireless link is in good state.

$$P_a^m = (1 - P_b^m) \tag{5.19}$$

$$P_a^m = \left(1 - \left[\sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} \leq \sum_{i=1}^{V_m} \theta_{m_i}, \\ M*S - Z(\phi) < \theta_{m_i}}} \frac{\theta_m V_m}{Z(\phi)} \pi(\phi) \right] \right) \tag{5.20}$$

P_a^m is the acceptance/admission probability when the wireless link is in moderate state.

$$P_a^b = \left(1 - P_b^b\right) \tag{5.21}$$

$$P_a^b = \left(1 - \left[\sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} \leq \sum_{i=1}^{V_b} \theta_{b_i} \\ M*S - Z(\phi) < \theta_{b_i}}} \frac{\theta_b V_b}{Z(\phi)} \pi(\phi) \right] \right) \tag{5.22}$$

d) Capacity (σ_n)

The capacity of the SU is the average service rate of the SUs. This implies the average number of SU service completion per time [145]. However, the capacity is dynamic since the SNR, the number of channel slots assembled by the CRBs and the number of SUs varies. For simplicity, it can be expressed as,

$$\sigma_n = \sum_{\phi \in \text{ɖ}} \theta_{ni} \, V_n \, \mu_s^n \pi(\phi) \tag{5.23}$$

e) Service rate (μ_s^n)

Service rate μ_s^n is the capacity of the secondary network divided by the number of admitted SUs at a particular time, which is a function of the SNRs/modes pair. It can be expressed as,

$$\mu_s^n = \frac{\sigma_n}{\sum_{\phi \in \text{ɖ}} V_n \, \pi(\phi)} \tag{5.24}$$

Note that, the generic symbols θ_n and V_n could not be used when representing blocking, forced termination and access/admission probability above because of their respective specificity (different criteria). Note, $\theta_n \equiv \theta_g, \theta_m, \theta_n^{min}, \theta_n^{max}$ or θ_b and $V_n \equiv V_g, V_m$ or V_b respectively. Also, V_g , $V_m, V_b \in V_n$ and $\theta_n, \theta_g, \theta_m, \theta_b, \theta_n^{min}, \theta_n^{max} \in \theta_{su}$

5.6.5 CTMC Analysis for Readjustment Based Strategy

This is similar to the IBS scheme. The difference is that the CRBS adjusts between the minimum and maximum number of channel slots a SU can aggregate depending on the availability of resources and the arrival of a PU. The feasible state can be expressed as,

$$\text{ɖ} = \left\{ \left(\omega, V_g, V_m, V_b \right) \middle| \; \omega + \theta_n^{max} \, V_n < M * S \right\} \cup \{ z(\phi) = M * S \} \tag{5.25}$$

5.6.6 Performance Measures of the Readjustment Based Strategy

The state transitions are summarized in Table III just like the IBS scheme and also on the premise of [4], [5]. However, there are some variations due to the flexibility of the RBS scheme when PU arrives and thus, makes their performance measures different.

a) *The Blocking Probability* $(*\,P_b^n)$

The blocking probability P_b^n, is the probability that a SU will be blocked from gaining access into spectrum when it arrives due to sufficient resources or no resources for it to commence transmission at particular channel state. It implies the sum of all probabilities of states that cannot admit/accept SU into the system due to resources availability. In this work P_b^n is expressed in rate as,

$$*\,P_b^n = \frac{Total\ \ SU\ blocking\ rate\ at\ a\ particular\ channel\ state}{SU\ arrival\ rate\ at\ a\ particular\ channel\ state} \tag{5.26}$$

$$*\,P_b^g = \left[\sum_{\substack{\phi\in\text{Ȼ} \\ \theta_{su}\leq\sum_{i=1}^{V_g}\ \theta_{g_i}^{min}, \\ M*S-Z(\phi)<\ \theta_{g_i}^{min}}} \frac{\theta_g^{min}V_g}{Z(\phi)}\,\pi(\phi)\right] \Big/ \lambda_s = \frac{1}{\lambda_s}\left[\sum_{\substack{\phi\in\text{Ȼ} \\ \theta_{su}\leq\sum_{i=1}^{V_g}\ \theta_{g_i}^{min}, \\ M*S-Z(\phi)<\ \theta_{g_i}^{min}}} \frac{\theta_g^{min}V_g}{Z(\phi)}\,\pi(\phi)\right] \tag{5.27}$$

Where P_b^g the blocking probability in good wireless link.

Note: the symbol $*$ (asterisk) is used to differentiate the RBS metrics form the IBS and not a multiplication or convolution.

$$*\,P_b^m = \left[\sum_{\substack{\phi\in\text{Ȼ} \\ \theta_{su}\leq\sum_{i=1}^{V_m}\ \theta_{m_i}^{min}, \\ M*S-Z(\phi)<\ \theta_{m_i}^{min}}} \frac{\theta_m^{min}V_m}{Z(\phi)}\,\pi(\phi)\right] \Big/ \lambda_s = \frac{1}{\lambda_s}\left[\sum_{\substack{\phi\in\text{Ȼ} \\ \theta_{su}\leq\sum_{i=1}^{V_m}\ \theta_{m_i}^{min}, \\ M*S-Z(\phi)<\ \theta_{m_i}^{min}}} \frac{\theta_m^{min}V_m}{Z(\phi)}\,\pi(\phi)\right] \tag{5.28}$$

Where P_b^m is the blocking probability in moderate wireless link.

$$*\,P_b^b = \left[\sum_{\substack{\phi\in\text{Ȼ} \\ \theta_{su}\leq\sum_{i=1}^{V_b}\ \theta_{b_i}^{min}, \\ M*S-Z(\phi)<\ \theta_{b_i}^{min}}} \frac{\theta_b^{min}V_g}{Z(\phi)}\,\pi(\phi)\right] \Big/ \lambda_s = \frac{1}{\lambda_s}\left[\sum_{\substack{\phi\in\text{Ȼ} \\ \theta_{su}\leq\sum_{i=1}^{V_b}\ \theta_{b_i}^{min}, \\ M*S-Z(\phi)<\ \theta_{b_i}^{min}}} \frac{\theta_b^{min}V_g}{Z(\phi)}\,\pi(\phi)\right] \tag{5.29}$$

Where P_b^b is the blocking probability in bad wireless link.

b) *The forced termination probability* $(*\,P_{ft}^{n})$

With similar definition as mentioned in IBS, it can be expressed as,

$$*\,P_{ft}^{n} = \frac{Total\ SU\ forecd\ termination\ rate\ at\ a\ particular\ channel\ state}{SU\ connections(rate\ of\ commensed\ SU\ service)} \tag{5.30}$$

$$*\,P_{ft}^{g} = \left[\lambda_p \sum_{\substack{\phi \in \text{ɖ} \\ \theta_{su} < \sum_{i=1}^{V_g} \theta_{g_i}^{min}, \\ M*S = Z(\phi)}} \frac{\theta_g^{min} V_g}{Z(\phi) - \omega}\, \pi(\phi)\right] \Big/ (1 - P_b^{g})\lambda_s$$

$$= \frac{1}{\left(1 - P_b^{g}\right)\lambda_s} \left[\lambda_p \sum_{\substack{\phi \in \text{ɖ} \\ \theta_{su} < \sum_{i=1}^{V_g} \theta_{g_i}^{min}, \\ M*S = Z(\phi)}} \frac{\theta_g^{min} V_g}{Z(\phi) - \omega}\, \pi(\phi)\right] \tag{5.31}$$

Where $P_{ft}^{g}$is the force termination (FT) probability in good wireless link

$$P_{ft}^{m} = \left[\lambda_p \sum_{\substack{\phi \in \text{ɖ} \\ \theta_{su} < \sum_{i=1}^{V_m} \theta_{m_i}^{min}, \\ M*S = Z(\phi)}} \frac{\theta_m^{min} V_m}{Z(\phi) - \omega}\, \pi(\phi)\right] \Big/ (1 - P_b^{m})\lambda_s$$

$$= \frac{1}{(1 - P_b^{m})\lambda_s} \left[\lambda_p \sum_{\substack{\phi \in \text{ɖ} \\ \theta_{su} < \sum_{i=1}^{V_m} \theta_{m_i}^{min}, \\ M*S = Z(\phi)}} \frac{\theta_m^{min} V_m}{Z(\phi) - \omega}\, \pi(\phi)\right] \tag{5.32}$$

Where $P_{ft}^{m}$is the forced termination (FT) probability at moderate wireless link

$$* P_{ft}^{b} = \left[\lambda_p \sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} < \sum_{i=1}^{V_b} \theta_{b_i}^{min}, \\ M*S = Z(\phi)}} \frac{\theta_b^{min} V_b}{Z(\phi) - \omega}\, \pi(\phi) \right] \Big/ (1 - P_b^b)\lambda_s$$

$$= \frac{1}{(1 - P_b^b)\lambda_s} \left[\lambda_p \sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} < \sum_{i=1}^{V_b} \theta_{b_i}^{min}, \\ M*S = Z(\phi)}} \frac{\theta_b^{min} V_b}{Z(\phi) - \omega}\, \pi(\phi) \right] \tag{5.33}$$

$P_{ft}^{m}$is the forced termination probability in bad wireless link

c) *Acceptance/Admission probability* $(* P_a^n)$

As states in the IBS scheme, the acceptance/admission probability is given as,

$$* P_a^n = (1 - P_b^n) \tag{5.34}$$

For each wireless link condition, it can be expressed respectively as follows:

$$* P_a^g = \left(1 - P_b^g\right) \tag{5.35}$$

$$* P_a^g = \left(1 - \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \le \sum_{i=1}^{V_g} \theta_{g_i}^{min}, \\ M*S - Z(\phi) < \theta_{g_i}^{min}}} \frac{\theta_g^{min} V_g}{Z(\phi)}\, \pi(\phi) \right] \right) \tag{5.36}$$

$$* P_a^m = (1 - P_b^m) \tag{5.37}$$

$$* P_a^m = \left(1 - \left[\sum_{\substack{\phi \in \mathfrak{C} \\ \theta_{su} \le \sum_{i=1}^{V_m} \theta_{m_i}^{min}, \\ M*S - Z(\phi) < \theta_{m_i}^{min}}} \frac{\theta_m^{min} V_m}{Z(\phi)} \pi(\phi)\right]\right) \tag{5.38}$$

P_a^m is the acceptance/admission probability when the wireless link is in moderate condition.

$$* P_a^b = \left(1 - P_b^b\right) \tag{5.39}$$

$$* P_a^b = \left(1 - \left[\sum_{\substack{\phi \in \mathfrak{C} \\ \theta_{su} \le \sum_{i=1}^{V_b} \theta_{b_i}^{min}, \\ M*S - Z(\phi) < \theta_{b_i}^{min}}} \frac{\theta_b^{min} V_b}{Z(\phi)} \pi(\phi)\right]\right) \tag{5.40}$$

P_a^b is the acceptance/admission probability when the wireless link is in bad condition.

d) Capacity $(* \sigma_n)$

The capacity of the SU is the average service rate of the SUs, i.e., the average number of SU completion per time [24]. It can be expressed as,

$$* \sigma_n = \sum_{\phi \in \mathfrak{C}} \sum_{i=1}^{V_n} * \mu_s^n \theta_{ni}^{max} \pi(\phi) \tag{5.41}$$

e) Service rate $(* \mu_s^n)$

Service rate μ_s^n is the capacity of the secondary network divided by the number of admitted SUs at a particular time, which it is a function of the SNRs/modes pair. It can be expressed as,

$$* \mu_s^n = \frac{* \sigma_n}{\sum_{\phi \in \mathfrak{C}} V_n \pi(\phi)} \tag{5.42}$$

Table 5.3

Transition state for the RBS Strategy $(\omega, \theta_{su}, \theta_n^{min}, \theta_n^{max})$ [8]

No.	Present State	Next state	Possible State Events	Transition Rate
(1)	(ω, V_g, V_m, V_b)	$(\omega - 1, V_g, V_m, V_b)$	PU departs from the system	$\mu_p \omega$
(2)		$(V_g - 1, V_m + 1, V_b)$ (external)	SU in good state with minimum/maximum number of channel slots $(\theta_n^{min}/\theta_n^{max})$ departs from system after service completion	$\theta_m^{min} \mu_s V_g$ $\theta_m^{max} \mu_s V_g$
(3)		$(V_g - 1, V_m + 1, V_b)$ (internal)	SU with minimum/maximum number of channel slots $(\theta_n^{min}/\theta_n^{max})$ transits from good to moderate state.	$\left[\frac{\theta_m^{min} V_m}{z(\phi)}\right] \lambda_s$ $\left[\frac{\theta_m^{max} V_m}{z(\phi)}\right] \lambda_s$
			SU in bad state with a minimum number of channel slots (θ_n^{min}) uses the released channel slots to achieve upper bound (θ_n^{max})	$[\theta_m^{min} \mu_s V_b]$
			SU in bad state depart from after service completion.	$[\theta_m^{max} \mu_s V_m]$
			SU in bad state **FT** due to PU arrival.	$\left[\frac{\theta_m^{min} V_m}{z(\phi) - \omega}\right] \lambda_p$
(4)		$(V_g + 1, V_m, V_b)$ (external)	SU arrives into the system in good state with the likelihood of being **admitted/accepted**, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation $(\sum_{i=1}^{V_g} \theta_{g_i}^{min})$ of the channel slots required by the V_g. i.e. If $\theta_{su} \geq \sum_{i=1}^{V_g} \theta_{g_i}^{min}, \forall\, z(\phi) < M * S$	$\left[\frac{\theta_g^{min} V_g}{z(\phi)}\right] \lambda_s$
			Otherwise, it is **blocked** which denotes **NOT accepted** i.e. if $\theta_{su} < \sum_{i=1}^{V_g} \theta_{g_i}^{min}$, $\forall\{M * S - z(\phi)\} < \theta_{g_i}^{min}$	
(5)		$(V_g + 1, V_m - 1, V_b)$ (internal)	SU AR. The SU in bad state with the maximum number of channel slots (θ_n^{max}) donates to newly arrived service.	$\left[\frac{\theta_b^{max} V_b}{z(\phi)}\right] \lambda_s$
			No **FT** occurred in this event i.e. FT $= 0$	FT $= 0$
			SU with minimum/maximum number of channel slot $(\theta_n^{min}/\theta_n^{max})$ transits from moderate to good.	Same as in (3)
			SU in good state with minimum number of channel slots (θ_n^{min}) uses the released channel slots to achieve upper bound (θ_n^{max})	$[\theta_g^{min} \mu_s V_g]$
			SU in good state **departs** from system after service completion.	$[\theta_g^{max} \mu_s V_g]$
			SU in good state **FT** due to PU arrival.	$\left[\frac{\theta_g^{min} V_g}{z(\phi) - \omega}\right] \lambda_p$
(6)		$(V_g, V_m, V_b - 1)$ (external)	SU in bad state with minimum/maximum number of channel slots $(\theta_n^{min}/\theta_n^{max})$ departs from the system after service completion (releases the channel slot).	$[\theta_b^{min} \mu_s V_b]$ $[\theta_b^{max} \mu_s V_b]$
(7)		$(V_g, V_m + 1, V_b - 1)$ (internal)	SU with minimum/maximum number of channel slot $(\theta_n^{min}/\theta_n^{max})$ transits from bad to moderate state.	$\left[\frac{\theta_m^{min} V_m}{z(\phi)}\right] \lambda_s$ $\left[\frac{\theta_m^{max} V_m}{z(\phi)}\right] \lambda_s$

			The SU in moderate state with minimum number of channel slots (θ_n^{min}) uses the released channel slots to achieve upper bound (θ_n^{max})	$[\theta_m^{min}\mu_s V_b]$
			SU in moderate state **departs** from the system after service completion.	$[\theta_m^{max}\mu_s V_m]$
			SU in bad state **FT** due to PU arrival.	$\left[\frac{\theta_m^{min}V_m}{z(\phi)-\omega}\right]\lambda_p$
(8)		(V_g, V_m, V_b+1) (external)	SU arrives into the system in bad state with the likelihood of being **admitted/accepted**, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation ($\sum_{i=1}^{V_b}\theta_b^{min}$) of the channel slots required by the V_b. i.e. If $\theta_{su} \geq \sum_{i=1}^{V_b}\theta_{b_i}^{min}$, $\forall\, z(\phi) < M * S$	$\left[\frac{\theta_b^{min}V_b}{z(\phi)}\right]$
			Otherwise, it is **blocked** which denotes **NOT accepted** i.e. if $\theta_{su} < \sum_{i=1}^{V_b}\theta_{b_i}^{min}$, $\forall\{M * S - z(\phi)\} < \theta_{b_i}^{min}$	
			SU AR. The SU in bad state with the maximum number of channel slots (θ_n^{max}) donates to the newly arrived service.	$\left[\frac{\theta_b^{max}V_b}{z(\phi)}\right]\lambda_s$
			No **FT** occurred in this event, i.e. FT = 0	FT = 0
(9)		(V_g, V_m-1, V_b+1) (internal)	SU with minimum/maximum number of channel slot ($\theta_n^{min}/\theta_n^{max}$) transits from moderate to bad state.	$\left[\frac{\theta_b^{min}V_b}{z(\phi)}\right]\lambda_s$ $\left[\frac{\theta_b^{max}V_b}{z(\phi)}\right]\lambda_s$
			SU in bad state with minimum number of channel slot (θ_n^{min}) uses the released channel slots to achieve upper bound (θ_n^{max})	$[\theta_b^{min}\mu_s V_b]$
			SU in bad state departs from the system after service completion.	$[\theta_b^{max}\mu_s V_b]$
			SU in bad state **FT** due to PU arrival.	$\left[\frac{\theta_b^{min}V_b}{z(\phi)-\omega}\right]\lambda_p$
(10)		(V_g, V_m-1, V_b) (external)	SU in moderate state with minimum/maximum number of channel slots ($\theta_n^{min}/\theta_n^{max}$) state departs from the system after service completion (releases the channel slots).	$[\theta_m^{min}\mu_s V_m]$ $[\theta_m^{max}\mu_s V_m]$
(11)		(V_g, V_m+1, V_b) (external)	The SU arrives into the system in moderate state with the likelihood of being **admitted/accepted**, if the number of idle channel slots (θ_{su}) available is greater than or equal to the summation ($\sum_{i=1}^{V_m}\theta_{m_i}^{min}$) of the channel slots required by the $\mathrm{V_b}$. i.e. If $\theta_{su} \geq \sum_{i=1}^{V_m}\theta_{m_i}^{min}$, $\forall\, z(\phi) < M * S$	$\left[\frac{\theta_m^{min}V_m}{z(\phi)}\right]\lambda_s$
			Otherwise, it is **blocked** which denotes **NOT accepted** i.e. if $\theta_{su} < \sum_{i=1}^{V_m}\theta_{m_i}^{min}$, $\forall\{M * S - z(\phi)\} < \theta_{m_i}^{min}$	
			SU arrive. The SU in moderate state with the maximum number of channel slots (θ_n^{max}) donates to newly arrived service.	$\left[\frac{\theta_m^{max}V_m}{z(\phi)}\right]\lambda_s$

5.7 Numerical Results and Discussions

In this section, the numerical results based on the analysis and simulation, are presented to evaluate the system performance. Like the strategies in literatures which assumed a homogeneous channel condition (uniform SNRs) for SUs, this work considered the varying nature of the wireless link and an enabling technique like AMC. These factors make the system model heterogeneous and more realistic. MATLAB tool was used to run the simulations for each of the strategies. Moreover, parameters in literature [4, 5], [96], [98] where adopted. 100 realized are averaged to obtain the final result from10^6 iterations however, the scenarios and concept differ slightly due to the introduction of AMC and SNR which are main factors of a varying wireless link. $\lambda_p = 0.5$, $\lambda_s = 1.5$, $\mu_p = 0.5$, $*\mu_{su} = \mu_{su} = 0.82, \omega \leq 6$, $*P_a^n = 0.5$, $*P_b^n \leq 0.5$, $P_a^n \leq 0.5$, $P_b^n \leq 0.5, P_{ft}^{n,} \leq 0.15$,$*P_{ft}^{n,} \leq 0.15$, $V_g = 6, V_m = 3, V_b = 2, \text{SNR} = 15 - 30\text{dB}, \theta_n^{min} = 2, \theta_n^{max} = 6$, $\theta_n = 3, M \geq 6$. Figure 5.4 shows SU blocking probability for the two strategies at different wireless links (channel conditions), since the varying nature of a wireless link considered. For each policy/strategy, different channel conditions have different blocking probabilities. However, comparing the RBS with the IBS, one can argue that there is a significant improvement of the RBS scheme over the IBS due to its flexibility. The RBS scheme outperformed the IBS scheme in terms of capacity, access/admission, blocking, and forced termination probability. As the service rate μ_{su} of the SUs increases as a result of good wireless link, the blocking probabilities decreases since more SUs will be served faster. However, in all scenarios (good, moderate and bad wireless links) assumed, RBS strategy has a lower blocking probability as compared to IBS.

