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by

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ABSTRACT

Cognitive radio (CR) is a promising technology available to that seeks the range and efficiency of spectrum dependent services. Its system maps unused spectrum, and arrange secondary user (SU) to operate within unoccupied license spectrum. The implementation of CR system guarantees that there are no interferences to primary user (PU) by prior observing and sensing the existing spectrum environment. Spectrum sensing is the main issue of CR system to prevent the harmful interference to PU as a license user. However, practically detection performance is often compromised with multipath fading, shadowing and uncertainty noises. In order to minimize the impact of these issues, cooperative spectrum sensing and access is an effective method to improve detection performance.

Partially Observable Markov Decision Process (POMDP) is a framework that assists users to make decision among variation choices. In CR system, POMDP is used as an aid for SU to sense and access licensed channel. This framework models the primary network activity as Markov discrete process, where idle and busy states are represented by number “0” and “1”.

This research work has investigated the performance of CR with limited sensing capability under POMDP. It proposes an optimization of the throughput performance through cross layer and ROC design, and also propose Decentralized Multiuser Cooperative Spectrum Sensing (DMCSS) model. Furthermore, using binomial distribution theory, it also derives probability of miss detection. To validate the proposed model, some comparisons are made against single user sensing, Centralized Multiuser Cooperative Spectrum Sensing (CMCSS) model, and full band random CSS model. Through dynamic and heuristic simulation, the proposed DMCSS model is shown to have a robust performance as compared to full band random CSS model. It outperforms CMCSS at a certain setting of probability of selected channel (p), collision threshold (ζ), and signal to noise ratio (SNR).

ABSTRAK

Kognitif radio (CR) merupakan salah satu teknologi yang paling menjanjikan dan disediakan untuk meningkatkan rangkaian dan kecekapan perkhidmatan spektrum. Sistemnya memetakan spektrum yang tidak digunakan, dan mengatur pengguna yang tidak berlesen (SU) untuk beroperasi dalam spektrum berlesen yang tersedia. Pelaksanaan sistem CR menjamin bahawa tidak ada gangguan kepada pengguna lain dengan sebelumnya memerhati dan penderiaan persekitaran spektrum yang sedia ada. Spektrum sensing adalah isu utama sistem CR untuk mengelakkan gangguan yang berbahaya terhadap lesen pengguna (PU). Walau bagaimanapun, boleh dikatakan prestasi pengesanan sering dikompromikan dengan *multipath fading, shadowing* dan rintangan-rintangan yang tidak pasti. Dalam usaha untuk mengurangkan kesan isu-isu ini, penderiaan spektrum koperasi dan akses adalah satu kaedah yang berkesan untuk meningkatkan prestasi pengesanan.

POMDP adalah satu rangka kerja yang membantu pengguna untuk membuat keputusan di kalangan pilihan variasi. Dalam sistem CR, POMDP digunakan sebagai bantuan kepada SU untuk memilih kanal untuk penderiaan dan akses. Rangka kerja ini memodelkan kanal berlesen sebagai proses Markov diskret yang mana kondisi *idle* dan *busy* diwakili oleh nombor "0" dan "1".

Kerja-kerja penyelidikan ini telah menyiasat prestasi CR dengan keupayaan terhad sensing dibawah rangka kerja POMDP melalui mengkaji penderiaan spektrum dan akses melalui saluran yang sempurna dan tidak sempurna, mengkaji dasar spektrum penderiaan optimum dan sub-optimum, mengoptimumkan prestasi pemprosesan melalui lapisan silang dan reka bentuk ROC, dan akhirnya mencadangkan model spektrum akses koperasi untuk sistem CR terpencar dan juga memperkenalkan teori taburan binomial untuk memperolehi *probability of miss-detection*. Untuk mengesahkan model yang dicadangkan, kami membuat beberapa perbandingan seperti dengan CMCSS model, sensing spektrum tunggal, dan band penuh rawak CSS

(*full band random CSS*). Melalui simulasi dinamik dan heuristik, ia telah mendapati bahawa model DMCSS yang dicadangkan mempunyai prestasi yang teguh berbanding dengan band penuh rawak CSS model dan melebihi performa CMCSS pada tetapan parameter tertentu seperti p, ζ, dan SNR.