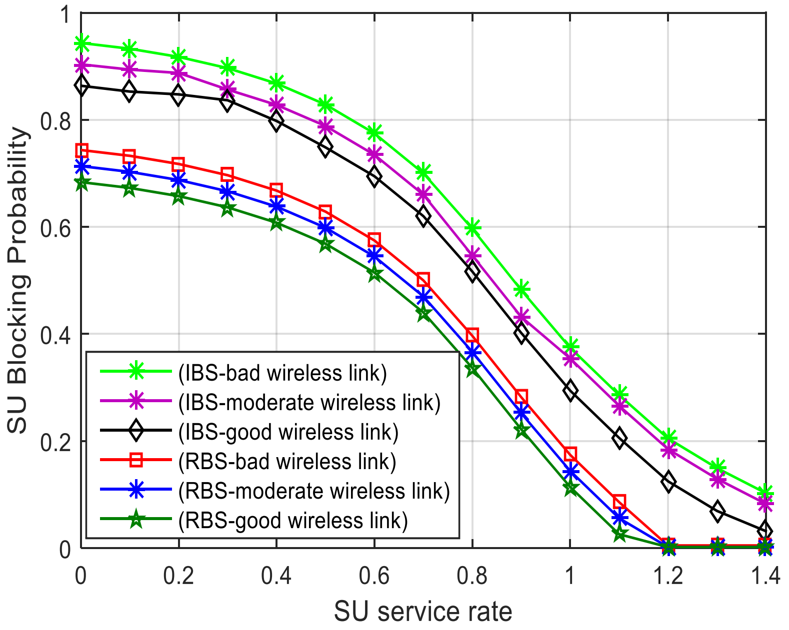

Figure 5.4 SU blocking probability P_b^n vs μ_{su}

In Figure 5.5, the SU experiences a sharp increase in blocking probability initially as λ_p grows due to heavier traffic load on the network system. This significantly affects the SU service because most channel slots are occupied by the PUs hence, access will not be granted to SUs. However, in each of the wireless link conditions, the RBS shows better improvement (lower blocking probability) than the IBS due to its flexibility.

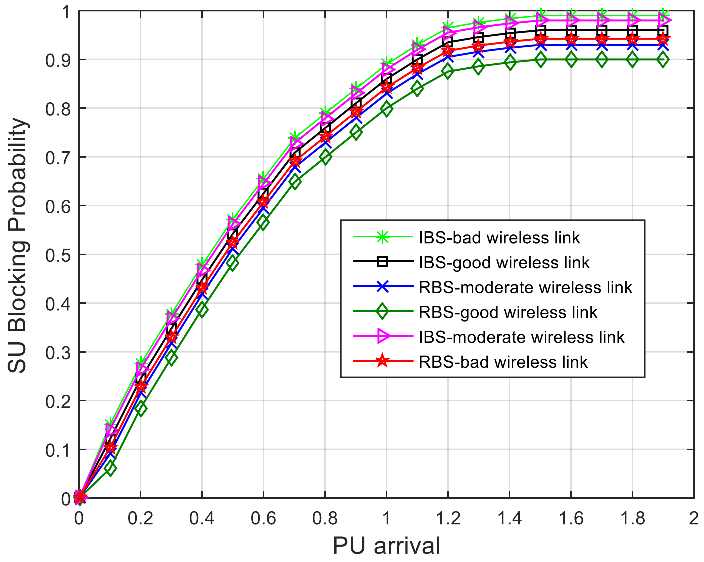

Figure 5.5 SU blocking probability P_b^n vs PU arrival λ_p

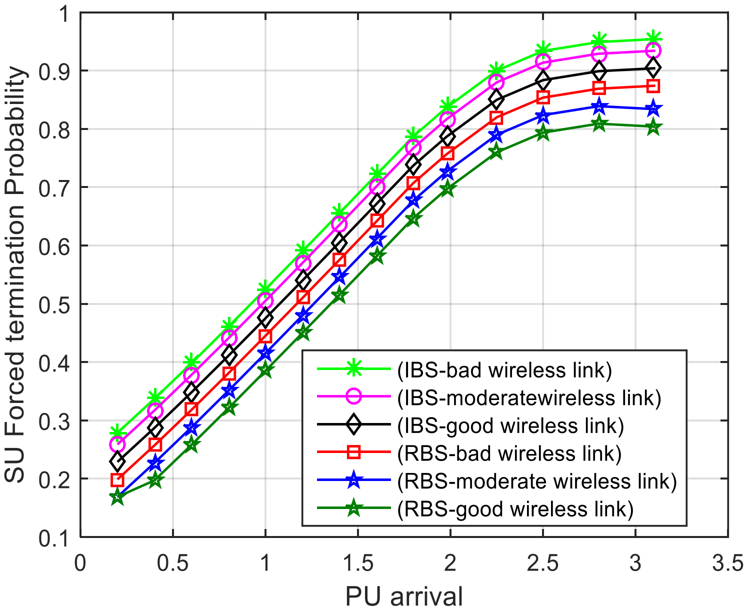

Figure 5.6 SU forced termination probability P_{ft}^n vs λ_p

In Figure 5.6, PU arrival and departure have a significant effect on SUs response in terms of when to aggregate resources (channel slots) and when to drop already aggregated channels. When PUs arrive in batches or individually, an ongoing SU must forcibly terminate its ongoing services if an idle channel does not exist elsewhere within the network. Similarly, when an SU arrives and enough channels are available, it is serviced and as such, the force terminate probability to the SU will reduced. Moreover, in all of these scenarios, the RBS appears a better strategy/policy than the IBS in all wireless links due to its adaptability.

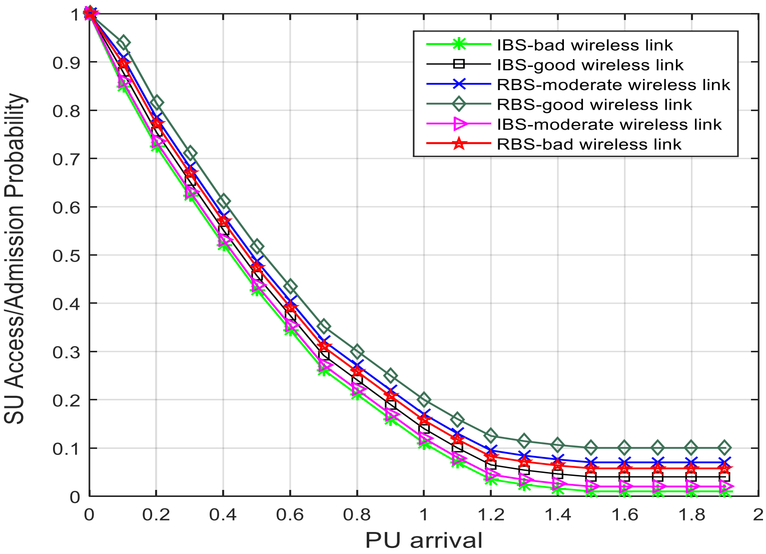

Figure 5.7 SU Access/Admission probability P_a^n vs λ_p

In the event of batch arrivals of PUs, the SUs will experience impediments in gaining access/admission into the spectrum. This is because very few slots or no slot(s) will be available for the SUs. Once the number of available slots is not enough based on the requirements, access will be denied. Similarly, when PU departs, more channels slots are made available for the SUs and vice-visa. However, the RBS still showed better performance as compared to the IBS in all the cases investigated due to adaptability with respect to PU arrival as shown in Figure 5.7. The relationship between Figure 5.5 and 5.7 is that when the PU arrival rate is zero, the blocking probability would be zero. Hence, the access/admission would be at the highest point (approximately 1) since no PU is interrupting the SU ongoing services. However, as the PU gradually arrives, the blocking probability begins to grow and access start dropping. In Figure 5.5, at PU arrival rate is 0 (PU absent) i.e. $P_b^n = 0$, access probability in Fig. 5.7 would be 1. Also, at PU arrival of 0.8, $P_b^n = 0.7$ while $P_a^n = 0.3$ with correlate and reaffirm the equation $P_a^n = 1 - P_b^n$.

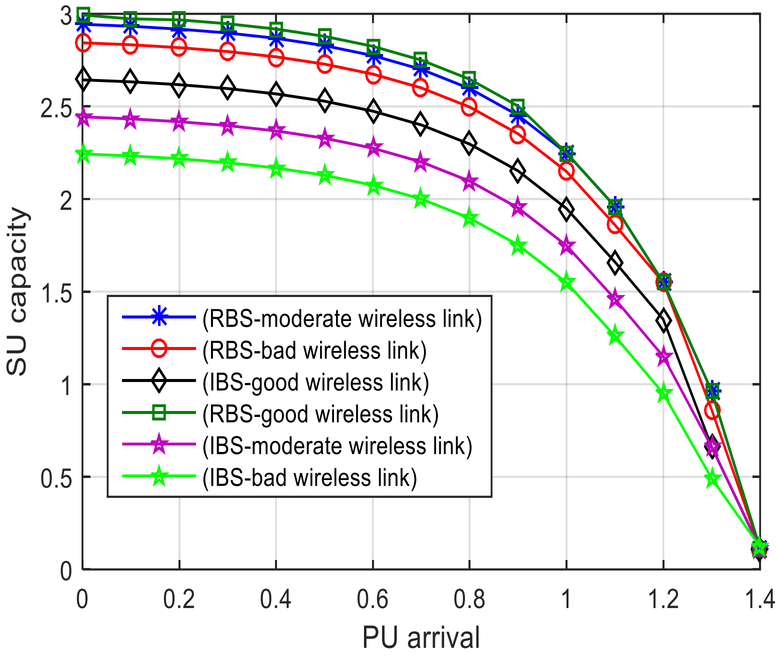

Figure 5.8(a) SU Capacity σ_n vs λ_p

In Figure 5.8(a), the result clearly shows that the capacity (average service rate of the SUs or the average number of SU completions per time) was at the highest when the PUs were absent from the network and as such, the SUs maximized the resources by assembling more channel-slots with high completion time irrespective of the wireless link condition. However, for each of the scenarios (good, moderate and bad) the RBS shows its robustness over the IBS when the PU begins to arrive into the spectrum. In an event of batch arrivals of PUs, the SUs will experience decrease in capacity because very few channel-slots will be available for the SUs to use and as such, very little will be assembled by the SU. Similarly, capacity will improve as PU departs and more channels-slots are made available for SUs to use.

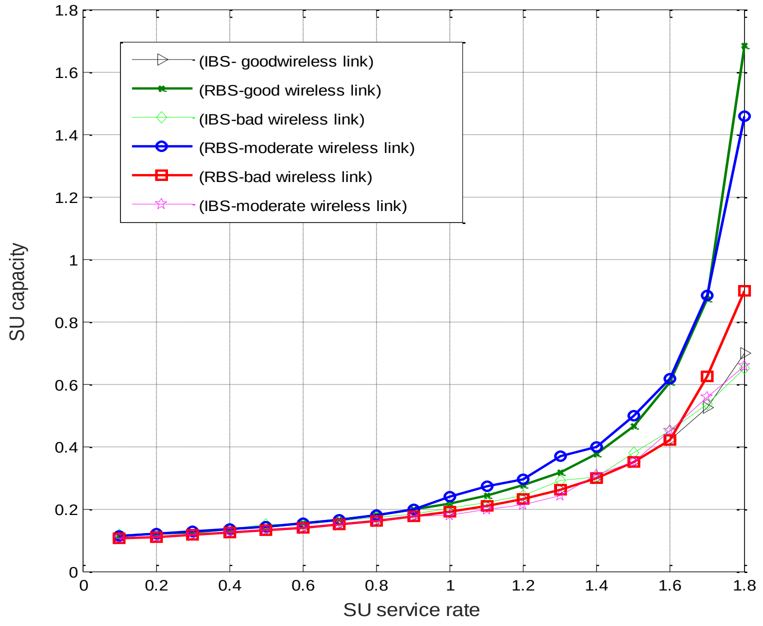

Figure 5.8(b) SU Capacity σ_n vs μ_s

Unlike in Figure 5.8(a) where the capacity decreases as a result of the PU's arrival, in Figure5.8 (b), it is the reverse. The capacity grows due to lesser traffic from the PU activities hence; the SUs have the opportunity to complete its transmission without much interruption from the PUs. Both strategies experience significant improvement at different wireless link conditions. However, in the case of the RBS, due to its capability to aggregate more channel-slots as long as it has not reached the upper bound, it will continuously assemble channels. This makes the service completion rate higher than the IBS which assembles a fixed number of channel slots.

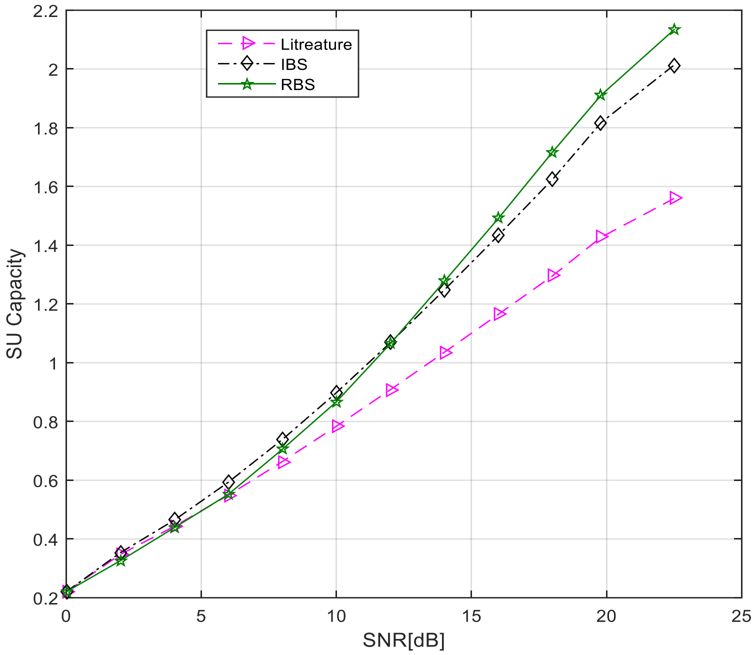

Figure 5.8(c) SU Capacity $\sigma_n \ vs \ \gamma$

Several literatures [4], [5], [30], [94], assumed that the SNRs are homogeneous. But this is not always the case especially when investigating a dynamic next generation wireless link. The result in Figure 5.8(c) has shown that each wireless condition has different capacities. For example, the capacity of a SU when the SNR is in good state is different from the capacity when the SNR is in bad or moderate condition respectively. Also, the incorporation of AMC makes it obvious that the capacity of the RBS and IBS will improve as the SNR gets better. The flexibility togther with AMC accounts for the reason why the RBS outperforms the IBS at some point. Note that the RBS is designed for non-real time SUs and IBS for real-time SU. This implies that the IBS aggregates fixed number of channel slots just as real-time SU (e.g. calls or video conferencing) requires fixed number of resources. The RBS scheme aggregates variable number of channel-slots just as non-real time SU (e.g. file downloading or browsing) do not have specific requirements. Therefore, it possible that at that particular SNR, enough channel slots exist in the system and because the IBS quickly aggregate its fixed number of channels, it slightly outperformed the RBS at some point. However, as the SNR becomes better, the adaptive features of the RBS comes into play and it begins to show its superiority over the IBS scheme.

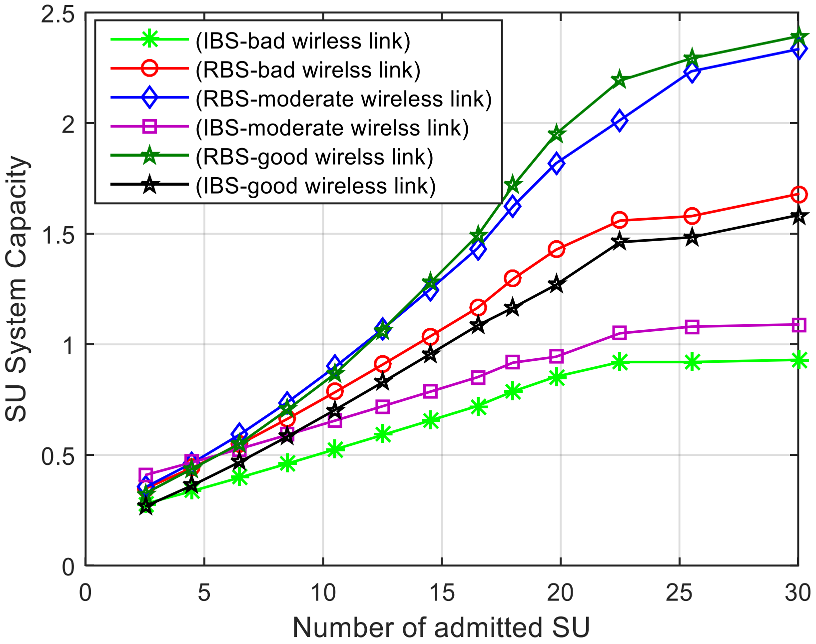

Figure 5.8(d) SU Capacity σ_n *vs V*

In Figure 5.8(d), when access/admission has been granted to the SU based on the criteria mentioned earlier, the SU then aggregates channel slots to commence transmission. The SU system capacity grows because it is the product of the number of admitted SUs and the number of channel slots assembled. As more SUs are admitted, more channel slots are allocated and the SU network capacity grows, showing that more PUs have departed from their channels. However, the RBS scheme improved the SU capacity compared to the IBS scheme for all channel conditions. This result has a similar interpretation as in Figure 5.8(e) because admitted SU implies it must have arrived. However, the RBS scheme improved the SU capacity as compared to the IBS scheme for all channel conditions be it good, moderate or bad.

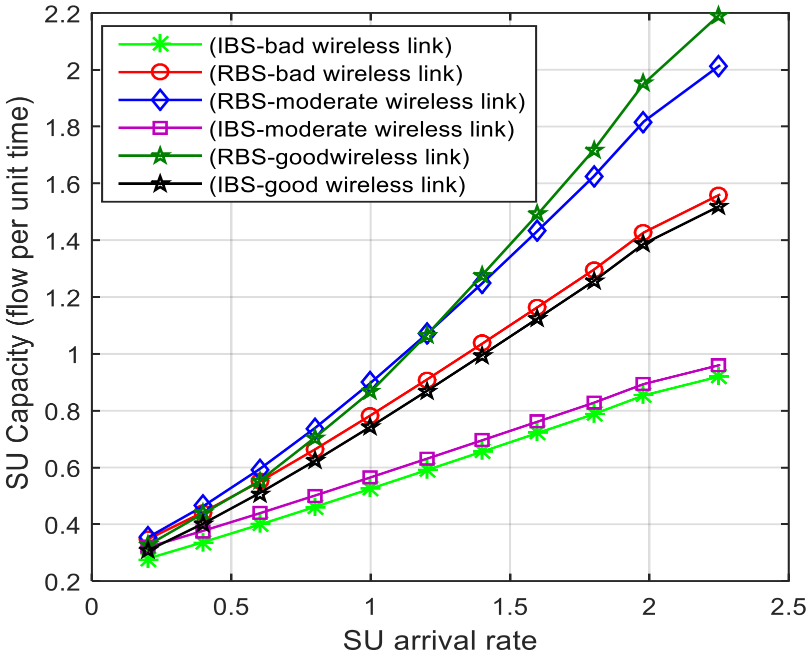

Figure 5.8(e) SU Capacity σ_n vs λ_S

In Figure 5.8 (e), it is observed that SU's arrival into the network has a direct link with the capacity, as shown in the results of Figures 5.8(b), 5.8(c), and 5.8(d) respectively. What this implies is that the more SUs arrives, the more likely they are served. Recall that the arrival/admission of the SU is controlled by the CRBS which has an occupancy map of the entire PU network and behaviour. However, the RBS has a higher capacity compared to the IBS in the three channel conditions and can manage limited (insufficient) resources.

5.8 Conclusion

In this chapter, two CAS featuring AMC are proposed. An analytical and simulation framework to evaluate the performance of the strategies is successfully developed. Investigations of the developed strategies are compared in different channel conditions. The numerical results demonstrate that the RBS scheme outperformed the IBS scheme in different scenarios because it shows lower blocking, force termination probability, higher capacity and access/admission probability. Similarly, this results demonstrates that AMC is a robust technique in improving channel allocation and throughput. Furthermore, this chapter extended the work done in part one of the previous chapter by developing an analytical and simulation framework to evaluate the performance of the proposed strategies (IBS and RBS) in a single class SU traffic. However, an analysis with multiclass SUs was not considered, and need to be investigated. The extension will be also introducing a queuing regime for multi-class SUs so that, those SUs traffic flows that would have been blocked or forcibly terminated could be queued in a buffer and possibly served later.

CHAPTER SIX

Channel Assembling Policy in Cognitive Radio Networks: A Queuing Based Approach

This chapter presents an analytical evaluation of the proposed CAS in CRN. Specifically, a queuing based approach employed in the analysis extend the study of part two of chapter four. The organization of this chapter is as follows: the next section present introduction while Section 6.2 summarized related works. The System model and wireless channel model is presented in Section 6.3 and Section 6.4 respectively. Thereafter, queuing-based channel assembling strategies (CAS+Q) is discussed in Section 6.5. The proposed CAS+Q scheme is found in Section 6.6. System analytical model is developed in Section 6.7, followed by numerical results and discussion in Section 6.8. The chapter is concluded Section 6.9.

6.1 Introduction

Through channel assembling strategies (CAS), more capacity and spectrum utilization can be achieved. However, high blocking and forced termination (FT) occurs whenever a PU arrives. Motivated by a realistic scenario in CAS in CRN, a joint CAS with queue (CAS+Q) is proposed which considers the dynamics of a wireless link and other factors that affect the quality and capacity of the accessible channel. For CAS+Q to be deployable, it must consider: the time varying wireless link, a finite buffer regime (queue), the traffic classes and AMC. The introduction of a queuing regime for SUs is such that those traffic flows that would have been blocked or forcibly terminated would otherwise be queued in a buffer and possibly served later. This strategy is targeted at further improving spectrum utilization, secondary network capacity and more especially, minimizing blocking and forced termination (FT) of the SUs' ongoing services.

With this strategy proposed scheme (CAS+Q) and other novel ones in literatures, it is obvious that CR's channel assembling strategies (policies) together with software define networks (SDN) would be a robust pair to realizing the Fifth Generation (5G) Network goals [146]. Thus, targeted at improving the capacity of the secondary network by allowing a SU to combine several idle channels if available, through a dynamic spectrum access scheme [97]. With this type of scheme, the spectrum utilization can be improved and spectrum allocation becomes much more flexible and robust compared to the conventional allocation schemes. Studies have shown that CAS can be achieved in two ways depending on the availability of unused channels in frequency and time domain. The first approach is the bonding of neighbouring (contiguous) channel into one logical channel while the other approach is the aggregation of non-contiguous (adjacent) into a single SU channel [147]. As fifth Generation (5G) will support multimedia services with diverse resource requirements, robust channel assembly strategies are required in CRN so as to enable the SU improve throughput. Moreover, the number of channels assembled for a SU depends on: the queuing discipline, the PU behaviour, the dynamics of the wireless link, the classes of the SUs, and AMC [24], [133], [144]. However, for the strategy to be more robust regardless of the unpredictable behaviour of the PUs, a buffer regime is incorporated to accommodate SU traffic that is interrupted due to PU arrival, and possibly served later. Furthermore, channel assembling with queuing is implementable under certain PU activities with most of which modelled as Markovian [34], [141], hence the performance of a robust channel assembly strategy must take into consideration the PU behaviours models as investigated in[36], [37].