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LIST OF ABBREVIATION

ADC	Analog to Digital Converter
AWGN	Additive White Gaussian Noise
C MAC	Cognitive MAC
CMCSS	Centralized Multiuser Cooperative Spectrum Sensing
CR	Cognitive Radio
CRN	Cognitive Radio Network
CRAHN	Cognitive Radio Ad Hoc Network
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
CCC	Common Control Channel
CSS	Cooperative Spectrum Sensing
CTS	Clear to Send
DSA	Dynamic Spectrum Access
DARPA XG	Defense Advanced Research Projects Agency NeXt Generation
DMCSS	Decentralized Multiuser Cooperative Spectrum Sensing
DOSS	Dynamic Open Spectrum Sharing
DCA MAC	Distributed Channel Assignment MAC
DySPAN	Dynamic Spectrum Access Networks
FRC	Federal Radio Commission
FCC	Federal Communication Commissions
FFT	Fast Fourier Transformation
HC MAC	Hardware Constraint MAC
ISM	Industrial, Scientific, and Medical
ITU	International Telecommunication Unit
MDP	Markov Decision Process
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
NP	Newman Pearson
OSA	Opportunistic Spectrum Access
OS MAC	Opportunistic MAC
OSI	Open System Interconnection
POMDP	Partially Observable Markov Decision Process
P_D	Probability of Detection
P_F	Probability of False alarm
P_M	Probability of Miss detection

PU	Primary User
PWLC	Piecewise Linier and Convex
QoS	Quality of Service
ROC	Receiver Operating Curve
RTS	Request to Send
RF	Radio Frequency
SDR	Software Define Radio
SU	Secondary User
SNR	Signal to Noise Ration
SRAC MAC	Single Radio Adaptive Channel MAC
SYN MAC	Synchronized MAC
UWB	Ultra Wideband
WiFi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WRAN	Wireless Regional Area Network

NOMENCLATURE

r_i	Reward function
r_{j,A_1,A_2}	number of transmitted bits in one slot when CR user take an action
$P_{i,j}$	Transition probability
A_1	Sensing action
A_2	Access action
B	Bandwidth
N	Number of channel
T	Number of slot
L_1	Number of sensed channel
L_2	Number of accessed channel
S	State of channel
P_r	Probability
a_*	Access action
V_t	Total reward function within T slot, bits/slot
W_t	Total reward function under sub optimal Greedy sensing strategy
H	Binary hypothesis
K	Acknowledgement
α	Probability of channel state from busy to idle
β	Probability of channel state remain unchanged (keep on idle state)
Θ	Observation
π	Belief vector
π'	Updated belief vector
θ	State of sensing outcome, 0 or 1
γ	Column vector
τ	Transformation of belief vector
ω	Belief vector under sub optimal Greedy sensing strategy
ε	Probability of false detection

δ	Probability of miss detection
ζ	Maximum collision allowable by PU (collision threshold)
λ_T	Signal detection threshold
Φ	Optimal access policy
Ω	Sufficient statistic for the optimal OSA protocol channels
a_*	Access action

CHAPTER 1

INTRODUCTION

1.1 Background

Wireless communication system is designed ultimately limited by spectrum allocation and transmission power [1]. The communication engineers and designers should consider these two resources in particular tradeoff among them under the constraint of implementation cost. For example, such communication systems are typically limited by battery power of mobile devices and the available of wireless frequency bands. Furthermore, current wireless sensor devices are very tiny and not rechargeable which severely limit their lifetime and transmission capacity as well [2]-[5].

In addition to the constraint of transmission power and capacity on mobile devices, wireless access spectrum is also limited due to the tremendous growth of wireless users and applications. This spectrum is accessed by a great number of wireless users and seen as essential resource. It grants mobile devices the right to legally communicate each other. Whenever new user emerges, FCC (Federal Communication Commission) should approve air interface rules of spectrum usage, so that the interference to other wireless users can be avoided.

Currently, wireless users and applications occupy most of the existing spectrum and the other hand, this spectrum resource is fixed. It certainly predicts that those spectrums will become scarce in the near future due to the increasing demand. Therefore finding the solution of this spectrum shortage must be a great challenge for the development of wireless communication system.

According to the study and measurement by FCC, the utilization of licensed spectrum located at range 15% - 85% [6]-[8]. This measurement stimulates to make a new regulation for a more efficient and adaptive spectrum allocation policy. As consequency, FCC revised its regulation from fix spectrum allocation into dynamic spectrum access which allow unlicensed users access those spectrum opportunistically.

Cognitive radio (CR) system is the enabling technology for opportunistic spectrum access. It is promising system to offer such opportunistically access capability without interferences to licensed users. It has a capability to fully aware its surrounding RF environtment and dynamically access the unoccupied spectrum by adaptively changing the operating parameter, e.q. operation frequency, power, modulation scheme, etc. Henceforward, the user who has a license to use the spectrum is defined as Primary User (PU) or licensed user, and the user who accesses unoccupied licensed spectrum opportunistically is known as Secondary User (SU), unlicensed user, or CR user.

1.2 Problem Statement

Cognitive radio must have a capability to sense spectrum opportunities, learn the spectrum usage in the transmission environment, and adjust the transmission parameter according to the learning results. Hence, the fidelity of sensing outcome is the main and critical issues in CR system. It must be taken to avoid conflicting with PU activity or among SU transmission.

Energy efficiency is a classical problem for wireless communication system and devices including CR system. Most of the existing works in CR assume that SU has a full band sensing capability. Moreover, SU monitor license band continuously even there is no packet to transmit over channel. In a fact, the cost (i.e. energy, complexity, hardware implementation) to achieve wideband spectrum sensing by single SU is quite high. In addition, continuous spectrum sensing over license band requires time consumption longer compared with partial sensing.

Furthermore, basic structure of cognitive MAC with limited sensing capability under POMDP is divided into 3 task; spectrum sensing, data transmission, and acknowledgment. There is tradeoff between spectrum sensing and data transmission where increasing sensing time can degrade the throughput performance. On the other hand, decreasing sensing time can improve the throughput performance, but unfortunately it will lower the fidelity of sensing outcome. Therefore, spectrum sensing must be performed as quickly as possible while optimizing the throughput performance. Subsequently, hidden and exposed terminal causes PU detection error that is potentially reducing spectrum sensing performance. The tradeoff between spectrum sensing and spectrum access (in term of throughput) is required to further study.

A lot of research and survey on spectrum sensing and collaborated user in CR networks was studied in [9]-[22]. However most of the previous studies were based on the assumption that SU has full band sensing capability. They focus on exploiting spatial spectrum opportunities that are static or slowly varying in time, such as the reuse of unused TV broadcast bands. In fact, the cost to achieve wide band spectrum sensing by a single SU is quite high. It should be realistic to assume that SU has capability to sense a limited bandwidth of spectrum during a certain amount of time. The limited sensing capability brings new challenges in the design of spectrum sensing and access strategy in CR system.

Cooperative spectrum sensing (CSS) was proposed as a solution for fading, shadowing, hidden and exposed terminal. However, most of the existing works on CSS focused on physical layer that explore spectrum sensing in term of probability of detection, probability of false detection and probability of miss detection. How the influence of spectrum sensing in physical layer to the throughput performance in MAC layer must be further investigated.

1.3 Motivation and Objective

Opportunistic spectrum access (OSA) system is one of the important resource allocation in wireless spectrum that is able to enhance the efficiency of spectrum utilization. In the near future, spectrum resource will become scarce due to the growth of wireless user and the increasing demand of spectrum access. However the actual spectrum measurement conducted by FCC shows that most of the existing spectrum is not occupied by PU at one time. Spectrum measurement result in the laboratory environment by Berkeley Wireless Research Center (BWRC) that is taken at mid day with 20 kHz resolution over a time span of 50 microseconds with 30 degree directional antenna [23] brings into relief that the measured existing spectrum is not used by license users at one time. The unused spectrum by PU is known as white space or spectrum holes.

The proposed enabling technology as a solution for this circumstance, CR is defined as an intelligent radio technology which has a capability to autonomously reconfigure the parameter by learning and adapting to its environment and exploit the unused spectrum to efficiently utilization by users. Simultaneously, management of dynamic spectrum based on CR and its classification was introduced in [24]-[26]. Cognitive radio system itself was proposed to support dynamic spectrum access (DSA) by learning the RF environment through spectrum sensing within short time period, and then automatically access those unoccupied license spectrum by prior adapting its parameter.