Through, the knowledge of the PU behaviour, SNR per frame and resource utilization planning, channel assembling can be effectively carried out by the CRBS. A realistic and dynamic wireless channel could be represented by numerous finite states by characterizing the received SNR as good, medium and bad quality respectively [6], [8], [24]. This is a more practical representation of the wireless channel conditions in contrast [4], [5], [30]. A robust channel assembling strategy should therefore take into account, the dynamics (varying nature) of the wireless link and a queuing regime hence, this forms part of the investigation. Strategies on channel assembling have been proposed in literature to mitigate on various losses of the communication network. This has shown significant advances in SUs performance in terms of high data rate, spectrum utilization and so on. Channel assembling can be deployed with or without queues. Several novel CAS without queues has been proposed in [4], [5], [30], [94], [95] while [97], [99] proposed channel assembling incorporating queues though; these strategies suffer from relatively high blocking and forced termination when PU arrives.

Also, the proposed schemes in literatures did not consider the varying nature of the wireless link (varying SNR) featuring AMC. Motivated by this, a joint channel assembling strategies that consider the dynamics of a wireless link featuring AMC is proposed with a queuing regime for SUs such that those traffic flows that would have been blocked or forcefully terminated could be queued in a buffer and possibly served later depending on the wireless link conditions. In this strategy, when the signal to SNR of the SU is improved, irrespective of where the SU finds itself (inside the queue or prior to queuing), the transmission rate is adjusted by the help of the AMC controller. The uniqueness of this proposed strategy is that the queuing regime is deployed in worst case scenario when the SU cannot complete its service, only then will it be queued. But, if the channel SNR is good (SU channel quality), before the PU arrives, there is high possibility that the SU service would have been completed by the help of AMC controller adjusting its transmission parameters. Also, this approach gives opportunity for more SUs to be admitted into spectrum and hence maximizing the TVWS.

6.2 Related Works

While various CAS have been proposed and evaluated by analytical models [4], [5], [94], how much performance benefits a SU can achieve at most with CA in terms of capacity, blocking and forced termination lives a lot to be desired. These strategies could be classified as with or without queues as mentioned earlier in this thesis. Strategies without queue have been proposed in [4], [5], [6] , [24], [30], [94], [95], [96] while [7], [24], [97], [99] [9] proposed CA incorporating queuing regime. [24] proposed and compared three different types of channel assembling strategies which are: the IBS where the SUs are immediately blocked if there are insufficient resources available or if PU interrupts its service; the RBS where there is channel adjustment (upward or downward) to accommodate new arrivals or to cater for PU arrivals and the QBS where some users are queued to avoid or reduce blocking/dropping. These proposed schemes take into account the multi-class SU traffic scenarios, the varying nature of a dynamic wireless link featuring AMC and they are evaluated through a simulation study without detailed analysis.

In [4], spectrum adaptation is proposed in CA with two schemes which dynamically adjust channel occupancy of ongoing SU traffic with the assumption that all the channels and SUs are homogenous. [5] developed an analytical model for CRNs with spectrum adaptation as an extension of their previous work in [4]. In this study, two representative channel assembling strategies that consider spectrum adaptation and heterogeneous traffic were proposed. [6] develops and compares through simulation study, two channel assembling strategies which are the IBS and RBS in a homogenous SU traffic on a dynamic wireless link featuring AMC without detailed analytical evaluations.The performance of these strategies are evaluated based on the proposed CTMC models. In [30], the performances comparisons of CA strategies were studied when spectrum adaptation is not implemented in three scenarios: without CA, with a fixed number of assembled channels and assembling all idle channels when SU services access the system. In [94], a constant and a variable channel assembling schemes were proposed and the performance analysis of two channel assembling schemes for wideband CRN were evaluated.

In the variable channel assembling scheme, the bandwidth of the cognitive user is assembling with a probability distribution on the basis of the number of the residual channels that are unoccupied by PUs or SUs. [95] extended the work in [94] through the evaluation of the same strategies but with the consideration for imperfect sensing scenarios for the wideband CRN. [96] investigated channel assembling for elastic traffic with channel adaptation depending on channel availability as well as other SUs' activities thus, comparing the greedy strategy with the proposed study in [4]. [97] introduced a queuing technique into the proposed strategies of [5]. In their study, when there are insufficient spectrum resources, like an open network model (lossy system), where a new secondary user request is pre-empted and the interrupted secondary services are dropped, it is instead queued and served later.

This significantly reduces blocking and force termination probabilities respectively of the SU services while increasing the capacity of the secondary network and improving spectrum utilization. [99] proposed a queuing method where interrupted SU are queued to wait for available channel. But if pre-determine maximum queuing time expires, it will be dropped/forced to terminate. However, the channel fragmentation (CF) part of their study in which SU dynamically split its channel which it currently occupied to finer granule in order to accommodate new arrival is not of interest in this present study. Nevertheless, the assembling aspect of their work did not consider the dynamics of a wireless link featuring AMC which this study investigated and analysed. [9] proposed joint channel assembling strategy with queue (CAS+Q) which considers: the dynamics of a wireless link, the traffic classes and an enabling technique called AMC. Thus, the introduction of a queuing regime for SU is such that those SU traffic that would have been blocked or forcibly terminated could be queued in a buffer and possibly served later.

The essence of introducing a queuing regime is to reduce blocking SU’s request and force terminating SU’s services. In spite of the notable work done on CA in CRNs, the heterogeneity of a real world wireless link was not considered which this study successfully executed as it proposes a robust joint queuing regime with AMC in CA. It employs queuing with AMC scheme which further improves SU network capacity, spectrum utilization, blocking and forced termination. The core contributions of this work are as follows:

- A robust strategy integrating queuing regime with AMC into channel assembling which was proposed and investigated.
- Proposed a finite buffer system (queuing regime) that will further reduce blocking and forced termination of the SU, considering the varying nature of the wireless link and the different traffic classes thus extending the CA strategies proposed in [5]**,** [8] , [99].
- An analytical framework is developed to evaluate the performance of the proposed joint scheme in CAS.

6.3 System Model and Assumptions

The proposed system model is built on a centralized infrastructure consisting of a PU base station (PUBS) and a SU fusion centre (SUFC) with buffers for different SU classes shown in Figure6.1. The PU base station is a TV transmitter base station with several associated users while the fusion centre is a CRBS with two finite buffer (queue) systems for the two classes of SUs, both users operating in the same frequency band.

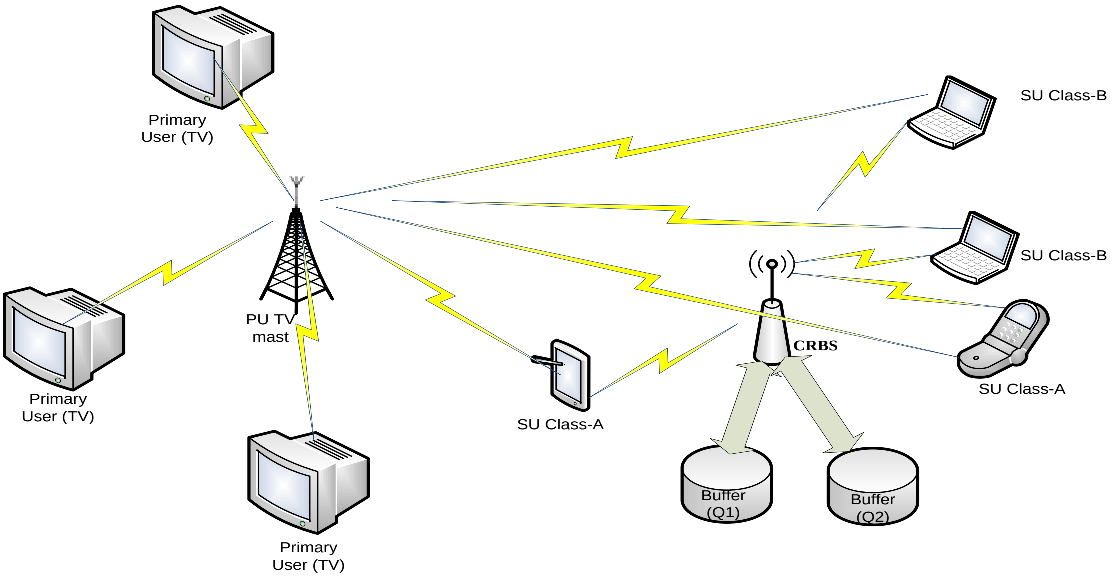

Figure 6.1 Network Architecture

The licensed user (PU), has higher privileged to use the channel and could interrupt a SU (unlicensed user) at any time regardless of the class. The licensed user uses one channel per time in an ON/OFF pattern while the SUs (class A or B) intelligently assembles several neighboring and non-adjacent channel-slot(s) across spectrum domains using the OFDMA access scheme within a coherent time interval as shown in Figure 4.2. The licensed user (SU) utilizes the PU channels (TV band) opportunistically through the deployment any of the proposed scheme. The primary network is made up of ω PUs with M channels where ω and M are positive integers. The CRBS help the SU to structure the channels in slots (frames) and resource utilization becomes on a slot basis for SUs. The channel frame utilization map for a determined PU ON/OFF behaviour is shown in Figure 4.2. The varying SNR per frames translate into a "*heterogeneous system"* with varying channel capacity. This implies that SU traffic QoS requires a precise transmitting rate and quantity of channel-slot. The CRBs decides which to admit, block, queue, terminate or allocate resources based on the SNR and accessibility as initiated by CAS. For simplicity of our analysis, we assumed a perfect sensing so that SU can accurately identify PU's ON/OFF events (arrival and departure) on any of the band.

6.4 Wireless Channel Model

Nakagami-*m* channel model is adopted to characterize the wireless link due to its versatility of covering a wide range of fading channels [131], [132], [133], [143]. The channel quality is captured by the received SNR of the SU. The received SNR per frame is a random variable with a Gamma probability density function [8].

6.4.1 AMC and Secondary User Frame Configuration

The essence of integrating AMC into this proposed scheme is of three folds. First, it significantly improves spectrum usage by categorizing the modulation scheme, spectral efficiency, code rate and SNR [132]. Secondly, if the SU SNR is good (SU channel quality), there are high possibility that before the PU arrives, SU service would have been completed. This is made possible by the help of the AMC controller, adjusting its transmission parameters. Thirdly, it optimizes the rate at which units of information (bit or packet) are sent and deliver with *targeted error rates* (TER) with respect to the condition of the wireless link [133], [143]. This dynamics of the SNR introduces the multi-rate capacities of wireless links in terms of the number of channels-slot used by SU as opposed to the constant homogeneous single rate systems [5], [97]. More importantly, this approach gives opportunity to more SUs to be admitted into spectrum and hence maximizes the TVWS which is the essence of CAS+Q into CRN. As earlier stated in Fig 4.2, the structure is such that the SU OFF frame duration is the time to transmit a packet of length L bits. R_n is the rate in bit/symbol for mode *n* while R_N is the highest rate in mode *N*. The number of SU channel-slots in is fixed (OFF frame duration) for a coherence time interval (CTI) and varies with the dynamic SNR (γ) when the wireless link is in state *n* as expressed in [8], [134]. The channel state utilization of PU is characterised by two-state Markov chain of Figure 4.4 with α_i, β_i, θ_{su}, $(M * S)$, well defined in chapter four of this thesis and [8] thus needs not be over emphasized.

6.4.2 Secondary User Mini-Slot Configuration

The numbers of channel-slot allocated to a SU decreases with increase in quality of SNR as shown in Figure 5.2. From Table I, the parameters are inversely proportional to the number of slots θ_n allocated [8]. Hence, in good channel condition, few channel-slots are aggregated while as the channel condition deteriorates, more slots are needed to meet the SU QoS requirement. θ_n is the number of slot a SU can assemble/aggregate in a given mode which has been expressed in Equation (5.10). Notation parameters are N which denotes the highest transmission mode, n denotes the n^{th} mode. From Table I, the number of SU channel-slots per frame is expressed in equation (5.10 (a) and 5.10 (b)) [8].

6.5 Queuing-Based CAS *(CAS+Q)*

The heterogeneity of this model as presented, does not only consider the varying nature of a wireless link, but also the queuing type, the SU classes and the resource requirements. To deal with these notable features of our model, two distinct queuing regimes Q_1 and Q_2 for the two classes (A and B) of SU traffic respectively are employed. Q_1 accommodates high priority class (class-A) while Q_2

accommodates low priority class (class-B). These two traffic classes have different delay tolerant level, hence the need for separate queues.

6.5.1 Queuing Regime

The purpose of integrating queuing regime is to further reduce blocking and forced termination when the SU traffic are pre-empted by the PU arrival thus, prompting the SU service to wait in the buffer until free channel-slots are available. However, this queued SUs have a dynamic SNR which is characterized by the varying nature of the wireless link. This will be discussed later in the next section. The proposed buffer system has two distinct queues for the two separate traffic classes of SUs are illustrated in Figure 6.2.

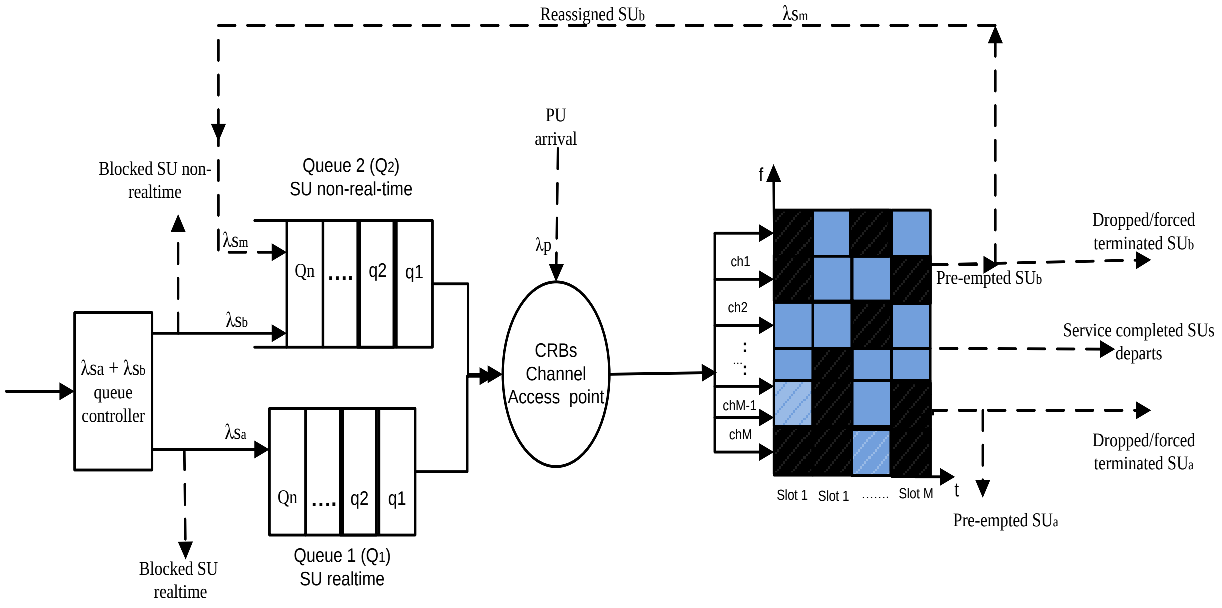

Figure 6.2 Schematic of the proposed queuing regime deployed

6.5.2 Queuing Strategy

In this strategy, new SU class-A arrivals will occupy Q_1 and wait to be served. The pre-empted SU class-B traffic which cannot detect vacant channel(s) in the network through channel adaptation are fed back into Q_2 together with new SU class-B arrivals, as shown in Figure 6.2. However, if Q_2 is full, the interrupted SU class-B are blocked from entering the queue. Because in the CRBS have set the queue waiting time so that other SU class-B are not starved. Theoretically, this fed back would cause aggregated arrivals as a result of both the interrupted SU Class-B and the newly arrived SU Class-B.

But for simplicity, all the arrivals are assumed to be exponentially distributed and λ_{sm} (mean average arrival rate of the feedback into Q_2) is negligible since is not a tangible value. Nevertheless, this could be an aspect for future investigation. Each queuing discipline (Q_1 and Q_2) applies the principle of First in First Out (FIFO) or rather Last in Last Out (LILO) since all SUs are homogeneous within their respective queues [97], [148], [149]. The queue controller separates the heterogeneous (SU class-A and SU class-B) arrivals to their respective queues. Details will be discussed in the next section.

6.6 Proposed CAS+Q $(\theta_{su}, \theta_n, \theta_n^{min}, \theta_n^{max}, Q_1, Q_2)$

In some published works of this thesis [6], [8], [24], a SU which cannot manage to aggregate the required channel-slot(s) with respect to the wireless link condition, is immediately blocked. Also, if PU arrives and selected from SU allotted resources, and there is sufficient idle channel-slot to make up for depletion, then, the SU is forced to terminate. However, effort was made to reduce blocking and forced termination by employing spectrum adaptation/handover scheme. This is such that the SU can adjust the number of channel-slots aggregated when PU arrives and keep probing for free idle resources as long as its residual resources are not below the lower bound set by the CRBS. In furtherance of this idea, channel assembling strategies was proposed with queue (CAS+Q) which will further reduce blocking, forced termination and improve SU admission into the spectrum in the face of the varying wireless link. In this strategy, SU_a (SU class-A) aggregates fixed resources (θ_n) while SU_b (SU class-B) aggregates a minimum of θ_n^{min} and maximum of θ_n^{max} resources depending on the condition where n could be good-quality, moderate-quality or bad-quality.

When a SU requests for service, the CRBS checks for resource availability and apply an assembling procedure similar to strategies in [6], [8], [24]. If the resources are available and sufficient, more than one user could be admitted [6], [8], [24] . If otherwise, as a result of PU arrival, the dynamic algorithm similar to, [6], [8], [24] will be executed to cater for that particular user(s) that needs the resources most. Because PU events (arrival/departure) are erratic, a queuing system was introduced for the two classes of SUs so that, those service that would have been forcibly terminated would then be queued and served later. The logic is that, whenever a PU interrupts SU class-B traffic, it will be queued through a feedback process and possibly served later. This is to the detriment of the SU class- B since long delay will be experienced on the queue. *One may ask, why is there no feedback mechanism for SU class-A?* The reason is that SU class-A is a real-time (delay-sensitive) traffic with spectrum adaptation (dynamic) capability. Therefore, if it is continually queued through a feedback process then, the SU class-B will not have opportunity to access the spectrum hence this will lead to starvation, to the point of dropping from the queue irrespective of its SNR and AMC parameters. Q_1, and Q_2 denotes current queue size of class of SU_a and SU_b while Q_{1max} and Q_{2max} are the maximum queue size for SU_a and SU_b

respectively. θ_n denotes the number of channel slot(s) a SU_a can aggregate while θ_n^{min} and θ_n^{max} are the minimum and maximum channel slots a SU_b can aggregate depending on the wireless link condition. The CTMC will capture these parameters during the general state representation [8], [97]. In this strategy, the conditions that can possibly cause blocking and force termination for SU traffic class are:

- When the available resources (channel-slot) are less than the summation of SU required resources.
- When spectrum adaptation has been executed, yet, no available/sufficient channel-slot to make up for the depletion as a result of PU arrival.
- When new SU arrives, and the queues are full.
- When the waiting time ∂_{CRBS} set by the CRBS exceeds the time spent ∂_{su} by a SUs on the queues.

Therefore, to admit a SU, the available resources (channel-slot) must be greater or equal to the SU required resources irrespective of the traffic class. Let V_n be the total number of SUs in the system and the resource requirements for SU_a be θ_n while θ_{su} denotes the available resources [6], [8], [24] the SU_a will be admitted/accepted if the condition in chapter 5 (Equation 5.4) is satisfied.

Else, the SU_a will be blocked. Thus, the condition for blocking satisfies equation (6.1)

$$\theta_{su} \leq \sum_{\substack{i=1 \\ Q_1=Q_{1max}}}^{V_n} \theta_{n_i}, \quad \forall\{\, M * S - z(\phi)\} < \theta_{n_i} \tag{6.1}$$

However, the SU_a can be forced to terminate if the arriving PU finds the SU utilizing of its resources and there are no free slot(s) available. The force termination occurs if condition (6.2) is satisfied

$$\left(\theta_{su} < \sum\nolimits^{V_n}{}_{\substack{i=1 \\ Q_1=Q_{1max}}} \theta_{n_i}\right), \ \forall\{\, M * S = z(\phi)\} \tag{6.2}$$

The assembly procedure for SU_a and SU_b traffic classes is shown in algorithms VII and VIII respectively which is an extension of fusion of chapter four and five respectively. These algorithms are similar to each other the difference is that the CRBS executes separate queueing procedures for the different traffic classes since their requirement differs.