The DSA systems are one of the most promising technologies available to increase the range and efficiency of spectrum dependent services. DSA systems locate unused spectrum, and organize their users to operate within the spectrum they have identified. Its systems ensure that there is no interference to other users by scanning and sensing the spectrum environment, as the Defense Advanced Research Projects Agency NeXt Generation (DARPA XG) spectrum sharing field tests have established, or through pre-existing knowledge, such as the geo-location database proposed for unlicensed access to TV band white space, or a combination of both [27]. Shortly, DSA affords the benefits to spectrum allocation problems such as providing the increased density, better system management, and inherent in-channel and co-site interference resolution as well as it enables opportunistic access to the spectrum for uncoordinated sharing of spectrum on a non-interference basis. In addition, the other projects related to DSA and CR networks that have been developed are DIMSUMnet project [28], DRiVE/overdrive project [29], E2R and E3 [30]. These projects aim to resolve the current inefficient usage of spectrum band and make the radio has the ability to intelligently recognize the status of radio spectrum environment and adaptively change its transmission parameter such as transmission frequency and bandwidth, power efficiency, and modulation scheme, etc.

According to the hierarchical access model, licensed spectrum is opened to SU under the condition that it does not interfere to PUs beyond a certain probability of collision [31] [32]. Spectrum underlay and overlay are two strategies allowing the coexistence of primary and secondary users. Underlay refers to the approach where the transmission power of SUs is limited to be less than the noise floor of PUs, whereas overlay does not limit the transmit power of SUs but imposes restriction on when and where SUs can transmit [33]. The hierarchical access model is likely the most compatible with the current spectrum management policies and provides better spectrum efficiency in the licensed bands.

OSA itself is referred to as DSA, and often included as part of the larger concept of cognitive radios. It has emerged as a way to dramatically improve spectrum utilization. The basic idea is to allow SU to identify available spectrum and characterize the presence of PU. According to that information, the unlicensed devices identify communication opportunities (spectrum holes) in frequency, time, or even code, and transmit using those opportunities in a manner that limits the interference perceived by PUs.

Medium Access Control (MAC) is one sub-layer of wireless system which has a responsibility to arrange how users access the spectrum and start to transmit data. Conventional MAC protocol for wireless networks was proposed in [34]-[40]. However, these protocols differ to OSA MAC protocol in CR networks due to the following reasons, which the parameters of these MAC protocols are fixed and they are not designed for opportunistically accessing licensed spectrum as well as cannot adapt to the changes and heterogeneous network environments. The design of OSA MAC protocol should consider where SUs adaptively and dynamically seeking and exploiting opportunities in both licensed and unlicensed spectrum. SU has responsibilities to make real time decision when and where to sense and determine which spectrums are available, select the best available channel for better spectrum utilization, coordinate spectrum sharing among different unlicensed and licensed users, and vacate the channel when licensed users are detected.

MAC protocol for OSA has responsibilities to coordinate channel sensing and access to licensed bands and designed to accomplish quality of service (QoS) for data transmission. It was discussed in [41]-[43] and clearly classified into random, time slotted, and hybrid protocols as briefly described in Fig. 1.1.