Pseudo-code for the SU_a traffic

CAS+Q Algorithm VII for SU_a traffic class

```
//SU arrival
CRBS check wireless link; // CRBS checks wireless link state (SNR) for SUs.
    CRBs check $\theta_{su}$; //CRBS checks available recourse for SU
If ($\theta_{su} \geq \sum_{i=1}^{V_n} \theta_{n_i}$); // test for $SU_a$ resources
      $SU_{a\_}$admit = true; // admit $SU_a$ and assemble
Else
  If  ($\sum_{i=1}^{V_n} \theta_{n_i}$) <  $\theta_{n_{inew}}$)] ;// test for new SU or PU arrivals
Do ($\theta_n^{max} - 1$), ++$SU_b$ ; // $SU_b$ with maximum channel, donate to $SU_a$ and iterate over $SU_b$ user resources.
$SU_{a\_}$admit = true; //admit $SU_a$ and assemble
    Else
 go to next step; // commence queuing procedure
  If ($Q_1 < Q_{1max}$) ;// (queue not full)
 $SU_{a\_}$admit_queue = true;// (grant $SU_a$access since queue not full)
    else
        $SU_{a\_}$admit = false (block);// (queue-full, block new $SU_a$ due to no free/insufficient slot)
if ( $\partial_{SU_a} < \partial_{CRBS}$);// (comparing delay times)
 $SU_{a\_}$drop_queue = false (continue to wait in the queue)
      else
 if ( $\partial_{su} > \partial_{CRBS}$) ;// (comparing delay times)
   $SU_{a\_}$drop_queue = true (forced terminate) ;// ($SU_a$timeout in the queue)
   End if
//PU arrival
CRBS check wireless link $\gamma_{su}$ // CRBS checks wireless link state (SNR) for SUs.
    if   $\theta_{su} < \sum_{i=1}^{V_n} \theta_{n_i}^{min}$) ; // PU arrival pick some SU resources
Go to Do procedure above// call subroutine for SU with maximum channel adjust downward
   else
     $SU_{a\_}$drop =true;// forced-terminate of ongoing $SU_s$
//PU departure
```

```
CRBS check wireless link $\gamma_{su}$ // CRBS checks wireless link for PU absence
If $PU_{i\_}$channel-slots=idle;// free channel slot exists
    $SU_{a\_}$admit = true;// admit $SU_s$ admit $SU_i$ and assemble
Do $\left(\theta_j^{min} + 1\right)$;// call subroutine for SU with minimum channel to adjust upward
  end
 Go to start.
```

The condition for admitting SU_b must satisfy condition (6.3)

$$\theta_{su} \geq \sum_{i=1}^{V_n} \theta_{n_i}^{min}, \quad \forall\, z(\phi) < M * S \tag{6.3}$$

Else it is blocked if it satisfies the condition in (6.4)

$$\theta_{su} \leq \sum_{\substack{i=1 \\ Q_2=Q_{2max}}}^{V_n} \theta_{n_i}^{min}, \quad \forall\{\, M * S - z(\phi)\} < \theta_{n_i}^{min} \tag{6.4}$$

Forced termination for SU_b as a result of PUs arrival must satisfy condition (6.5)

$$\left(\theta_{su} < \sum^{V_n}{}_{\substack{i=1 \\ Q_2=Q_{2max}}} \theta_{n_i}^{min}\right), \tag{6.5}$$

The Pseudo-code for the SU_b traffic is given as

```
CAS+Q Algorithm VIII for $SU_b$ traffic class
// SU arrival
 CRBS check wireless link $\gamma_{su}$ // CRBS checks wireless link state (SNR) for SUs.
  CRBs check $\theta_{su}$; // CRBS checks available recourse for SU
 If ($\theta_{su} \geq \sum_{i=1}^{V_n} \theta_{n_i}^{min}$); // test for $SU_a$ resources
    $SU_{b\_}$admit = true; // admit $SU_b$ and assemble
 Else
```

```
If ($\sum_{i=1}^{V_n} \theta_{n_i}^{min}$) < $\theta_{ni_{new}}^{min}$)];// test for new SU arrival
  Do ($\theta_n^{max} - 1$), ++$SU_b$; // $SU_b$ with maximum channel, donate to new $SU_b$ and iterate over other higher $SU_b$ user resources.
 $SU_b$ admit = true; //admit $SU_b$ and assemble
   Else
 go to next step; // commence queue procedure
  If ($Q_2 < Q_{2max}$)
 $SU_b$_admit_queue = true; // (grant $SU_a$access since queue not full)
     Else
       $SU_b$_admit = false (block);// (queue-full, block     new  $SU_b$ no free/insufficient slot)
 If ( $\partial_{SU_b} < \partial_{CRBS}$);// (comparing delay times)
  $SU_b$_drop_queue =false; // ($SU_b$ still waiting in the queue)
      Else
  If ( $\partial_{SU_b} > \partial_{CRBS}$) ;//(comparing delay times)
  $SU_b$_Drop_queue = true (forced terminate) ;// ($SU_b$ timeout in the queue)
```

//PU arrival

```
CRBS check wireless link $\gamma_{su}$ // CRBS checks wireless link state (SNR) for SUs.
   If    $\theta_{su} < \sum_{i=1}^{V_n} \theta_{n_i}^{min}$)  ; // PU arrival pick some SU resources
Go to Do procedure above// call subroutine for SU with maximum channel adjust downward
  Else
    $SU_b$_drop =true;// forced-terminate of ongoing  $SU_s$
```

//PU departure

```
CRBS check wireless link $\gamma_{su}$ // CRBS checks wireless link for PU absence
 If $PU_i$_channel-slots=idle;// free channel slot exists
     $SU_b$_admit = true;// admit $SU_s$ admit $SU_i$ and assemble
Do ($\theta_j^{min} + 1$);// call subroutine for SU with minimum channel to adjust upward
end
 Go to start.
```

6.7 System Analytical Models and Assumptions

To develop the system analytical model, some assumptions were made. The resource requirements for the static SU is fixed while the dynamic SU has a flexible requirements bounded between θ_n^{min} and θ_n^{max}. The arrivals for PU and SUs (class-A and class-B) are Poisson process with arrival rates λ_p,λ_{sa} λ_{sb} respectively. The service times for PU and SUs (class-A and class-B) services are exponentially distributed with service rates μ_p , μ_{s_a} and μ_{s_b} for the PU and SU respectively. For simplicity, the arrival rates and service time were assumed for the respective users channel conditions are similar i.e., $\lambda_s = (\lambda_{s_g},\ \lambda_{s_m}, \lambda_{s_b}, \lambda_{sa}, \lambda_{sb}\ )$ and $\mu_s = (\mu_{sg}\ , \mu_{sm}\ , \mu_{sb}, \mu_{s_a}, \mu_{s_b})$. The total service for SUs (class-A and class-B) is assumed to be the product of the service rate and the number of assembled channel-slots $\theta_{su}\mu_{su}$ like in, [5], [24], [97]. The system can be modelled as a CTMC with state denoted by $\phi = \{\omega, V_{g(a,b)} .. , V_{m(a,b)} .. , V_{b(a,b)}, Q_1, Q_2\}$ where $V_{g(a,b)}$, $V_{m(a,b)}$ and $V_{b(a,b)}$ represent the number of SUs (class-A and class-B) in a good, moderate and bad state respectively. Q_1, Q_2 are the queue sizes of SU_a and SU_b respectively. The total channel-slot utilization can be expressed as;

$$z(\phi) = \ \omega + \left(\theta_g V_{g(a,b)} + \theta_m V_{m(a,b)} +\ \theta_b V_{b(a,b)}\right) \tag{6.6}$$

Where θ_g, θ_m, and θ_b are the number of channel-slots assembled by the CRBS and SU with respect to the channel state. The system/state transitions are categorized as internal/horizontal (transition from good to moderate and to bad channel state) respectively. External/vertical transitions imply arrival or departure of PU/SU [8].

6.7.1 CTMC Analysis for CAS+Q

Possible states of the system is represented as $ȼ = \{\phi \mid \omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2\ \geq 0;\ z(\phi) \leq M * S, Q_1 \leq Q_{1max},\ Q_2 \leq Q_{2max};\ \sum_{i=1}^{V_n} \theta_{n_i}^{min}\ < \theta_{n_i}^{min},$ if $Q_2 > 0;\ \sum_{i=1}^{V_n} \theta_{n_i}\ < \theta_n$, if $Q_1 > 0\}$. The steady state probabilities $\pi(\phi)$ can be calculated with the balance and the normalized equation as shown in Equation (6.7) where $\boldsymbol{\psi}$ is the transition rate matrix [8].

$$\pi\ \boldsymbol{\psi} = 0, \qquad \sum_{\phi \in ȼ} \pi(\phi) = 1 \tag{6.7}$$

Subsequently, the summary of all the possible state transitions is found in the tables below. The transition tables captures the varying wireless channel conditions and three event pairs of PU/SU (departure and arrival) which are; PU arrival/departure, SU_a and SU_b arrival/departure respectively.

Table 6.1

External transitions from present state $\phi = \{\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2\}$ of CAS+Q *[9]*

A PU Departure

No.	Next state	Possible State Events	Transition Rate
		PU Departure	PU rate
(1)	$(\omega - 1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	PU departure irrespective of the SUs channels condition.	$\omega\mu_p$
PU departure is independent of the varying channel condition of the SUs			

Table 6.2

External transitions from present state $\phi = \{\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2\}$ of CAS+Q

A SU_b / SU_a Arrivals

No.	Next state	Possible State Events	SU Transition Rate
		SU_b Arrival	
[1]	$(\omega, V_{g(a)} \ldots, \ldots V_{g(b)} + 1, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	A SU_b in good state arrivals. Sufficient idle channel-slots available, with the likelihood of being **admitted,** If the number of idle slots (θ_{su}) available is greater than or equal to the summation of channel-slots required by V_g i.e. If $\theta_{su} \geq \sum_{i=1}^{V_g} \theta_{g_i}^{min}$, $\forall\, z(\phi) < M * S$ as in equation (6.3)	$\left[\frac{\theta_g^{min} V_{g(b)}}{z(\phi)}\right]$
		Otherwise, it is **blocked** which implies **NOT admitted** i.e. if $\theta_{su} \leq \sum_{i=1}^{V_g} \theta_{g_i}^{min}$, $\forall \{ M * S - z(\phi)\} < \theta_g^{min}$ as in equation (6.4)	
[2]	$(\omega, V_{g(a,b)}, V_{m(a)} \ldots, V_{m(b)} + 1, V_{b(a,b)}, Q_1, Q_2)$	A SU_b in moderate state arrivals. Sufficient idle channel-slots available, with the likelihood of being **admitted**, If the number of idle slots (θ_{su}) available is greater than or equal to the summation of channel-slots required by V_m i.e. If $\theta_{su} \geq \sum_{i=1}^{V_m} \theta_{m_i}^{min}$, $\forall\, z(\phi) < M * S$ as in equation (6.3)	$\left[\frac{\theta_m^{min} V_{m(b)}}{z(\phi)}\right]$
		Otherwise, it is **blocked** which implies **NOT admitted** i.e. if $\theta_{su} <$	

		$\sum_{i=1}^{V_m} \theta_{m_i}^{min}$, $\forall\{ M * S - z(\phi)\} <$ θ_m^{min} as in equation (6.4)	
[3]	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)} .. V_{b(b)} + 1, Q_1, Q_2)$	A SU_b in bad state arrivals. Sufficient idle channel-slots available, with the likelihood of being admitted, If the number of idle slots (θ_{su}) available is greater than or equal to the summation of channel-slots required by V_b i.e. If $\theta_{su} \geq \sum_{i=1}^{V_b} \theta_{b_i}^{min}$,$\forall\, z(\phi) < M * S$ as in equation (6.3)	. $\left[\frac{\theta_b^{min} V_{b(b)}}{z(\phi)}\right]\lambda$
		Otherwise, it is **blocked** which implies **NOT admitted** i.e. if $\theta_{su} \leq$ $\sum_{i=1}^{V_b} \theta_{b_i}^{min}$, $\forall\{ M * S - z(\phi)\} <$ θ_b^{min} as in equation (6.4).	
[4]	$(\omega, V_{g(a)} .., V_{g(b)} + 1, ., V_{g(b)}^{max-} ., V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	SU_b arrivals in good state. A $SU_b$with maximum no. of channel-slots(θ_g^{max}) donates minimum no. of channel-slots (θ_g^{min}) ….	λ_s
[5]	$(\omega, V_{g(a,b)}, V_{m(a)} \dots, V_{m(b)} + 1, ., V_{m(b)}^{max-}, V_{b(a,b)}, Q_1, Q_2)$	SU_b arrivals in moderate state. A SU_b with maximum no. of channel-slots(θ_m^{max}) donates minimum no. of channel-slots (θ_m^{min})….	λ_s
[6]	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)} .., V_{b(b)} + 1, V_{b(b)}^{max-}, Q_1, Q_2)$	SU_b arrivals in bad state. A $SU_b$with maximum no. of channel-slots(θ_b^{max}) donates minimum no. of channel-slots (θ_b^{min})….	λ_s
[7]	$(\omega, V_{g(a)} .., V_{g(b)} + 1, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2 - 1)$	SU_b arrivals in good state. New SU_b call/request is queued in Q_2	same as (4)
[8]	$(\omega, V_{g(a,b)}, V_{m(a)} .., V_{m(b)} + 1, V_{b(a,b)}, Q_1, Q_2 - 1)$	SU_b arrivals in moderate state. New SU_b call/request is queued in Q_2	same as (5)
[9]	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)} .., V_{m(b)} + 1, Q_1, Q_2 - 1)$	SU_b arrivals in bad state. New SU_b call/request is queued in Q_2….	same as (6)
SU_a Arrival			
[10]	$(\omega, V_{g(a)} + 1 .., . V_{g(b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	An SU_a in good state Arrivals. Sufficient idle channel-slots available, with the likelihood of being **admitted,** If the number of idle slots (θ_{su}) available is greater than or equal to the summation of channel-slots required by V_g i.e. If $\theta_{su} \geq \sum_{i=1}^{V_g} \theta_{g_i}$,$\forall\, z(\phi) <$ $M * S$ as in equation (5.4) ….	$\left[\frac{\theta_g V_{g(a)}}{z(\phi)}\right]\lambda_s$
		Otherwise, it is **blocked** which implies **NOT admitted** i.e. if $\theta_{su} \leq$ $\sum_{i=1}^{V_g} \theta_{g_i}$, $\{ M * S - z(\phi)\} <$ θ_g as in equation (6.2)	
[11]	$(\omega, V_{g(a,b)}, V_{m(a)} + 1 .., V_{m(b)}, V_{b(a,b)}, Q_1, Q_2)$	A SU_a in moderate state arrivals. Sufficient idle channel-slots available, with the likelihood of being **admitted**,	

		If the number of idle slots (θ_{su}) available is greater than or equal to the summation of channel-slots required by V_m i.e. If $\theta_{su} \geq \sum_{i=1}^{V_m} \theta_{m_i}$,$\forall\, z(\phi) < M * S$ as in equation (5.4)	$\left[\frac{\theta_m V_{m(a)}}{z(\phi)}\right] \lambda_s$
		Otherwise, it is **blocked** which implies **NOT admitted** i.e. if $\theta_{su} \leq \sum_{i=1}^{V_m} \theta_{m_i}$, $\forall\{M * S - z(\phi)\} < \theta_m$ as in equation (6.2)	
[12]	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)} + 1, ..V_{b(a)}, Q_1, Q_2)$	A SU_a in bad state arrivals. Sufficient idle channel-slots available, with the likelihood of being **admitted**, If the number of idle slots (θ_{su}) available is greater than or equal to the summation of channel-slots required by V_b i.e. If $\theta_{su} \geq \sum_{i=1}^{V_b} \theta_{b_i}$,$\forall\, z(\phi) < M * S$ as in equation (5.4)	$\left[\frac{\theta_b V_{b(a)}}{z(\phi)}\right] \lambda_s$
		Otherwise, it is **blocked** which implies **NOT admitted** i.e. if $\theta_{su} \leq \sum_{i=1}^{V_b} \theta_{b_i}$, $\forall\{M * S - z(\phi)\} < \theta_b$ as in equation (6.1)	
[13]	$(\omega, V_{g(a)} + 1, ..V_{g(b)}^{max-}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	SU_a arrivals in good state. A SU_b with θ_g^{max} donates θ_g channel-slots.	λ_s
[14]	$(\omega, V_{g(a,b)}, V_{m(a)} + 1, ..V_{m(b)}^{max-}, V_{b(a,b)}, Q_1, Q_2)$	SU_a arrivals in moderate state. An SU_b with θ_m^{max} donates θ_m channel-slots	λ_s
[15]	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)} + 1, ..V_{b(b)}^{max-}, Q_1, Q_2)$	SU_a arrivals in good state. A SU_b with θ_b^{max} donates θ_b channel-slots…	λ_s
[16]	$(\omega, V_{g(a)} + 1, ..V_{g(b)}^{max-}, V_{m(a,b)}, V_{b(a,b)}, Q_1 - 1, Q_2)$	SU_a arrivals in good state. New SU_a call/request is queued in Q_1	same as (4)
[17]	$(\omega, V_{g(a,b)}, V_{m(a)} + 1, ..V_{m(b)}^{max-}, V_{b(a,b)}, Q_1 - 1, Q_2)$	SU_a arrivals in moderate state. New SU_a call/request is queued in Q_1	same as (5)
[18]	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)} + 1, ..V_{b(b)}^{max-}, Q_1 - 1, Q_2)$	SU_a arrivals in bad state. New SU_a call/request is queued in Q_1	same as (6)

Table 6.3

External transitions from present state $\phi = \{\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2\}$ of CAS+Q

A SU_a Departure

No.	Next state	Possible State Events	Transition Rate
		SU_a **Departure**	SU rate
(1)	$(\omega, V_{g(a,b)} - 1, V_{m(a,b)}, V_{b(a,b)}, Q_1 - 1, Q_2)$	SU_a departure. An SU_a in good state, queued in Q_1 uses the idle channel-slots (θ_g).	$V_g \theta_g \mu_S$
(2)	$(\omega, V_{g(a,b)}, V_{m(a,b)} - 1, V_{b(a,b)}, Q_1 - 1, Q_2)$	SU_a departure. An SU_a in moderate state, queued in Q_1 uses the idle channel-slots (θ_m).	$V_m \theta_m \mu_s$
(3)	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)} - 1, Q_1 - 1, Q_2)$	SU_a departure. An SU_a in bad state, queued in Q_1 uses the idle channel-slots (θ_b).	$V_b \theta_b \mu_s$
(4)	$(\omega, V_{g(a,b)} - 1, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2 - 1)$	SU_a departure. An SU_b in good state, queued in Q_2 uses the idle channel-slots (θ_g).	Same as (1)
(5)	$(\omega, V_{g(a,b)}, V_{m(a,b)} - 1, V_{b(a,b)}, Q_1, Q_2 - 1)$	SU_a departure. An SU_b in moderate state, queued in Q_2 uses the idle channel-slots (θ_m).	Same as (2)
(6)	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)} - 1, Q_1, Q_2 - 1)$	SU_a departure. An SU_b in bad state, queued in Q_2 uses the idle channel-slots (θ_b).	Same as (3)
(7)	$(\omega, V_{g(a)} - 1, .. V_{g(b)}^{+}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	SU_a departure. A transmitting SU_b in good state with minimum no. of channel-slots (θ_g^{min}) uses all the idle channel-slot	Same as (1)
(8)	$(\omega, V_{g(a,b)}, V_{m(a)} - 1, ., V_{m(b)}^{+}, V_{b(a,b)}, Q_1, Q_2)$	SU_a departure. A transmitting SU_b in moderate state with minimum no. of channel-slots (θ_b^{min}) uses all the idle -slot	Same as (2)
(9)	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)} - 1, .. V_{b(b)}^{+}, Q_1, Q_2)$	SU_a departure. A transmitting SU_b in bad state with minimum no. of channel-slots (θ_b^{min}) uses all the idle channel-slot.	Same as (3)
(10)	$\omega, V_{g(a)} - 1, ..0, ..0, ., V_{g(b)}^{max}, V_{m(a,b)}, V_b, Q_1, Q_2)$	SU_a departure. other SU_b in good state, uses the idle channel-slots (θ_g^{min}) to attain maximum bound θ_g^{max}	Same as (1)
(11)	$(\omega, V_{g(a,b)}, V_{m(a)} -, ..0..0., V_{m(b)}^{max}, V_{b(a,b)}, Q_1, Q_2)$	SU_a departure. other SU_b in moderate state, uses the idle channel-slots (θ_m^{min}) to attain maximum bound θ_m^{max}	Same as (2)
(12)	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)} - 1, , ..0, .., V_b^{max}, Q_1, Q_2)$	SU_a departure. other SU_b in bad state, uses the idle channel-slots	Same as (3)

		(θ_b^{min}) to attain maximum bound θ_b^{max}	
(13)	$(\omega, V_{g(a,b)} - 1, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	SU_a departure. New SUs in good state cannot use the channel-slots.	same as 1
(14)	$(\omega, V_{g(a,b)}, V_{m(a,b)} - 1, V_{b(a,b)}, Q_1, Q_2)$	SU_a departure. New SUs in moderate state cannot use the channel-slots.	same as 2
(15)	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)} - 1, Q_1, Q_2)$	SU_a departure. New SUs in bad state cannot use the channel-slots.	same as 3
$\mu_s = \mu_g, \mu_m, \mu_b$ i.e., SU service rate is same irrespective of the channel condition.			