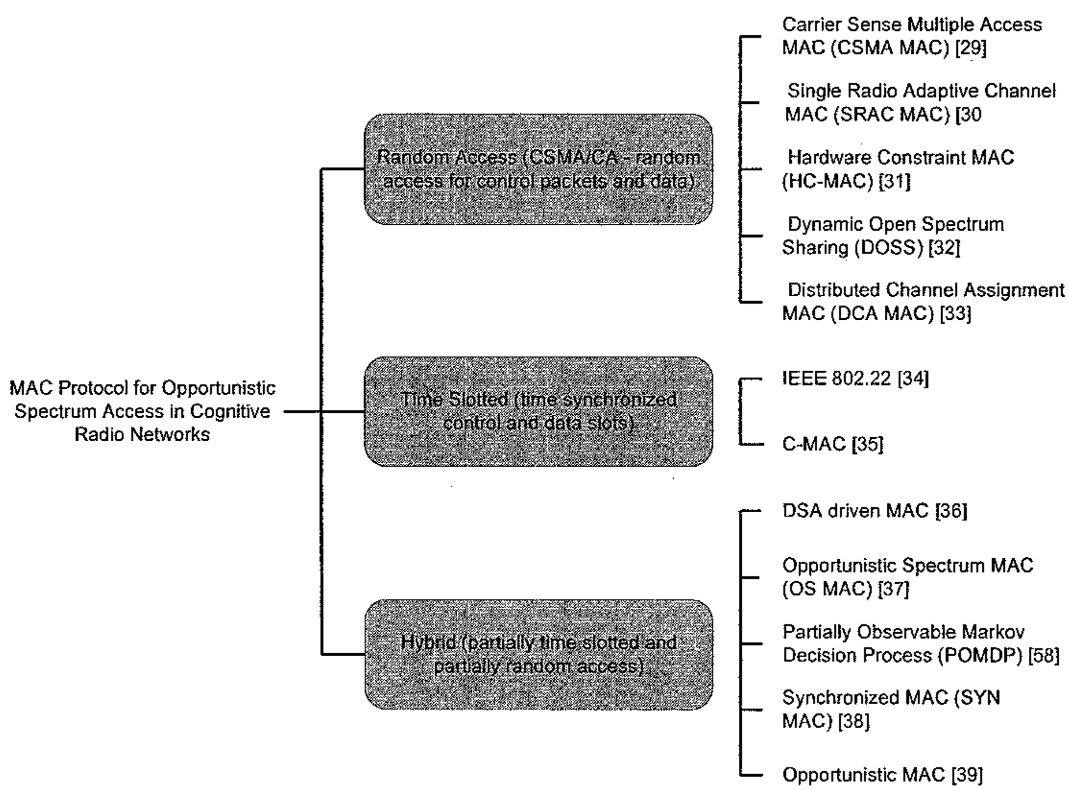

Figure 1.1 Brief review of MAC protocol for OSA

Random access protocol does not need time synchronization, and generally based on the Carrier Sense Multiple Accesses with Collision Avoidance (CSMA/CA) principle. In this protocol, SU users monitor the spectrum band and when there is no transmission from the other SUs, they are allowed to transmit after backoff duration. Time slotted protocol need network wide synchronization, where time is divided into control channel and data transmission slots. Furthermore, hybrid protocol exploits partially time slotted and partially random access. In this protocol, control signaling generally over synchronized time slot. However, the following data transmission may have random channel access schemes without time synchronization. The detail classification of MAC can be referred to [44]-[54].

According to the condition above and referring to the problem statement as described in previous section, the research objective is defined as follow:

1. To propose decentralized multiuser cooperative spectrum sensing and access model (DMCSS) with limited sensing capability under POMDP framework.

2. To derive probability of miss-detection using binomial distribution theory.

To accomplish those two objectives above, we use energy detector method to sense and detect PU activity as license spectrum holder. It is presented further by detail on chapter 3.

1.4 Scope of study

Dynamic spectrum access system is the promising technology available to increase the spectrum efficiency. It is predicted to replace current spectrum allocation that is statically utilized by license user. It locates unused spectrum and organize their users to operate within the spectrum they have identified. The committee of dynamic spectrum access networks (DySPAN) standard classified DSA system into three categories, dynamic exclusive use model, open sharing model, and hierarchical access model.

The scope of research work concentrate on spectrum underlay that is categorized into hierarchical access model of DSA. Especially, it focuses on cognitive radio that enables user to access with prior sensing to avoid interference to license user. Through spectrum access management, CR can increase the spectrum efficiency. The concept of energy detector was adopted to detect PU activity.

Spectrum sensing policy is further studied and investigated. The three of sensing policy was evaluated that are optimal, sub-optimal greedy and full band random sensing policies. Optimal and sub-optimal greedy sensing policies under POMDP avoid channels that have been sensed by other SU. Secondary user partially sense the existing channel and select those channels when SU has a packet to transmit while full band random sensing policy detect channel spectrum opportunity randomly even it has been sensed by other SU. The principle of random sensing policy is the more the number of SU, the more likely the number of sensed channel is large. When the number of SU is large enough, SU can sense all of the licensed channels.

Sub-optimal greedy sensing policy was proposed as a solution to reduce the complexity and energy inefficiency that happened in optimal sensing policy. Comparisons among these three sensing policies mentioned are made. Optimal and sub-optimal greedy can gain the throughput as a function of slot while random sensing policy cannot exploit the information from previous slots to gain the throughput.