Table 6.4

External transitions from present state $\phi = \{\omega, V_{g(a,b)}.., V_{m(a,b)}, .. V_{b(a,b)}, Q_1, Q_2\}$ of CAS+Q

A SU_b Departure

No.	Next state	Possible State Events	SU Transition Rate
		SU_b **Departure**	
(1)	$(\omega, V_{g(a,b)} - 1, V_{m(a,b)}, V_{b(a,b)}, Q_1 - 1, Q_2)$	SU_b departure. An SU_a in good state, queued in Q_1 uses the idle channel-slots (θ_g).	$V_g\theta_g^{min}\mu_s$
(2)	$(\omega, V_{g(a,b)}, V_{m(a,b)} - 1, V_{b(a,b)}, Q_1 - 1, Q_2)$	SU_b departure. An SU_a in moderate state, queued in Q_1 uses the idle channel-slots (θ_m).	$V_g\theta_m^{min}\mu_s$
(3)	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)} - 1, Q_1 - 1, Q_2)$	SU_b departure. . An SU_a in bad state, queued in Q_1 uses the idle channel-slots (θ_b).	$V_g\theta_b^{min}\mu_s$
(4)	$(\omega, V_{g(b)} - 1, .. V_{g(a)}^{+}, V_{m(a,b)}, V_{b(a,b)}, Q_1 - 1, Q_2)$	SU_b with θ_n^{max} departure. An SU_ain good state, queued in Q_1 uses the all the idle channel-slots.	. same as 1
(5)	$(\omega, V_{g(a,b)}, V_{m(b)} - 1, .. V_{m(a)}^{+}, V_{b(a,b)}, Q_1 - 1, Q_2)$	SU_b with θ_n^{max} departure. An SU_a in moderate state, queued in Q_1 uses the all the idle channel-slots.	same as 2
(6)	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(b)} - 1, .. V_{b(a)}^{+}, Q_1 - 1, Q_2)$	SU_b with θ_n^{max} departure. An SU_a in bad state, queued in Q_1 uses the all the idle channel-slots.	same as 3
(7)	$(\omega, V_{g(a)}, V_{g(b)} - 1, .. V_{g(b)}^{+}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2 - 1)$	SU_b with θ_n^{max} departure. A SU_b with (θ_g^{min}) in good state, queued in Q_2 uses the all the idle channel-slots.	same as 1
(8)	$(\omega, V_{g(a,b)}, V_{m(a)}, V_{m(b)} - 1, V_{m(b)}^{+}, V_{b(a,b)}, Q_1, Q_2 - 1)$	SU_b with θ_n^{max} departure. A SU_b with (θ_m^{min}) in moderate state, queued in Q_2 uses the all the idle channel-slots.	same as 2

(9)	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}, V_{b(b)} - 1, .. V_{b(b)}^{+}, Q_1, Q_2 - 1)$	SU_b with θ_n^{max} departure. A SU_b with (θ_b^{min}) in bad state, queued in Q_2 uses the all the idle channel-slots.	same as 3
(10)	$\omega, V_{g(a)}, .. V_{g(b)}^{max} - 1, V_{g(b)}^{+}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	SU_b with θ_n^{max} departure. A transmitting SU_b in good state with minimum no. of channel-slots (θ_g^{min}) uses all the idle channel-slots.	same as 1
(11)	$\omega, V_{g(a,b)}, V_{m(a)}, .. V_{m(b)}^{max} - 1, V_{m(b)}^{+}, V_{b(a,b)}, Q_1, Q_2)$	SU_b with θ_n^{max} departure. A transmitting SU_b in moderate state with minimum no. of channel-slots (θ_m^{min}) uses all the idle channel-slots.	same as 2
(12)	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}, .. V_{b(b)}^{max} - 1, V_{b(b)}^{+}, Q_1, Q_2)$	SU_b with θ_n^{max} departure. A transmitting SU_b in bad state with minimum no. of channel-slots (θ_m^{min}) uses all the idle channel-slots.	same as 3
(13)	$(\omega, V_{g(a)}, ..0, ..0, ., V_{g(b)}^{+} .. V_{g(b)}^{max}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	SU_b with θ_n^{max} departure. Every other SU_b in good state, uses the idle channel-slots (θ_g^{min}) to attain maximum bound θ_g^{max}	same as 1
(14)	$(\omega, V_{g(a,b)}, V_{m(a)}, ..0..0., V_{m(b)}^{+} .. V_{m(b)}^{max}, V_{b(a,b)}, Q_1, Q_2)$	SU_b with θ_n^{max} departure. Every other SU_b in good state, uses the idle channel-slots (θ_m^{min}) to attain maximum bound θ_m^{max}	same as 2
(15)	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}, ..0, ..0., V_{b(b)}^{+} .. V_{b(b)}^{max}, Q_1, Q_2)$	SU_b with θ_n^{max} departure. Every other SU_b in good state, uses the idle channel-slots (θ_b^{min}) to attain maximum bound θ_b^{max}	same as 3
(16)	$(\omega, V_{g(a,b)}, .. V_{g(b)}^{max} - 1, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	SU_b with θ_n^{max} departure. New SUs in good state cannot use the channel-slots.	same as 1
(17)	$(\omega, V_{g(a,b)}, V_{m(ab)}, ,, V_{m(b)}^{max} - 1, V_{b(a,b)}, Q_1, Q_2)$	SU_b with θ_n^{max} Departure. New SUs in moderate state cannot use the channel-slots.	same as 2
(18)	$(\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)} . , . V_{m(b)}^{max} - 1, Q_1, Q_2)$	SU_b with θ_n^{max} departure. New SUs in bad state cannot use the channel-slots.	same as 3

Table 6.5

External transitions from present state $\phi = \{\omega, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2\}$ of CAS+Q

A PU Arrival

No.	Next state	Possible State Events	PU Transition Rate
		PU **Arrivals**	
(1)	$(\omega + 1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	PU arrival. An idle channel-slot is available irrespective of the channel state.	λ_p
(2)	$(\omega + 1, V_{g(a)}, V_{g(b)} .., V_{g(b)}^{max-}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	PU arrival. An SU_b in good state with θ_g^{max} is interrupted and adjust-down channel-slots.	$\left[\frac{\theta_g^{max} V_{g(b)}}{z(\phi) - \omega}\right] \lambda_p$
(3)	$(\omega + 1, V_{g(a,b)}, V_{m(a)}, V_{m(b)} \ldots V_{m(b)}^{max-}, V_{b(a,b)}, Q_1, Q_2)$	PU arrival. An SU_b in moderate state with θ_m^{max} is interrupted and adjust-down channel-slots.	$\left[\frac{\theta_m^{max} V_{g(b)}}{z(\phi) - \omega}\right] \lambda_p$
(4)	$(\omega + 1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}, V_{b(b)} .., V_{b(b)}^{max-}, Q_1, Q_2)$	PU arrival. An SU_b in bad state with θ_b^{max} is interrupted and adjust-down channel-slots.	$\left[\frac{\theta_b^{max} V_{g(b)}}{z(\phi) - \omega}\right] \lambda_p$
(5)	$(\omega + 1, V_{g(a)}, V_{g(b)}^{min-}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2 + 1)$	PU arrival. The pre-empted SU_b with θ_g^{min} in good state, is queued (Q_2) and no spectrum adjustment.	$\left[\frac{\theta_b^{min} V_{g(b)}}{z(\phi) - \omega}\right] \lambda_p$
(6)	$(\omega + 1, V_{g(a,b)}, V_{m(a)}, V_{m(b)}^{min-}, V_{b(a,b)}, Q_1, Q_2 + 1)$	PU arrival. The pre-empted SU_b with θ_m^{min} in moderate state, is queued (Q_2) and no spectrum adjustment.	$\left[\frac{\theta_b^{min} V_{m(b)}}{z(\phi) - \omega}\right] \lambda_p$
(7)	$(\omega + 1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}, V_{b(b)}^{min-}, Q_1, Q_2 + 1)$	PU arrival. The pre-empted SU_b with θ_b^{min} in bad state, is queued (Q_2) and no spectrum adjustment.	$\left[\frac{\theta_b^{min} V_{m(b)}}{z(\phi) - \omega}\right] \lambda_p$
(8)	$(\omega + 1, V_{g(a)}, V_{g(b)}^{min} - 1 .., V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2 + 1)$	PU arrival. Pre-empted SU_b with θ_b^{min} in good state is forced terminated and no spectrum adjustment.	Same as (5)
(9)	$(\omega + 1, V_{g(a,b)}, V_{m(a)}, V_{m(b)}^{min} - 1 .., V_{b(a,b)}, Q_1, Q_2 + 1)$	PU arrival. Pre-empted SU_b with θ_b^{min} in moderate state is forced terminated and no spectrum adjustment.	Same as (6)
(10)	$(\omega + 1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}, V_{b(b)}^{min} - 1, .., Q_1, Q_2 + 1)$	PU arrival. Pre-empted SU_b with θ_b^{min} in bad state is forced terminated and no spectrum adjustment.	Same as (7)
(11)	$(\omega + 1, V_{g(a)}, ..0, ..0, .. V_{g(b)}^{max}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2 + 1)$	PU arrival. An SU_b in good state is queued (Q_2). while another SU_b in good state	Same as (5)

		uses the idle channel-slots to attain upper bound θ_g^{max}	
(12)	$(\omega+1, V_{g(a,b)}, V_{m(a)}, ..0..0.,..V_{m(b)}^{max}, V_{b(a,b)}, Q_1, Q_2+1)$	PU arrival. An SU_b in moderate state is queued (Q_2). while another SU_b in moderate state uses the idle channel-slots to attain upper bound θ_g^{max}	Same as (6)
(13)	$(\omega+1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}, ..0,..0.,..V_{b(b)}^{max}, Q_1, Q_2+1)$	PU arrival. An SU_b in bad state is queued (Q_2). while another SU_b in bad state uses the idle channel-slots to attain upper bound θ_g^{max}	Same as (7)
(14)	$(\omega+1, V_{g(a)}, ..0,..0,..V_{g(b)}^{max}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2+1)$	PU arrival. An SU_b in good state is forced terminated, while another SU_b in good state uses the idle channel-slots to attain upper bound θ_g^{max}	Same as (5)
(15)	$(\omega+1, V_{g(a,b)}, V_{m(a)}, ..0..0.,..V_{m(b)}^{max}, V_{b(a,b)}, Q_1, Q_2+1)$	PU arrival. An SU_b in moderate state is forced terminated, while another SU_b in moderate state uses the idle channel-slots to attain upper bound θ_g^{max}	Same as (6)
(16)	$(\omega+1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}, ..0,..0.,..V_{b(b)}^{max}, Q_1, Q_2+1)$	PU arrival. An SU_b in bad state is forced terminated, while another SU_b in bad state uses the idle channel-slots to attain upper bound θ_g^{max}	Same as (7)
(18)	$(\omega+1, V_{g(a)}^{-}, .., V_{g(b)}^{max-}., V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	PU arrival. An SU_a in good state is pre-empted and SU_b with θ_g^{max} donate channel-slots.	$\left[\frac{\theta_g V_{g(a)}}{z(\phi)-\omega}\right]\lambda_p$
(19)	$(\omega+1, V_{g(a,b)} V_{m(a)}^{-}, .., V_{m(b)}^{max-}., V_{b(a,b)}, Q_1, Q_2)$	PU arrival. SU_a in moderate state is pre-empted and SU_b with θ_m^{max} donate channel-slots.	$\left[\frac{\theta_m V_{m(a)}}{z(\phi)-\omega}\right]\lambda_p$
(20)	$(\omega+1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}, V_{b(a)}^{-}, .., V_{b(b)}^{max-}, Q_1, Q_2)$	PU arrival. SU_a in bad state is pre-empted and SU_b with θ_b^{max} donate channel-slots.	$\left[\frac{\theta_b V_{b(a)}}{z(\phi)-\omega}\right]\lambda_p$
(21)	$(\omega+1, V_{g(a)}-1, V_{g(b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	PU arrival. SU_a in good state is forced terminated no spectrum adjustment/adaptation.	Same as (18)
(22)	$(\omega+1, V_{g(a,b)}, V_{m(a)}-1, V_{m(b)} V_{b(a,b)}, Q_1, Q_2)$	PU arrival. SU_a in moderate state is forced terminated no spectrum adjustment/adaptation.	Same as (19)

(23)	$(\omega+1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}-1, V_{b(b)}, Q_1, Q_2)$	PU arrival. SU_a in bad state is forced terminated no spectrum adjustment/adaptation.	Same as (20)
(24)	$(\omega+1, V_{g(a)}-1, V_{g(b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2-1)$	PU arrival. SU_a in good state is forced terminated, SU_b in good state, queued in Q_2 uses all the idle channel-slots …….	Same as (18)
(25)	$(\omega+1, V_{g(a,b)}, V_{m(a)}-1, V_{m(b)}V_{b(a,b)}, Q_1, Q_2-1)$	PU arrival. SU_a in moderate state is forced terminated, SU_b in moderate state, queued in Q_2 uses all the idle channel-slots …………	Same as (19)
(26)	$(\omega+1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}-1, V_{b(b)}, Q_1, Q_2-1)$	PU arrival. SU_a in bad state is forced terminated, SU_b in bad state, queued in Q_2 uses all the idle channel-slots …	Same as (20)
(27)	$(\omega+1, V_{g(a)}-1, ..V^{+}_{g(b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	PU arrival. An SU_a in good state is forced terminated, SU_b with θ_g^{min} in good state, uses all the idle channel-slots….	Same as (18)
(28)	$(\omega+1, V_{g(a,b)}, V_{m(a)}-1, ..V^{+}_{m(b)}, V_{b(a,b)}, Q_1, Q_2)$	PU arrival. An SU_a in moderate state is forced terminated, SU_b with θ_m^{min} in good state, uses all the idle channel-slots.	Same as (19)
(29)	$(\omega+1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}-1, ..V^{+}_{b(b)}, Q_1, Q_2)$	PU arrival. An SU_a in bad state is forced terminated, SU_b with θ_b^{min} in good state, uses all the idle channel-slots. …….	Same as (20)
(30)	$(\omega+1, V_{g(a)}, ..0, ..0, ..V^{max}_{g(b)}, V_{m(a,b)}, V_{b(a,b)}, Q_1, Q_2)$	PU arrival. An SU_a in good state is pre-empted and SU_b in good state is forced terminated. All other SU_b s in good state uses the idle channel-slots to attain θ_g^{max} …	Same as (18)
(31)	$(\omega+1, V_{g(a,b)}, V_{m(a)}, ..0..0., ..V^{max}_{m(b)}, V_{b(a,b)}, Q_1, Q_2)$	PU arrival. An SU_a in moderate state is pre-empted and SU_b in moderate state is forced terminated. All other SU_bs in good state uses the idle channel-slots to attain θ_m^{max}…	Same as (19)

(32)	$(\omega+1, V_{g(a,b)}, V_{m(a,b)}, V_{b(a)}, ..0, ..0., ..V_{b(b)}^{max}, Q_1, Q_2)$	PU arrival. An SU_a in bad state is pre-empted and SU_b in bad state is forced terminated. All other SU_b s in good state uses the idle channel-slots to attain θ_b^{max}…	Same as (20)

6.7.2 Performance Measures

These derivations are based on the premise of [4], [5], [8], [97]. In this study, three channel conditions were considered upon the arrival or departure of PUs/SUs [8, 9].

a) Blocking Probability

The blocking probability $P_{b(a,b)}^n$ is the sum of all probabilities of states that cannot admit SUs (class A or B) into the system. The arriving SUs will be blocked if: there are insufficient idle channel-slots to commence service, the respective queues (Q_1 and Q_2) are filled and if the sum of the available idle channel-slots is less than the required. It can be expressed as;

$$P_{b(a,b)}^n = \frac{Total\ \ SU\ blocking\ rate\ at\ a\ particular\ channel\ state}{SUs\ arrival\ rate\ at\ a\ particular\ channel\ state} \qquad (6.8a)$$

Let $P_{b(a)}^g$ be the blocking probability for class-A service in good channel condition and so for moderate and bad respectively.
Therefore,

$$P_{b(a)}^g = \frac{Total\ \ SUa\ blocking\ rate\ at\ a\ particular\ channel\ state}{SUa\ arrival\ rate\ at\ a\ particular\ channel\ state} \qquad (6.8b)$$

$$P_{b(a)}^g = \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_g} \theta_{g_i} \\ M*S-Z(\phi)<\theta_{g_i} \\ Q_1=Q_{1max}}} \frac{\theta_g V_{g(a)}}{Z(\phi)}\, \pi(\phi) \right] \Big/ \lambda_s = P_{b(a)}^g = \frac{1}{\lambda_s} \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_g} \theta_{g_i} \\ M*S-Z(\phi)<\theta_{g_i} \\ Q_1=Q_{1max}}} \frac{\theta_g V_{g(a)}}{Z(\phi)}\, \pi(\phi) \right] \qquad (6.9)$$

Similarly, the blocking probability $P_{b(b)}^g$ for class-B service in good condition is given as;

$$P^{g}_{b(b)} = \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_g} \theta_{g_i}^{min}, \\ M*S - Z(\phi) < \theta_{g_i}^{min} \\ Q_2 = Q_{2max}}} \frac{\theta_g^{min} V_{g(b)}}{Z(\phi)} \pi(\phi) \right] \Bigg/ \lambda_s = \frac{1}{\lambda_s} \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_g} \theta_{g_i}^{min}, \\ M*S - Z(\phi) < \theta_{g_i}^{min} \\ Q_2 = Q_{2max}}} \frac{\theta_g^{min} V_{g(b)}}{Z(\phi)} \pi(\phi) \right] \qquad (6.10)$$

The blocking probabilities $P^{b}_{b(a,b)}$ for class-A in moderate channel condition is given as;

$$P^{m}_{b(a)} = \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_m} \theta_{m_i}, \\ M*S - Z(\phi) < \theta_{m_i} \\ Q_1 = Q_{1max}}} \frac{\theta_m V_{m(a)}}{Z(\phi)} \pi(\phi) \right] \Bigg/ \lambda_s = \frac{1}{\lambda_s} \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_m} \theta_{m_i} \\ M*S - Z(\phi) < \theta_{m_i} \\ Q_1 = Q_{1max}}} \frac{\theta_g V_{m(a)}}{Z(\phi)} \pi(\phi) \right] \qquad (6.11)$$

While that for class-B is given as

$$P^{m}_{b(b)} = \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_g} \theta_{m_i}^{min}, \\ M*S - Z(\phi) < \theta_{m_i}^{min} \\ Q_2 = Q_{2max}}} \frac{\theta_m^{min} V_{g(b)}}{Z(\phi)} \pi(\phi) \right] \Bigg/ \lambda_s = \frac{1}{\lambda_s} \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_g} \theta_{m_i}^{min}, \\ M*S - Z(\phi) < \theta_{m_i}^{min} \\ Q_2 = Q_{2max}}} \frac{\theta_m^{min} V_{g(b)}}{Z(\phi)} \pi(\phi) \right] \qquad (6.12)$$

The blocking probabilities $P^{b}_{b(a,b)}$ for bad channel condition, is given as

$$P^{b}_{b(a)} = \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_b} \theta_{b_i}, \\ M*S - Z(\phi) < \theta_{b_i} \\ Q_1 = Q_{1max}}} \frac{\theta_b V_{b(a)}}{Z(\phi)} \pi(\phi) \right] \Bigg/ \lambda_s = \frac{1}{\lambda_s} \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_b} \theta_{b_i}, \\ M*S - Z(\phi) < \theta_{b_i} \\ Q_1 = Q_{1max}}} \frac{\theta_b V_{b(a)}}{Z(\phi)} \pi(\phi) \right] \qquad (6.13)$$

$$P^{b}_{b(b)} = \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_b} \theta_{b_i}^{min}, \\ M*S - Z(\phi) < \theta_{b_i}^{min} \\ Q_2 = Q_{2max}}} \frac{\theta_b^{min} V_{b(b)}}{Z(\phi)} \pi(\phi) \right] \Bigg/ \lambda_s = \frac{1}{\lambda_s} \left[\sum_{\substack{\phi \in \text{ȼ} \\ \theta_{su} \leq \sum_{i=1}^{V_b} \theta_{b_i}^{min}, \\ M*S - Z(\phi) < \theta_{b_i}^{min} \\ Q_2 = Q_{2max}}} \frac{\theta_b^{min} V_{b(b)}}{Z(\phi)} \pi(\phi) \right] \qquad (6.14)$$

b) Forced termination probability

The forced termination $P_{f(a,b)}^{n}$ occurs whenever an ongoing SU (class A or B) is pre-empted by the PU arrival irrespective of the wireless channel state and the SU class. This implies that the SU cannot successfully hands-off from PU idle channel. However, in this work, forced termination probability denotes the total forced termination rate divided by the total admitted SU rate. It can be expressed as;

$$P_{f(a,b)}^{n} = \frac{Total\ SU\ forced\ termination\ rate\ at\ a\ particular\ channel\ state}{rate\ of\ commensed\ SU\ service(SUconnections\ rate)} \tag{6.15}$$

The rate of commenced SU service indicates that admission has been granted thus, can be expressed as, $\left(1 - P_{b(a,b)}\right)\lambda_s$. Let $P_{f(a)}^{g}$ be the forced termination probability for class-A service in good channel condition, then,

$$P_{f(a)}^{g} = \left[\lambda_p \sum_{\substack{\phi \in \mathcal{C} \\ [(\theta_{su} < \sum_{i=1}^{V_g} \theta_{g_i}) \\ M*S=Z(\phi) \\ Q_1=Q_{1max}}} \frac{\theta_g V_{g(a)}}{Z(\phi) - \omega} \pi(\phi) \right] \Big/ (1 - P_{b(a)}^{g})\lambda_s$$

$$= \frac{\lambda_p}{(1 - P_{b(a)}^{g})\lambda_s} \left[\sum_{\substack{\phi \in \mathcal{C} \\ [(\theta_{su} < \sum_{i=1}^{V_g} \theta_{g_i}) \\ M*S=Z(\phi) \\ Q_1=Q_{1max}}} \frac{\theta_g V_{g(a)}}{Z(\phi) - \omega} \pi(\phi) \right] \tag{6.16}$$

Similarly, the forced termination probability $P_{f(b)}^{g}$ for class-B service in good channel condition is given as;

$$P_{f(b)}^{g} = \left[\lambda_p \sum_{\substack{\phi \in \text{ȼ} \\ (\theta_{su} < \sum_{i=1}^{V_g} \theta_{g_i}^{min}) \\ M*S=Z(\phi) \\ Q_2 = Q_{2max}}} \frac{\theta_g^{min} V_{g(b)}}{Z(\phi) - \omega} \pi(\phi) \right] \Bigg/ (1 - P_{b(b)}^{g})\lambda_s$$

$$= \frac{\lambda_p}{(1 - P_{b(b)}^{g})\lambda_s} \left[\sum_{\substack{\phi \in \text{ȼ} \\ (\theta_{su} < \sum_{i=1}^{V_g} \theta_{g_i}^{min}) \\ M*S=Z(\phi) \\ Q_2 = Q_{2max}}} \frac{\theta_g^{min} V_{g(b)}}{Z(\phi) - \omega} \pi(\phi) \right] \tag{6.17}$$

The forced termination probability for class-A service in moderate channel condition, is given as;

$$P_{f(a)}^{m} = \left[\lambda_p \sum_{\substack{\phi \in \text{ȼ} \\ (\theta_{su} < \sum_{i=1}^{V_m} \theta_{m_i}) \\ M*S=Z(\phi) \\ Q_1 = Q_{1max}}} \frac{\theta_m V_{m(a)}}{Z(\phi) - \omega} \pi(\phi) \right] \Bigg/ (1 - P_{b(a)}^{m})\lambda_s$$

$$= \frac{\lambda_p}{(1 - P_{b(a)}^{m})\lambda_s} \left[\sum_{\substack{(\theta_{su} < \sum_{i=1}^{V_m} \theta_{m_i}) \\ M*S=Z(\phi) \\ Q_1 = Q_{1max}}} \frac{\theta_m V_{m(a)}}{Z(\phi) - \omega} \pi(\phi) \right] \tag{6.18}$$

While the forced termination probability $P_{f(b)}^{m}$ for class-B service in moderate channel condition is given as;

$$P_{f(b)}^{m} = \left[\lambda_p \sum_{\substack{\phi \in \mathcal{C} \\ (\theta_{su} < \sum_{i=1}^{V_m} \theta_m^{min}) \\ M*S = Z(\phi) \\ Q_2 = Q_{2max}}} \frac{\theta_m^{min} V_{m(b)}}{Z(\phi) - \omega} \, \pi(\phi) \right] \Bigg/ (1 - P_{b(b)}^{m}) \lambda_s$$

$$= \frac{\lambda_p}{\left(1 - P_{b(b)}^{m}\right) \lambda_s} \left[\sum_{\substack{\phi \in \mathcal{C} \\ (\theta_{su} < \sum_{i=1}^{V_m} \theta_m^{min}) \\ M*S = Z(\phi) \\ Q_2 = Q_{2max}}} \frac{\theta_m^{min} V_{m(b)}}{Z(\phi) - \omega} \, \pi(\phi) \right] \tag{6.19}$$

The forced termination probability for class-A service in bad channel condition, is given as;

$$P_{f(a)}^{b} = \left[\lambda_p \sum_{\substack{\phi \in \mathcal{C} \\ (\theta_{su} < \sum_{i=1}^{V_b} \theta_{b_i}) \\ M*S = Z(\phi) \\ Q_1 = Q_{1max}}} \frac{\theta_b V_{b(a)}}{Z(\phi) - \omega} \, \pi(\phi) \right] \Bigg/ \left(1 - P_{b(a)}^{b}\right) \lambda_s$$

$$= \frac{\lambda_p}{(1 - P_{b(a)}^{b}) \lambda_s} \left[\sum_{\substack{\phi \in \mathcal{C} \\ (\theta_{su} < \sum_{i=1}^{V_b} \theta_{b_i}) \\ M*S = Z(\phi) \\ Q_1 = Q_{1max}}} \frac{\theta_b V_{b(a)}}{Z(\phi) - \omega} \, \pi(\phi) \right] \tag{6.20}$$

While the forced termination probability $P_{f(b)}^{b}$ for class-B service in bad channel condition, is given as;

$$P_{f(b)}^{b} = \left[\lambda_p \sum_{\substack{\phi \in \text{ȡ} \\ (\theta_{su} < \sum_{i=1}^{V_b} \theta_{b_i}^{min}) \\ M * S = Z(\phi) \\ Q_2 = Q_{2max}}} \frac{\theta_b^{min} V_{b(b)}}{Z(\phi) - \omega} \pi(\phi) \right] \Big/ (1 - P_{b(b)}^{b}) \lambda_s$$

$$= \frac{\lambda_p}{(1 - P_{b(b)}^{b}) \lambda_s} \left[\sum_{\substack{\phi \in \text{ȡ} \\ (\theta_{su} < \sum_{i=1}^{V_b} \theta_{b_i}^{min}) \\ M * S = Z(\phi) \\ Q_2 = Q_{2max}}} \frac{\theta_b^{min} V_{b(b)}}{Z(\phi) - \omega} \pi(\phi) \right] \tag{6.21}$$

c) Admission/Acceptance probability

The admission probability $P_{a(a,b)}$ is the probability that enough resources (channel-slots) exist for the SUs (class A and class B) when both arrives or the likelihood that the resources left over after PU occupancy, is greater than or equal to the resources required by the SUs. It can be expressed as the rate of *Not-Blocking* with respect to the channel condition.

$$P_{a(a,b)}^{n} = \left(1 - P_{b(a,b)}^{n}\right) \tag{6.22}$$

The admission/acceptance probability for SU class-A in good channel condition is given as;

$$P_{a(a)}^{g} = \left(1 - P_{b(a)}^{g}\right) \tag{6.23}$$

$$P_{a(a)}^{g} = \left(1 - \frac{1}{\lambda_s} \left[\sum_{\substack{\phi \in \text{ȡ} \\ \theta_{su} \leq \sum_{i=1}^{V_g} \theta_{g_i} \\ M * S - Z(\phi) < \theta_{g_i} \\ Q_1 = Q_{1max}}} \frac{\theta_g V_{g(a)}}{Z(\phi)} \pi(\phi) \right] \right) \tag{6.24}$$

While for SU class-B in good channel condition is given as;

$$P_{a(b)}^{g} = \left(1 - P_{b(b)}^{g}\right) \tag{6.25}$$

$$P^{g}_{a(b)} = \left(1-\left[\frac{1}{\lambda_s}\sum_{\substack{\phi\in \text{ȼ} \\ \theta_{su}\le\sum_{i=1}^{V_g}\theta_{g_i}^{min} \\ M*S-Z(\phi)<\theta_{g_i}^{min} \\ Q_2=Q_{2max}}}\frac{\theta_g^{min}V_{g(b)}}{Z(\phi)}\,\pi(\phi)\right]\right) \tag{6.26}$$

The admission/acceptance probability for SU class-A in moderate channel condition is given as;

$$P^{m}_{a(a)} = \left(1-P^{m}_{b(a)}\right) \tag{6.27}$$

$$P^{m}_{a(a)} = \left(1-\left[\frac{1}{\lambda_s}\sum_{\substack{\phi\in \text{ȼ} \\ \theta_{su}\le\sum_{i=1}^{V_m}\theta_{m_i}, \\ M*S-Z(\phi)<\theta_{m_i} \\ Q_1=Q_{1max}}}\frac{\theta_m V_{m(a)}}{Z(\phi)}\,\pi(\phi)\right]\lambda_s\right) \tag{6.28}$$

Whereas for SU class-B in moderate channel condition is given as;

$$P^{m}_{a(b)} = \left(1-P^{m}_{b(b)}\right) \tag{6.29}$$

$$P^{m}_{a(b)} = \left(1-\left[\frac{1}{\lambda_s}\sum_{\substack{\phi\in \text{ȼ} \\ \theta_{su}\le\sum_{i=1}^{V_m}\theta_{m_i}^{min}, \\ M*S-Z(\phi)<\theta_{m_i}^{min} \\ Q_1=Q_{1max}}}\frac{\theta_m^{min}V_{m(b)}}{Z(\phi)}\,\pi(\phi)\right]\right) \tag{6.30}$$

The admission probability for SU class-A in bad channel condition is given as;

$$P^{b}_{a(a)} = \left(1-P^{b}_{b(a)}\right) \tag{6.31}$$

$$P^{b}_{a(a)} = \left(1-\left[\frac{1}{\lambda_s}\sum_{\substack{\phi\in \text{ȼ} \\ \theta_{su}\le\sum_{i=1}^{V_b}\theta_{b_i}, \\ M*S-Z(\phi)<\theta_{b_i} \\ Q_1=Q_{1max}}}\frac{\theta_b V_{b(a)}}{Z(\phi)}\,\pi(\phi)\right]\right) \tag{6.32}$$

Similarly, for SU class-B in bad channel condition is given as;

$$P_{a(b)}^{b} = \left(1 - P_{b(b)}^{b}\right) \tag{6.33}$$

$$P_{a(b)}^{b} = \left(1 - \left[\frac{1}{\lambda_s} \sum_{\substack{\phi \in \text{ɖ} \\ \theta_{su} \leq \sum_{i=1}^{V_b} \theta_{b_i}^{min} \\ M*S - Z(\phi) < \theta_b^{min} \\ Q_2 = Q_{2max}}} \frac{\theta_b^{min} V_{b(b)}}{Z(\phi)} \pi(\phi) \right] \right) \tag{6.34}$$

d) Capacity $\sigma_{n(a,b)}$

The capacity of the SU (class A and class B) is the average service rate of the SUs. This implies the average number of SU completion per unit time [8]. However, in this thesis, the capacity varies from due varying channel link thus it can be expressed as;

$$\sigma_{n(a)} = \sum_{\phi \in \text{ɖ}} \theta_n V_{n(a)} \mu_s \pi(\phi) \tag{6.35}$$

$$\sigma_{n(b)} = \sum_{\phi \in \text{ɖ}} \sum_{\theta_n^{min} = k}^{\theta_n^{min}} \theta_n^{min} V_{n(b)} \mu_s \pi(\phi) \tag{6.36}$$

e) Spectrum Utilization $\vartheta_{n(a,b)}$

Spectrum utilization is the mean number of utilized channel-slot over the total number of channel-slots (total capacity of the system) irrespective of the channel state. It indicates that a total of $Z(\phi)$ is utilized out of $M * S$ as in [8], [97]. It can be expressed as;

$$\vartheta_{n(a,b)} = \sum_{\phi \in \text{ɖ}} \frac{Z(\phi)}{M * S} \pi(\phi) \tag{6.37}$$

f) Average queue size $\delta_{l(a,b)}$:

In this work, the size (length) of the queue is a function of the arrival of the SUs (class A and class B) and service completion rates. However, Q_1 and Q_2 are the queue sizes for buffer 1 and buffer 2 respectively at each state $\phi \in \text{ɖ}$. The average queue sizes of the SUs (class-A and class-B) can be expressed respectively as;

$$\delta_{l(a)} = \sum_{\phi \in \text{ɖ}} Q_{1(a)} \, \pi(\phi) \tag{6.38}$$

$$\delta_{l(b)} = \sum_{\phi \in \text{ɖ}} Q_{1(b)} \pi(\phi) \tag{6.39}$$

g) *Mean total delay* $T_{(a,b)}$

The mean total delay of the SUs (class-A and class-B) is the sums of the mean transmission time $T^{t}_{(a,b)}$ and the average waiting time $T^{q}_{(a,b)}$ of SUs (class A and class B) services in the queues respectively. Let $\Phi^{s}_{(a)}$ and $\Phi^{s}_{(b)}$ be the average number of ongoing SU class A and B services while $T^{t}_{(a)}$ and $T^{t}_{(b)}$ denotes the mean transmission time of SUs services. $T^{q}_{(a)}$ and $T^{q}_{(b)}$ represents the mean waiting time of SUs (class A and class B) services in the queues and $T_{(a)}$ and $T_{(b)}$ are the mean total delay of SUs (class A and class B) respectively. Therefore, the average number of ongoing SU (class A and class B) services can be expressed respectively as;

$$\Phi^{s}_{(a)} = \sum_{\phi \in \text{ɖ}} \theta_n \, V_{n(a)} \, \pi(\phi) \tag{6.40}$$

$$\Phi^{s}_{(b)} = \sum_{\phi \in \text{ɖ}\, k=} \; \sum_{\theta_n^{min}=k}^{\theta_n^{max}} \theta_n^{min} \, V_{n(b)} \, \pi(\phi) \tag{6.41}$$

From little's theorem [150], [151], the mean total delay of the SU class-B services, $T_{(b)}$ is given as;

$$T_{(b)} = T^{q}_{(b)} + T^{t}_{(b)} = \frac{\delta_{l(b)}}{\lambda_{s(b)} + \lambda_{sm}} + \frac{\Phi^{s}_{(b)}}{\lambda_{s(b)} + \lambda_{sm}} \tag{6.42}$$

Where $\lambda_{s(b)}$ and λ_{sm} are the mean arrival rate of the admitted SU_b and average feedback arrival rate of SU_b into Q_2 respectively.

Hence,

$$T_{(b)} = T_{(b)}^{q} + T_{(b)}^{t} = \frac{\delta_{l(b)} + \Phi_{(b)}^{s}}{\lambda_{s(b)} + \lambda_{sm}} = \frac{\delta_{l(b)} + \Phi_{(b)}^{s}}{\lambda_{s(b)}} \tag{6.43}$$

If λ_{sm} is negligible as earlier assumed, therefore,

$$T_{(b)} = \frac{\delta_{l(b)} + \Phi_{(b)}^{s}}{\lambda_{s(b)}} \tag{6.44}$$

Let $\Delta_{(b)}$ be denote the number of times an ongoing SU_b is fed back into Q_2 after interrupted. Then

$$T_{(b)} = \left(\frac{\delta_{l(b)} + \Phi_{(b)}^{s}}{\lambda_{s(b)}}\right)\Delta_{(b)} = \left(T_{(b)}^{q} + T_{(b)}^{t}\right)\Delta_{(b)} \tag{6.45}$$

$\Delta_{(b)}$ can be set to a value

Similarly, the mean total delay for SU_a service is straight forward and can be expressed as;

$$\begin{aligned} T_{(a)} &= T_{(a)}^{q} + T_{(a)}^{t} \\ &= \frac{\delta_{l(a)}}{\lambda_{s(a)}} + \frac{\Phi_{(a)}^{s}}{\lambda_{s(b)}} = \frac{\delta_{l(a)} + \Phi_{(a)}^{s}}{\lambda_{s}} \end{aligned} \tag{6.46}$$

6.8 Numerical Results and Discussion

The numerical results of the proposed strategy are discussed and evaluated in terms of blocking probability, capacity, spectrum utilization, forced termination probability, access/admission probability, and mean total delay. The proposed strategy is compared with [8] which is a strategy without queue. The extensive simulation and analysis for the strategy is done by developing Matlab code using Matlab and Excel tools. Moreover, the parameters of, [8], [24] were adopted and 100 realized are averaged to obtain the final result from 10^6 iterations. However, the scenarios concept differs slightly since three channel conditions are taken into account. Thus, $\lambda_p = 0.5,\ \lambda_s = 1.5,\ \mu_p = 0.5,\ \mu_{s(a)} =* \mu_{s(b)} = 0.82, Q_{2max}, Q_{1max} \geq 2, \omega \leq 6, * P_a^n, * P_a^n \geq 0.5,\ * P_b^n,\ P_b^n \leq 0.25,\ *_{ft}^n, P_{ft}^n \leq 0.25,\ V_g = 6, V_m = 4, V_b = 2, \mathrm{SNR} = 15 - 30\mathrm{dB}, \theta_n^{min} \leq 2, \theta_n^{max} \leq 6,\ \theta_n = 3,\ M \geq 6,\ T_{(b)}^t \leq 2.5,\ T_{(a)}^t \leq 1.55$. The essence of introducing queuing regime is to further improve the performance of the proposed strategy unlike [8], where there was no queue regime to cater for SUs in the event of PU arrival and departure respectively. Figures 6.3 (a) and 6.3(b) clearly shows that once a SU cannot be served, instead of immediate blocking due to insufficient resources in the event of PU arrival, the SU class-B will be buffered. Thus, make the system more dynamic. Similarly, because of the nature of class-A traffic, it is served first before class-B due to its delay constrains. However, as the channel state changes from good to moderate or bad, the SUs (class-A or B) assembles different number of channel-slots with each channel state having different transmission rates via AMC controller.

At a glance, while the queue length increases (more SUs queued) the blocking probability drops in different channel state. However, the SU class-A has a lower blocking probability compared to class-B in the three channel conditions. This is due to the high priority given to it by the CRBS for its delays intolerance.

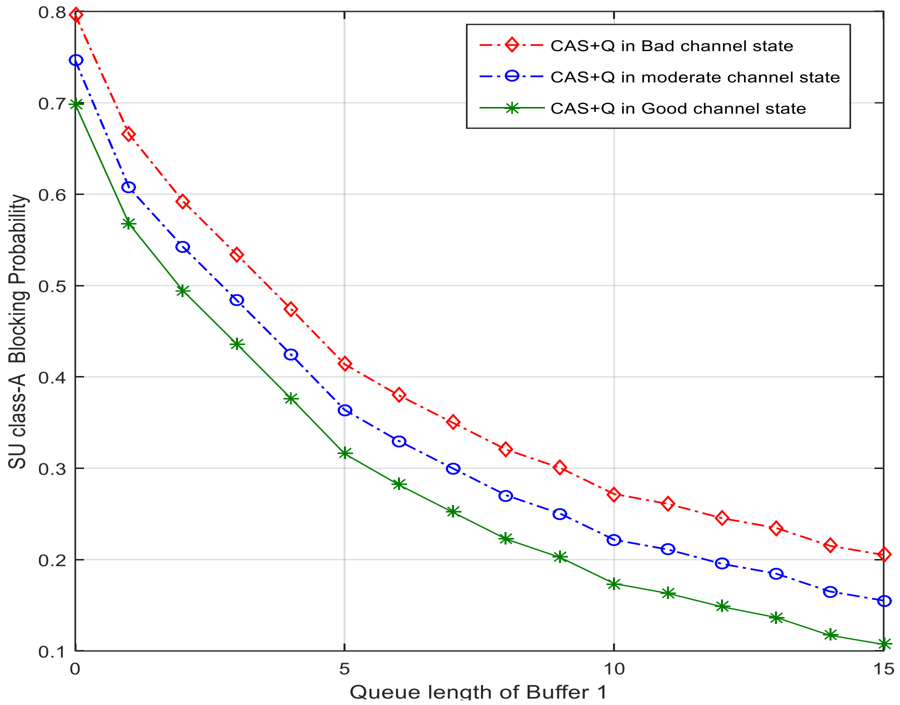

Figure 6.3(a) SU_a Blocking probability, $P_{b(a)}$vs Queue length, Q_{1max}

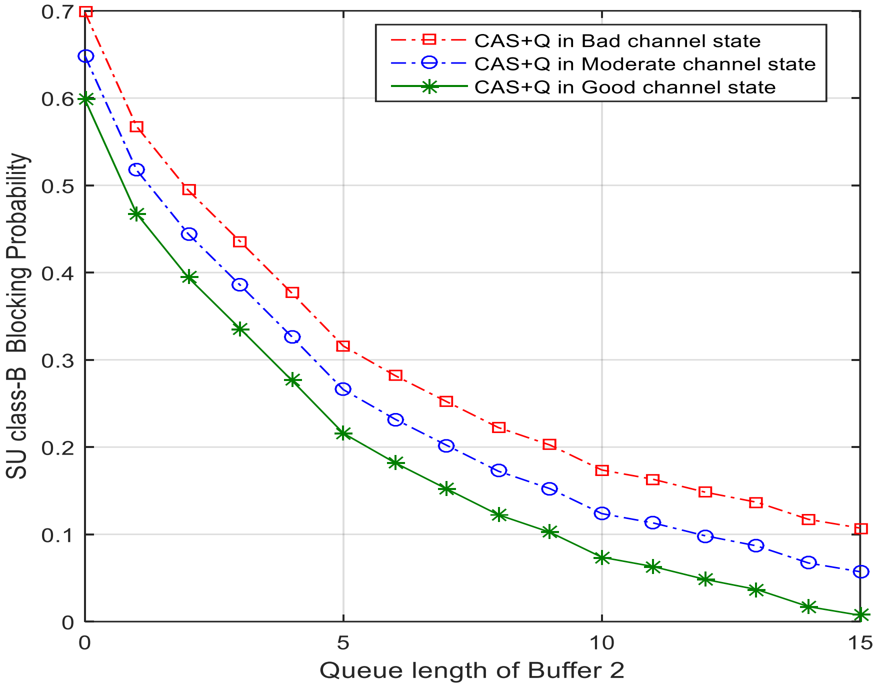

Figure 6.3(b) SU_b Blocking probability, $P_{b(b)}$vs Queue length, Q_{2max}

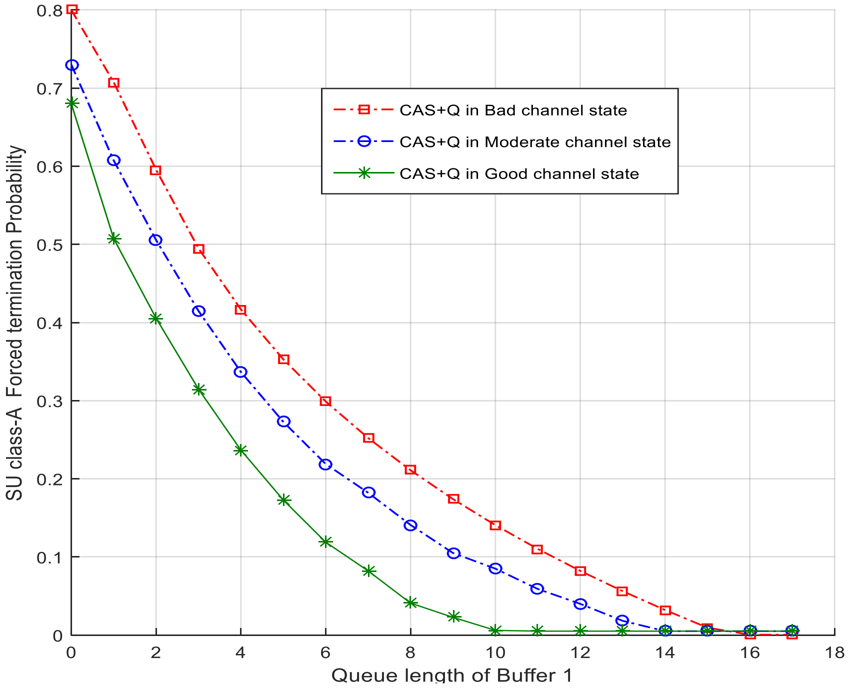

Figure 6.4(a) SU_a FT probability, $P_{f(a)}$vs Queue length, Q_{1max}

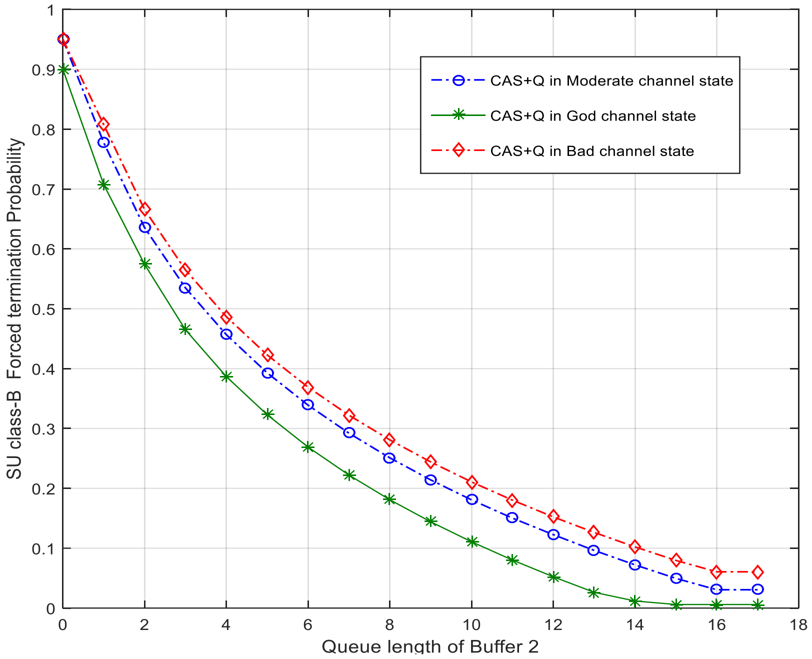

Figure6.4 (b) SU_b FT probability, $P_{f(b)}$vs Queue length, Q_{2max}

Blocking and FT are the two most common challenges that SUs suffer from. This is common because SUs are the unlicensed users hence, the PU can arrive any time and pre-empty any SU using it channels. This explains the reason why the two performance metrics have similar behaviour at times.Figures 6.4(a) and 6.4(b) illustrate the effects of a queuing regime on forced termination when the PU interrupts a transmitting SU. When a SU overstays its expected time in the queue, irrespective of the classes, will be dropped. This is to avoid starvation of other users waiting on the queue. From the result, the SU_a have relatively lower force termination probability compared to the SU_b irrespective of the channel conditions.. This is because, it is given priority access to the PU channel and are not fed back like the SU_b. But in overall performance, the queues have significantly reduced force termination.