Decentralized multiuser CSS (DMCSS) model is proposed to optimize the throughput performance. Secondary user with a packet to transmit partially selects, senses, and accesses channel independently. Secondary user receiver gives the reward (bits/slot) for successful packet transmission that improves performance slot by slot until transmission completion.

Sensing error (i.e. probability of miss detection) is included to evaluate the proposed model. Binomial distribution statistical theory was introduced to derive probability of miss detection. It is defined as discrete probability distribution for a sequence number of independence experiment with probability of successful selection p. Centralized multiuser CSS (CMCSS) is used as reference to validate the proposed model as well as single user sensing and full band random CSS model.

1.5 Thesis Organization

The rest of this thesis is organized as follow:

In chapter 2, detail of literature review related to the works accomplished is clearly presented. Brief history of radio spectrum, spectrum management including dynamic spectrum access, opportunistic spectrum access, and cognitive radio as a solution for spectrum scarcity are presented. The detail of physical layer, MAC layer, and cross layer design of cognitive radio networks are presented as well. Moreover, general POMDP framework including the main parameters, such as belief state, value function, reward is further discussed

In chapter 3, we clearly present our research methodology. POMDP model is used to further investigation in CR system. This chapter discusses implementation of POMDP for CR system, its main parameters, formulations, and decision theoritic approach. This chapter also presents sub optimal greedy sensing policy that is used as an alternative solution when number of channel increases. Moreover, our proposed DMCSS model along with mathematic formulation is discussed as well

In chapter 4, simulation results with discussion are presented. It is divided into three sections, optimal and sub optimal greedy sensing policies under perfect and imperfect channel, cross layer design principles for CR system, and DMCSS model to optimize throughput performance. Performance comparison is made for optimal sensing against sub optimal greedy sensing policies as well as perfect against imperfect channel sensing. Moreover, simulation results comparing spectrum sensing and throughput performance is presented. Tradeoff between sensing capability and throughput performance and how to achieve a good fidelity of sensing outcome when maintaining the throughput performance is further discussed in this chapter. End of this chapter is closed by results and discussion for our proposed DMCSS model

Finally, in chapter 5, we draw the main conclusions and the outline of the recommendation for future research directions.

CHAPTER 2

LITERATURE REVIEW

This research work is concerned with CR as part of DSA system. The performance is further investigated by POMDP as an aid for SU to select channel for sensing and access. This chapter discusses a review of literature research that is compiled to provide knowledge and information, to clarify issues that should be considered, and to support basic theory of this research work.

This chapter is divided into 7 sections. First section gives the description of DSA system. It begins with history of radio spectrum, spectrum management, opportunistic spectrum access, and CR system. The following sections discuss about the concept of CR system, physical layer, MAC layer, and basic concept of POMDP as a decision theoretic approach for CR system and aid in decision-making for spectrum sensing and access. Finally, related works that discusses the previous series of work about protocol for spectrum sensing and access, spectrum sensing and access under POMDP, and CSS model. Finally, this chapter is closed by brief summary of the whole section.

2.1 Dynamic Spectrum Access

The sofware defined radio (SDR) now has performed the beneficial task to help wireless users overcome the wireless communication network problems and spectrum congestion due to the demands and growth of wireless users. Some radio can use the assigned spectrum with limited ways and the least noise and interference on that channel and time slot. Due to spectrum scarcity, the future technology should overcome the static spectrum allocation problem by considering the following points:

- Spectrum management and optimization.

- Interface with other wireless networks, including the management and optimization of networks resources.
- Interface with the human, leading to ease the human life activities.

Cognitive radio is one technology to overcome spectrum scarcity by optimizing the spectrum utilization, can be interfaced with other wireless network, sharing spectrum usage, and make the life of human easier. Cognitive radio technology is considered as an application of SDR platform. The following sub section will be described the brief history of radio spectrum, what spectrum management, dynamic spectrum access, protocols for spectrum access, and other things related to cognitive radio system.

2.1.1 History of Radio Spectrum

In December 1901, Guglielmo Marconi proved that wireless wave was not influenced by curvature of the earth. He said that long distance wireless transmission can be performed by using sufficient transmission power and large enough antenna [55]. Thus, he is currently known as the inventor of radio [56][57].