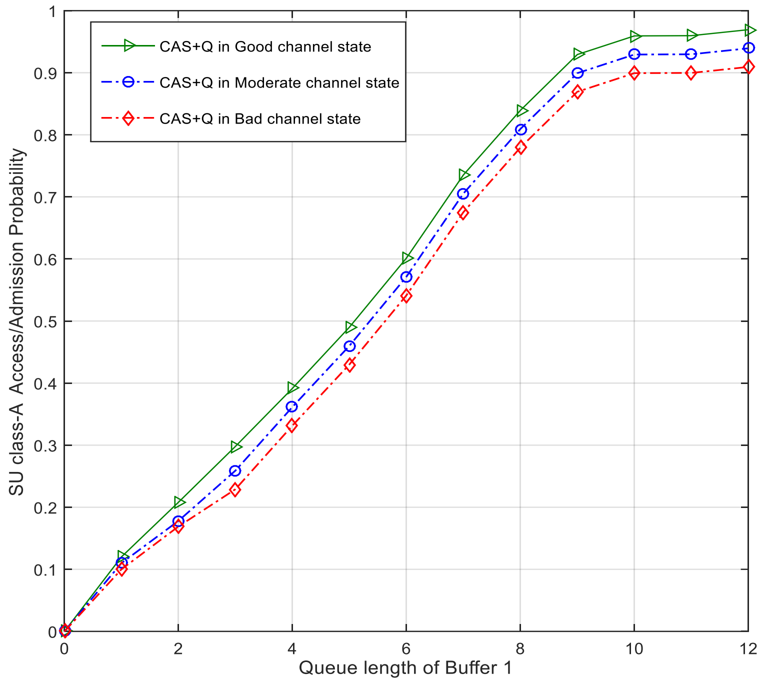

Figure 6.5(a) SU_a Access probability, $P_{a(a)}$vs Queue length, Q_{1max}

Figures 6.5 (a) and 6.5(b) results illustrate the impact of incorporating a queuing regime into channel assembling. This gives the SUs (particularly SU_b) another opportunity to access the spectrum whenever the PU interrupts or whenever the SU experience insufficient resources. Nevertheless, the access/admission probability of the SUs grows as the queue length increases. This implies that more SUs are given the opportunity to access the scarce resources. Because of the preferential treatment given to SU_a, its access/admission probability grows higher in good channel state than SU_b in any other channel conditions. After point $Q_{2max} = Q_{1max} = 10$, the access probability of SU_b begin to drop due to continuous feedbacks (arrivals of interrupted SU_b) which added up with the new arrivals as expressed in equation (6.42).

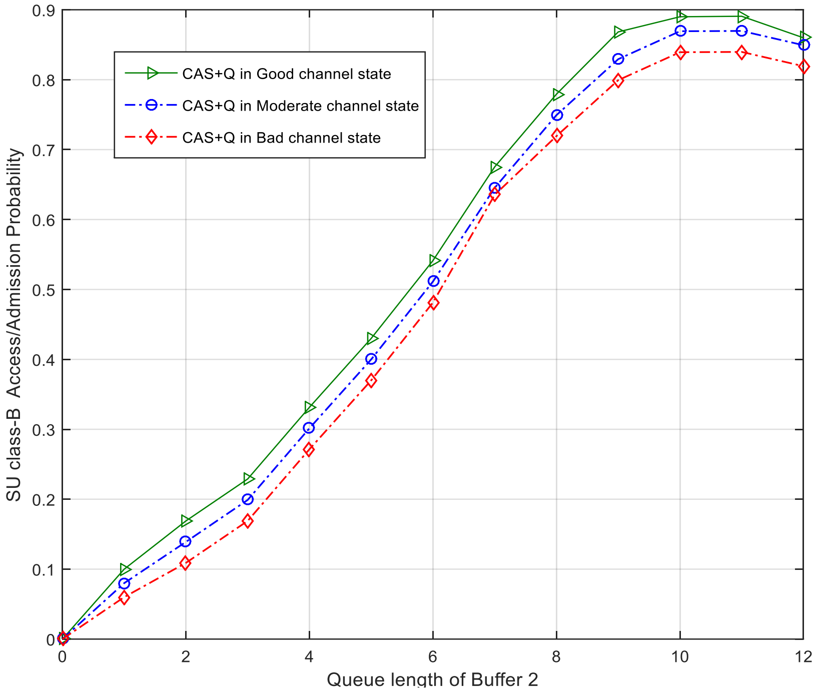

Figure 6.5(b) SU_b Access probability, $P_{a(b)}$vs Queue length, Q_{2max}

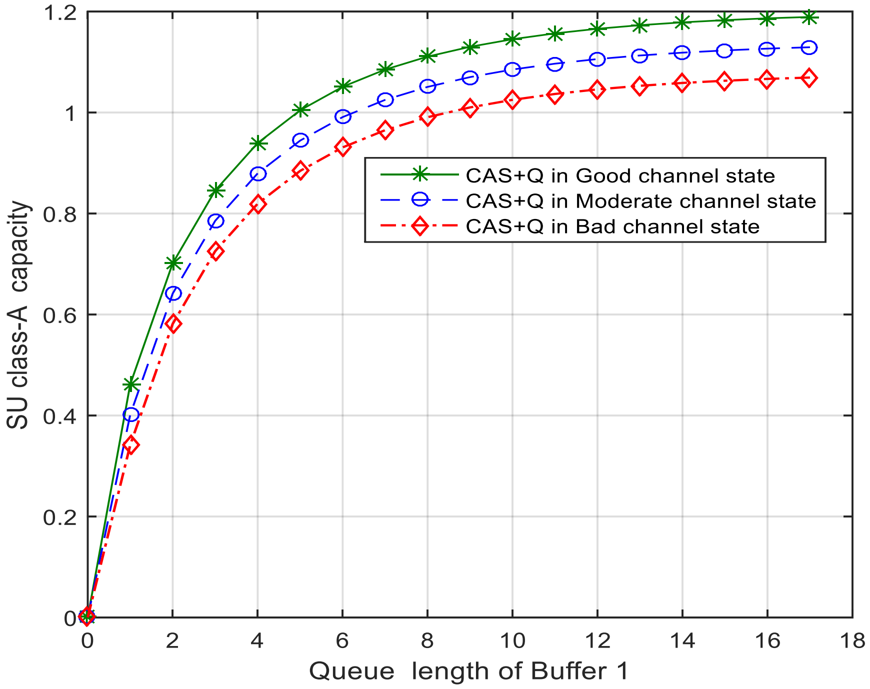

Figure 6.6(a) SU_a Capacity, $\sigma_{n(a)}$vs Queue length, Q_{1max}

Although both users at different channel conditions showed improved capacity as the queue length increases in Fig. 6.6 (a) and 6.6(b), SU_a displays approximately $12\%, 8\%$ and 13% higher capacity when the channel state is good, moderate and bad respectively, when compared to SU_b. This further shows that more SUs can improve and complete their previous transmission session, by getting a second chance of transmitting their packets (data) when vacant exists.

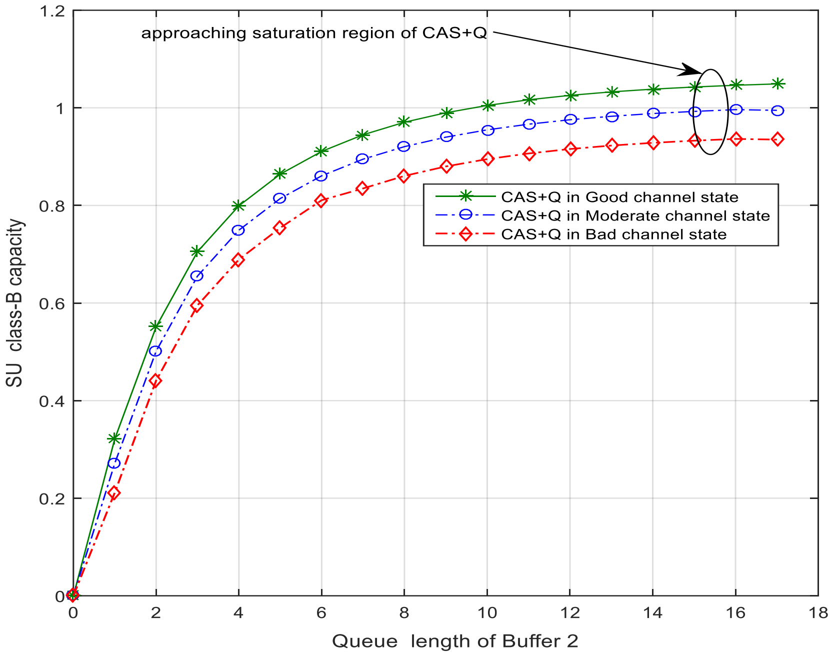

Figure 6.6(b) SU_b Capacity, $\sigma_{n(b)}$vs Queue length, Q_{2max}

The result shown in Figures 6.7 (a) and 6.7(b) depicts the response of the proposed strategy on the varying the wireless link. Spectrum utilization for the two classes of users is improved since the queues are avenue that gives the SUs the advantage to access the spectrum. With AMC, each channel condition has a particular transmission rate mode pair that supports the rates at which SUs are serviced. Good channel state has the highest transmission rate followed by moderate and bad channel state respectively. However, because of the priority given to class-A SU, it outperformed the class-B irrespective of the channel state.

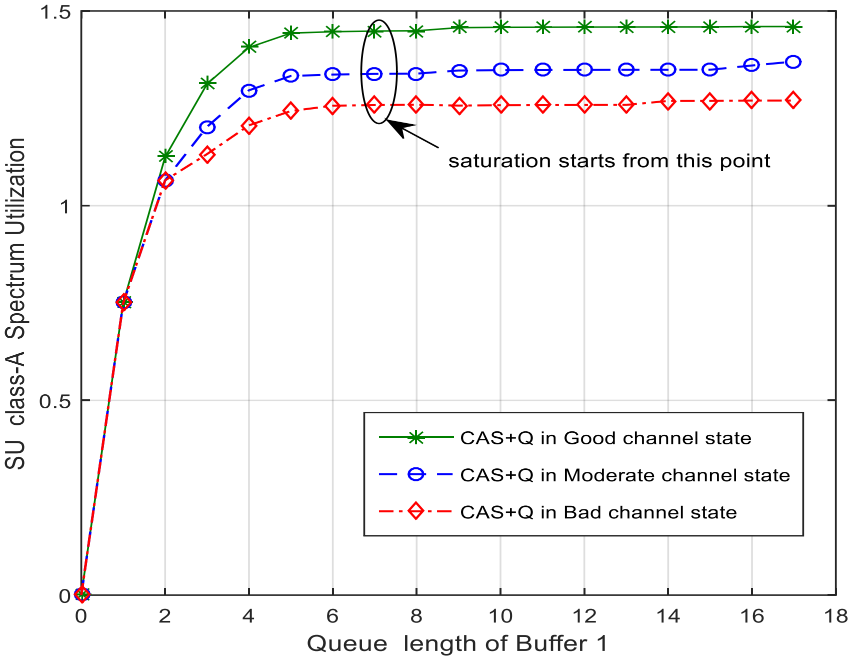

Figure 6.7(a) SU_a Spectrum Utilization, $\vartheta_{n(a)}$ vs Queue length, Q_{1max}

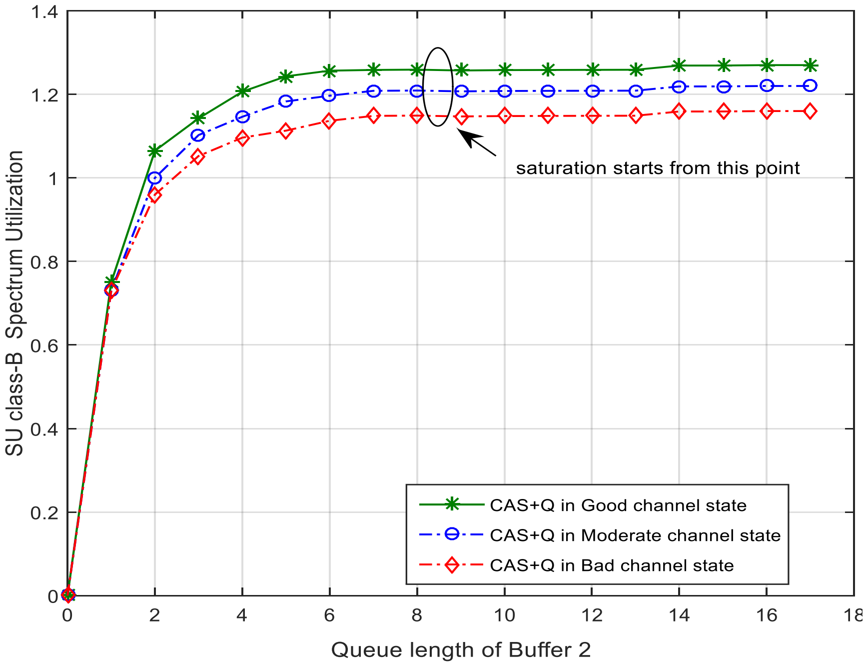

Figure 6.7(b) SU_b Spectrum Utilization, $\vartheta_{n(b)}$ vs Queue length, Q_{2max}

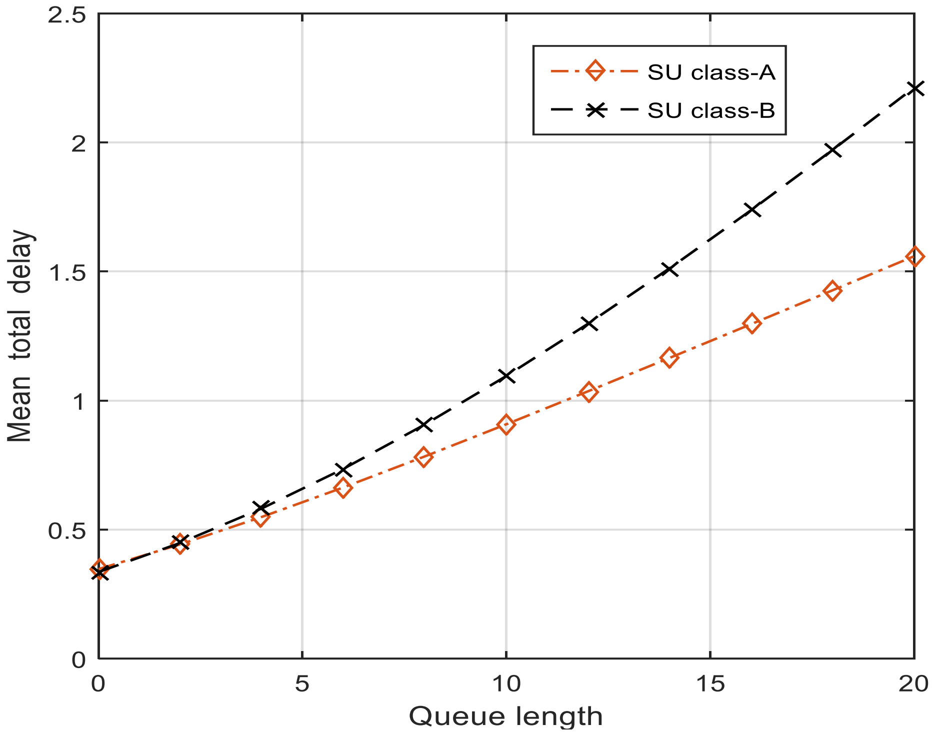

Figure6.8 SU Mean total delay vs Queue length

The consequence of incorporating a queuing regime into the proposed strategy is the additional waiting time (delays) the SU spent on the queue, waiting to be served. Figure 6.8 illustrates the effect of queue length on the total delay particularly on the SU class-B. The interrupted SU_b is fed back into the queue to reduce instant forced termination while the new arriving SU is queued to avoid instant blocking hence, both arrivals increase the queue length (number of SUs in the buffer waiting to be serves). SU class-A has an arrival rate of $\lambda_{s(a)}$ while SU class-B has a joint arrival of $\lambda_{s(b)} + \lambda_{sm}$ for the new and interrupted SU_b respectively. Therefore, the queue length of the SU_b will be longer due to more arrival unlike SU_a with no such feedback mechanism coupled with its high priority access.

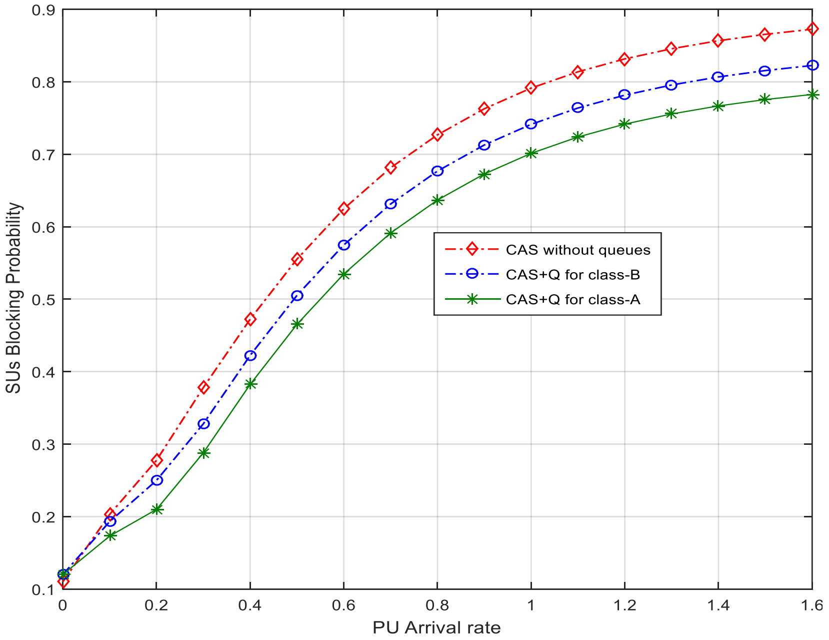

Figure 6.9(a) SU blocking probability, P_b vs PU arrival, λ_p

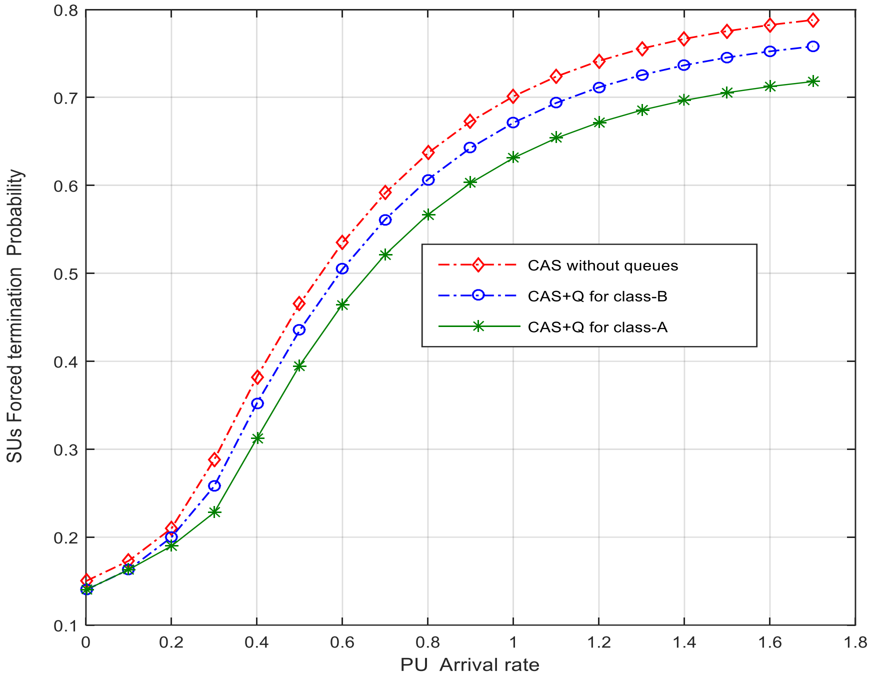

Figure 6.9(b) SU Forced termination probability, P_b vs PU arrival, λ_p

In Figures 6.9 (a) and 6.9(b), the SUs blocking and forced termination probabilities increases for both strategies (CAS+Q and CAS without queues), due to PU arrivals. This significantly affects the SU service because more SUs will be interrupted and hence vacates the channel since the PU is the licensed owners of the spectrum. However, in the event of batch arrival of PUs, new SU will be denied access to the spectrum because the channel would be fully occupied and ongoing SU service will be pre-empted. This increases the blocking and forced termination statistics yet, at every point of PU arrival, CAS+Q for SU_a shows better improvement (low blocking and forced termination probability) compared to CAS+Q for SU_b and CAS without queues for obvious reasons like priority access and flexibility.

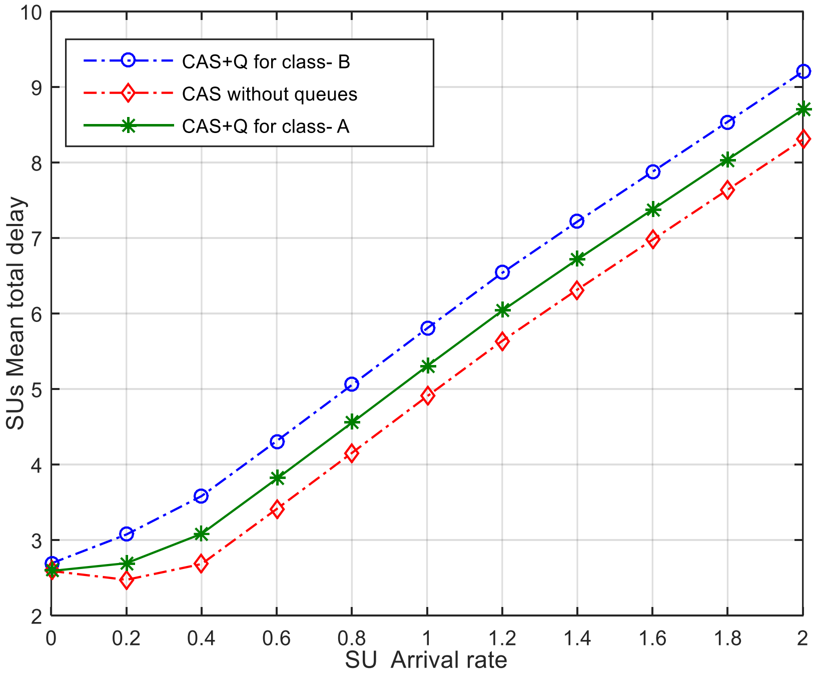

Figure6.10 SU Mean total delay vs SU arrival rates

Figure 6.10 shows significant increase in delay for the SU class-B compared to class-A. The reason is that class-B queue is often occupied due to feedback arrivals of interrupted class-B and new arrivals trying to gain access to the spectrum. However, the CAS without queuing [8] has the lowest mean total delay compared to CAS+Q for class-A and B with the higher delay due to longer queue sizes irrespective of the channel conditions. However, CAS+Q for class-B have the longest queue length, which translates to longer delays on the queue.

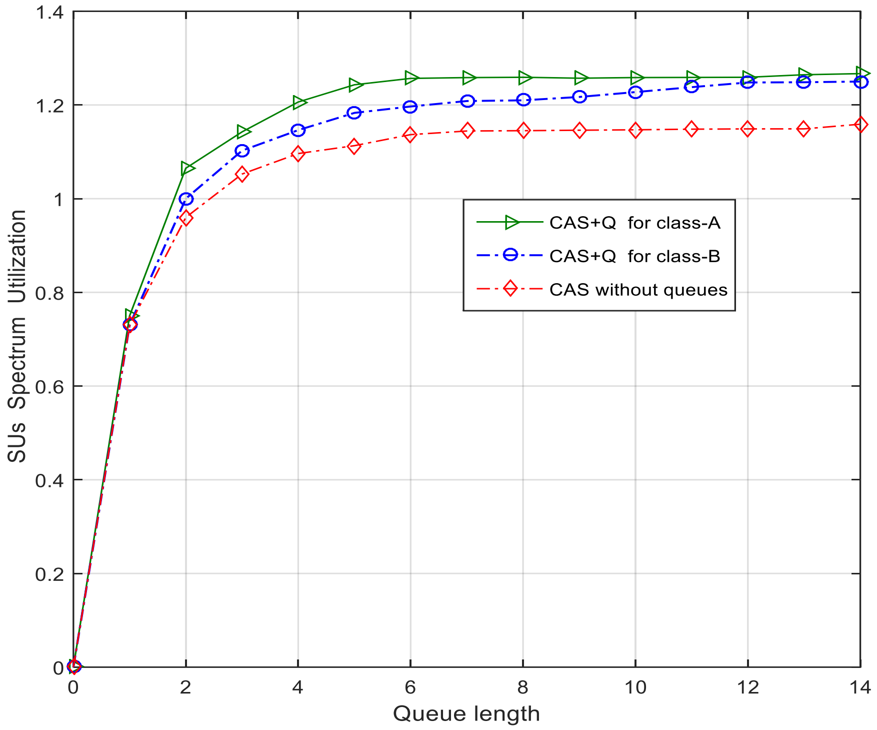

Figure 6.11 Spectrum Utilization ϑ_n vs Queue length

As mentioned in Figures 6.7 (a) and 6.7(b), spectrum utilization for SU_a and SU_b will be maximized in the sense that the queue creates an avenue that gives the SUs the opportunity to access the spectrum after several interruptions. Therefore, the more they arrive, the higher the possibility for them to utilize the spectrum. The proposed strategy for both classed of SUs showed improvement when compared to strategies without queue [8]. However, SU_a showed a better response compared to SU_b in Figure 6.11.

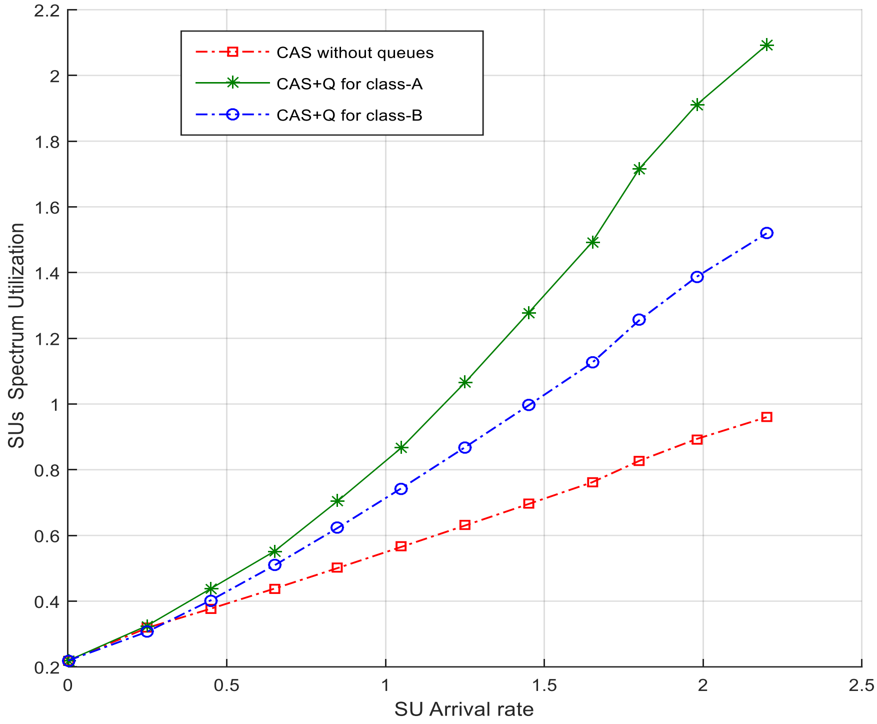

Figure 6.12. Spectrum Utilization, ϑ_n vs SU arrival, λ_s

From Figure 6.12, spectrum utilization is improved using the proposed strategy for both classes of SUs. However, when the scheme is implemented without queues [8], it showed less improvement compared to the proposed strategy [9]. As SU arrivals increases the spectrum utilization improves since more SU are served. For both queues set at $Q_{1max} = 3,\ Q_{2max} = 6\quad \lambda_s = 2,$ respectively, the spectrum utilization is improved compared to when the queues are set at $Q_{1max} = 1\ Q_{2max} = 2$. Also, with larger queue length, new SUs can be accommodated in the buffer. Therefore, when a PU channel becomes vacant, there is likelihood that it will be utilized by a SU. However, to increase spectrum utilization, it is essential to reduce the idle period thus; larger queue length could fulfil this requirement since more SU requests will be allowed.

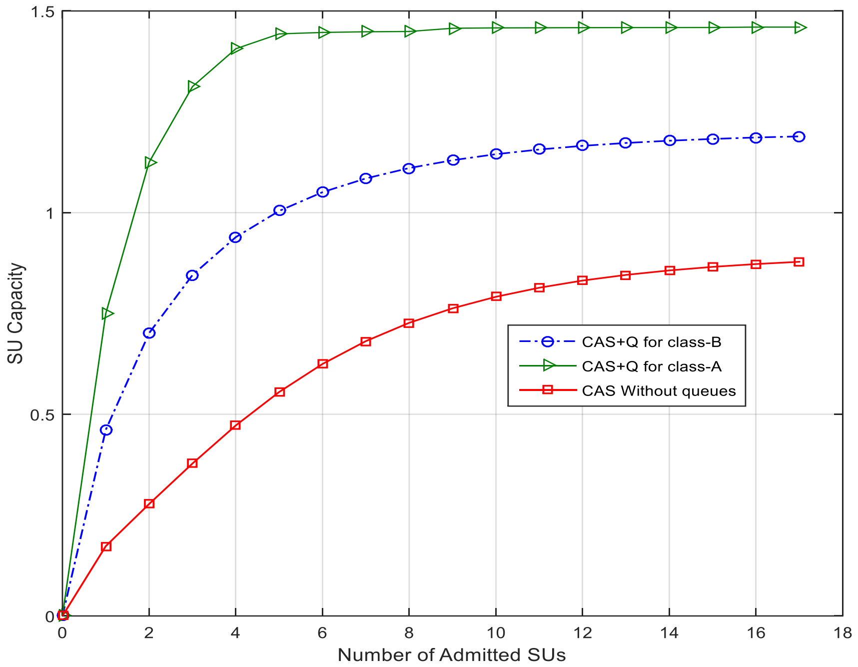

Figure 6.13 Capacity, $\sigma_n$vs Number of admitted SU

The result in Figure 6.13 shows that when access/admission has been granted to the SUs based on the criteria mentioned earlier, the SU then aggregates the required channel slots. This in turn makes the SU capacity to increase since it is the product of the number of admitted SUs and the number of channel slots assembled. However, the CAS+Q for class A and B respectively, improve the SU capacity compared to the CAS without queues [8]. As explained earlier, the queues reduced FT and blocking of the SUs. Therefore, since more SUs have the privilege of using the spectrum, their total occupancy and utilization will increase significantly.

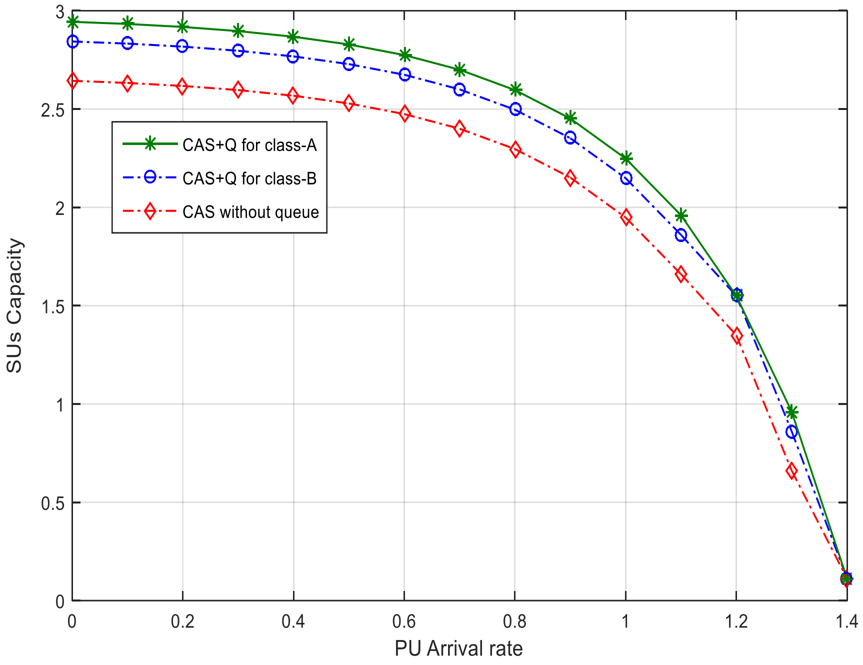

Figure 6.14 Capacity, $\sigma_n$vs PU arrival, λ_p

Figure 6.14 clearly shows that SU capacity was at the highest when the PUs are absent from the spectrum. This implies that more SUs are given access into the spectrum and as such, the SUs maximized the resources by assembling more channel-slots with high completion time irrespective of the channel state and the strategies (with or without queues) used by the SUs. However, for each of the scenario, the CAS+Q showed its robustness over the CAS without queues [8], when the PU begins to arrive into the spectrum. However, in an event of batch arrivals of the PUs, the SUs will experience decrease in capacity because very few channel-slots will be available for the SUs to use and as such, not much will be assembled by the SU. Conversely, capacity will increase when PU departs and more channels-slots are made available for SU.

6.9 Conclusion

This chapter has extended the work done in this thesis [6], [8], [24] (chapter four and five) by proposing a joint channel assembling strategy with queues (CAS+Q) featuring AMC in CRN. The strategy is improved by introducing a buffer regime consisting of separate queues to accommodate interrupted SUs of different classes. An analytical and simulation framework to evaluate the performance of the strategies is developed and compared with [8]. The performance of the system is evaluated in different scenarios (channel conditions) and selected parameters. It showed that the proposed CAS+Q outperformed the existing ones in [8] in terms of blocking and forced termination probability, secondary network's capacity, access/admission probability and spectrum utilization. Similarly, this proposed scheme demonstrates that AMC is a robust technique in improving channel assembling. However, increasing the queue length, the forced termination and blocking probability of SUs could be further reduced, but at the expense of longer delays. Thus, the queue length of SU_a is kept as low as possible in order to reduce the delay experienced as a result, to achieve higher capacity for SU_b. Since SU_b traffic benefits more from low blocking/forced termination probabilities and high capacity rather than overall delay, Q_2 is designed with relatively large queue length.

CHAPTER SEVEN

Conclusion Recommendation and Future Works

7.1 Conclusion

This study has shown that if the set targets for the smooth takeoff of fifth generation (5G) wireless network must be realized, then, robust models must be developed and this is what cognitive radio's CAS is bringing to bear. The conclusion of this thesis is drawn from chapter two, three, four, five and six.

In chapter 2, a brief survey/overview of CRN was presented. In the same vein, what makes it cognitive radio is embedded in its capabilities to: (1) intelligently sense the primary user's channel to avoid collision (interference) using appropriate sensing techniques; (2) dynamically and opportunistically access the primary user's spectrum before it arrives; (3) make decisions based on its radio environment and neighboring users activities; (4) centrally or otherwise share spectrum resources among each other to avoid starvation of weaker users; (5) hop to another free channel/spectrum if it cannot coexist with the PU and last but not the least; (6) assemble/aggregate spectrum resources (white space) across frequency and time domain to improve SU throughput.

Chapter 3 presents two important aspects of CRN which are: the primary users ON/OFF behaviour and its effect on the secondary users' channel in a centralized scenario. However, this chapter is divided into two. The first part investigated and compared the commonly assumed ON/OFF behaviour with illustration as to the behaviour(s) that is relatively stable and best suit the SU since the SUs has to opportunistically use the primary users' channels. So far, the Markovian process showed a relatively stable behaviour compared to the exponential and geometric processes respectively. But, there exists interaction-effect among the primary and secondary users on the primary users' channel due to opportunistic spectrum access of the SUs. An analytical approach was developed to evaluate the performance of the opportunistic spectrum access strategy with different occupancy statistics.

Chapter 4 established the fact that though TV white space (spectrum holes) are scattered across the spectrum bands. Therefore, there is need for these scarce and wasting resources to be organized (assembled) and used optimally for SUs. The chapter investigated, proposed and evaluated three channel assembling strategies (QBS, RBS and IBS) in two case (single and multiclass users) traffics in CRN. Also, the varying nature of a wireless link was considered in the evaluation, depicting the fact that wireless link cannot be assumed as homogeneous all the time but rather heterogeneous which makes it more realistic and practical to real world scenario. The investigation of the proposed strategies showed that integrating queuing technique and AMC into channel assembling strategies in cognitive radio network is a robust approach. This accounts for why the QBS performed better than RBS and IBS respectively, especially in a very busy PU network.

Chapter 5 extended the work done in part one of chapter four by developing an analytical and simulation framework to evaluate the performance of the two proposed strategies (IBS and RBS) with a single (homogenous) class SUs. It gave an insight of the effect of the licenced user on secondary network in a dynamic wireless link in terms of their performance and the potentials of integrating AMC in channel assembling strategies. The developed strategies showed improved system performance in terms of secondary network capacity, blocking, forced termination and acceptance/admission probabilities respectively, depending on the system selected parameters.

Chapter 6 advanced the work carried out in chapter four and part of chapter 5. It proposed, developed and analysed a joint queuing based channel assembling strategies (CAS+Q) featuring AMC in varying wireless link. Unlike the previous chapters that focused on single class SU traffic without queues, this work expanded the investigation by considering a multi-class SU traffic flows with separate queuing regimes. Furthermore, it opened another window on the impact of integrating a queuing regime with AMC in channel assembling. The essence is to improve spectrum utilization, secondary network capacity and more especially, minimizing blocking and force termination of the SUs and possibly allows interrupted SU service to be queued and served later.

7.2 Recommendations

From our study and lesion learnt, we cannot claim that the RBS has a superior performance over the IBS scheme in all SU traffic scenarios at all time. Although, CAS+Q is an RBS scheme with a queuing regime. But, we can recommend a policy depending on the SU traffic behaviour. For instance, when there are abundant spectrum resources (TV white space), and only non-real time users wants to use the resources, any of the strategies (IBS, RBS, and CAS+Q) can be recommend. However, if the network comprises of real time SU traffic, the RBS or CAS+Q will be better. When the network model comprises of both type of SU traffic, and the PU is relatively predictable, then the CAS+Q will be an optimal policy. If the network model consists of real time, non-real time SU traffic, and the PU is relatively unpredictable CAS+Q will fit in.

7.3 Future Works

In chapter 4, 5 and 6, the concept of channel assembling strategies and its benefits to both present and next generation wireless communication system general was emphasized. Assembling to many channel-slots irrespective of the channel conditions, AMC technique and queuing regime notwithstanding, might affect PER and BER especially in a dynamic wireless link and this forms part of future investigation.

In chapter 6 particularly, a queuing regime was introduced so that, those SUs traffic that would have been blocked or forcibly terminated could be queued in a buffer and possibly served later. But, it was assumed that all arrivals are exponentially distributed including the feed backs arrival (λ_{sm}) of SU_b into Q_2. However, in reality, when these two arrivals (feedback arrival due to interruptions and new secondary users' arrivals) meet, they sum up and this might not be assumed as an exponential arrival. Future works will consider the effects of λ_{sm} and λ_{sb} on the overall system performance.

Channel assembling and fragmentation (CAF) featuring AMC (CAFA) can be jointly studied in a varying wireless link in CRN, as a means of further maximizing the scarce spectrum by splitting the channel into finer granular with higher rates/mode pair.

Lastly, two queuing regime can be integrated into CAFA (CAFA+Q) to further improve spectrum utilization and possible performance improvement for cognitive users. All these ideas are laying the foundation/road map for the actualization of next generation communication network.

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APPENDIX

Editors' Decision on Journals Article in This Thesis

11/11/2016 Gmail-[IJETI] Editor Decision

Gmail

EBENEZER ESENOGHO <ebenic4real@gmail.com>

[IJETI] Editor Decision
1 message
Editor in Chief <ijeti@nfu.edu.tw> 10 November 2016 at 13:40
Reply To:
"Prof. Wen Hsiang
Hsieh" <ijeti.taeti@gmail.com>
To: Mr EBENEZER ESENOGHO ebenic4real@gmail.com

The following message is being delivered on behalf of IJETI journal.

Dear Mr EBENEZER ESENOGHO:
After months of rigorous reviews and resubmissions, we have reached a decision regarding your final submission to International Journal of Engineering and Technology Innovation, "Two Channel Assembling Strategies in Cognitive Radio Networks: A Performance Analysis".
Our decision is to: **Accept**
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10/10/2016 Gmail-[IRECAP] Editor Decision

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EBENEZER ESENOGHO <ebenic4real@gmail.com>

[IRECAP] Editor Decision
2 messages
Editorial Staff <editorialstaff@praiseworthyprize.org> 7 October 2016 at 17:49
To: ebenic4real@gmail.com
EBENEZER ESENOGHO:
It is my great pleasure to inform you that your paper ID 9840 "Channel Assembling Strategy in Cognitive Radio Networks: A Queuing Based Approach" **has been accepted** and will be published on the International Journal on Communications Antenna and Propagation (IRECAP).
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