In the following years, many researchers and engineers followed up Marconi's experiment [58]. They also considered the transmission collision among adjacent radio. To avoid these collisions, modulation technology has been developed to create different transmitter which is operated in the different frequency band. In 1914, mathematical model for amplitude modulation (AM) was firstly proposed by C.R. Englund [59], then tested and implemented by the US Navy in year 1915. At the same year, J.R. Carson found single sideband modulation (SSB) [60], and published the famous Carson's Rule [61] in 1922 related to frequency modulation (FM).

The concept of license spectrum was not introduced yet until early 1900. However, due to the issues regarding collision among radio stations, it is necessary to form an agency, which has a responsibility to manage spectrum access. The radio act of 1912 [62] was the first federal law of US to realize the concept of license radio. Its rule is not allowing the unauthorized usage of frequency bands to access special commercial and military application bands. In the following years, many radio technologies were found, which helped the development of radio communications. It can increase the bandwidth efficiency and reduce the cost of radio equipment.

After World War II, the military radio equipment flew into commercial application. During the early 1950s, the transistor invention was achieved. These transistor can be used to generate more stable signals which more popular and implemented in most of the communication devices at that time.

In 1927, the United State (US) congress passed the Radio Act of 1927 [63] and created the federal radio commission (FRC) [64], which has a function to regulate all radio communication in the US. Then, after seven years, the name of Radio Act of 1927 was replaced by Radio Act of 1934 [65], and FRC was replaced by FCC (Federal Communication Commission's) to handle communication regulation including the entire wireless license spectrum, radio and television broadcasting, and some wire-line communication. The FCC regulation uses 3 ways to define a license frequency spectrum as follows:

- *Command and control.* This method is based on request. The spectrum can be allocated by releasing a license when the agreement is approved. However, this method is inefficient when number of license application increases.
- *Auction.* This method is used when many users will assign the same frequency band. In such case, FCC resolves by placing the main priority for the potential users to allocate the frequency bands.
- *Lottery.* In this method, FCC decided which user could allocate the license spectrum by lottery to achieve a fairer licensing. In auction method, there could be some users who buy the license and re-sell it with the higher price to have a profit. Thus, lottery method is expected to be the fairer method for license spectrum allocation.

The three spectrums licensing above is implemented concerning of fix license spectrum, since when license has been issues, the other users cannot use it. Furthermore, FCC also designed some special frequency bands for unlicensed spectrum access, such as ISM (Industrial, Scientific, and Medical) band, where unlicensed users can access and transmit over the license band under the condition that its transmission power is low or below the noise floor. Ultra wideband (UWB) technology is one wireless system that adopts this concept where user operates on underlay system. Henceforward, the spectrum management of dynamic spectrum access will be briefly presented in the following section.

2.1.2 Spectrum Management

The unlicensed bands, for examples 2.4 GHz and 5 GHz are used for wireless computer and networking. These bands are popularly known as the industrial, scientific, and medical (ISM) band. Microwave oven is also operated in the 2.4 GHz band. Wireless fidelity (WiFi) or worldwide interoperability for microwave access (WiMAX) and bluetooth are designed to operate in this band. It is possible to coexist with variety of interference within this band. So, it is impractical to license 2.4 GHz band for a particular purpose.

Although the mentioned application and technology using the same unlicensed band, they are regulated to what frequencies used and how much radiated power is allowed. Subsequently, they must accept any existing interferences and transmit through the band without interference to other users. However, this condition is too critical problem when the combined noises from many transmitters add together cumulatively and increase the noise floor at the receiver side. Consequently, it will reduce the quality of signal and decrease the system performance and quality of service (QoS).

Management of spectrum is the rule to organize how and by whom the existing spectrum is used. Its objective is to maximize the spectrum utilization by allowing many users as efficient as possible as well as to prevent interference among users of adjacent frequencies or from neighboring geographic areas, particularly for reasons of defense and security. Shortly, the interference of each users remains manageable [66].

The existing radio spectrum is divided into frequency bands which specify a particular type of services and applications. This allocation of frequency bands is regulated by international body. For example, International Telecommunication Unit (ITU) as a specialised agency of the United Nations (UN), regulate the spectrum allocation from 9 kHz to over 275 GHz. This ITU's regulation is used by national body of different countries to manage their spectrum allocation, e.q. for bussiness users, public safety users and cellular users. Fig. 2.1 show those frequency spectrum allocations. It is divided into different sevices and application.

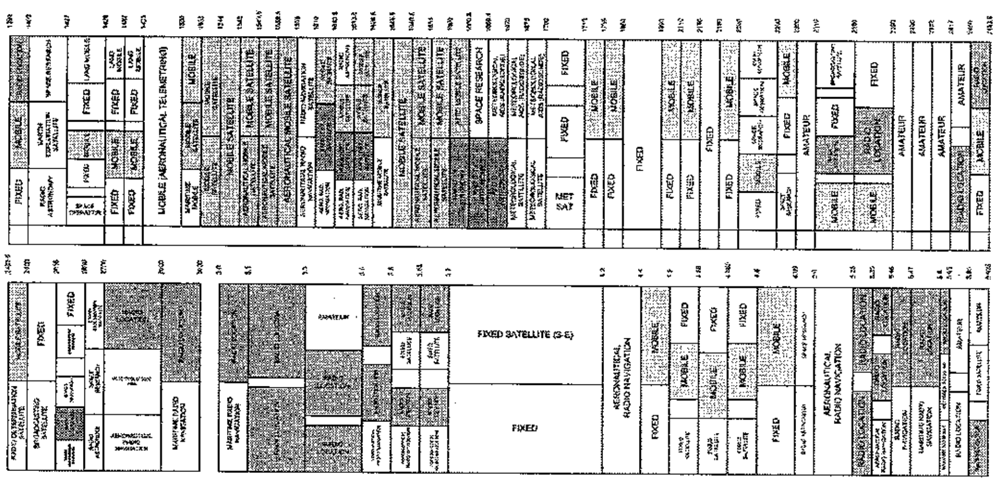

Figure 2.1 Frequency spectrum allocation [6]

However due to the tremendous growth of wireless user number and the demand of wireless spectrum significantly in the near future, the existing spectrum will become scarce. Subsequently, the fix spectrum regulation cannot solve such problems. Hence, it is necessary to find a new frequency spectrum regulation and management in order to make these one more effectively and efficiently used.

According to the real measurement conducted by BRWC as previously presented, verify that not all existing spectrum utilized by licensed users at one time. For such reasons, many researchers and engineerers directed to dynamic spectrum than static spectrum, which allows unlicensed users to access the licensed bands.

2.1.3 Dynamic Spectrum Access

In order to address the critical problem of spectrum scarcity, FCC has approved unlicensed users to used licensed bands. Consequently, dynamic spectrum access

(DSA) was proposed as a solution to increase spectrum efficiency through real time adjustment of radio resources, such as sensing the available local spectrum, observing, and establish local wireless connection among CR users and networks. This DSA systems are one of the promising technologies available to improve the range of spectrum efficiency dependent services. It locates unused spectrum and organize their users to operate within the spectrum they have identified.

The DSA systems confirm that there is no interferences to other users by prior scanning and sensing the spectrum environment, as the Defense Advanced Research Projects Agency NeXt Generation (DARPA XG) spectrum sharing field tests have established, or through pre-existing knowledge, such as the geolocation database proposed for unlicensed access to TV band white space, or a combination of both. Shortly, DSA affords the benefits to spectrum allocation problems such as providing the increased density, better system management, and inherent in-channel and co-site interference resolution as well as it enables opportunistic access to the spectrum for uncoordinated sharing of spectrum on a non-interference basis.

The committe of dynamic spectrum access networks (DySPAN) standard as presented in [67], classified DSA system into three categories as described in Fig. 2.2. They are dynamic exclusive use model, open sharing model, and hierarchical access model. The following sub section briefly present those three models of DSA

2.1.3.1 Dynamic Exclusive Use Model

Dynamic exclusive use model is dedicated to service of exclusive use, which has objectives to spectrum efficiency use and flexibility. It has two variants was introduced, spectrum property rights [68][69] and dynamic spectrum allocation [70]. The spectrum property right is long term exclusive use which manage the spectrum by frequency, space, and type of service dimensions and guarantees for exclusive ownership during a long period of times. Furthermore, dynamic spectrum allocation has a purpose to improve spectrum efficiency through dynamic spectrum assignment. It can be reached by exploting the spatial and traffic statistics of different services.

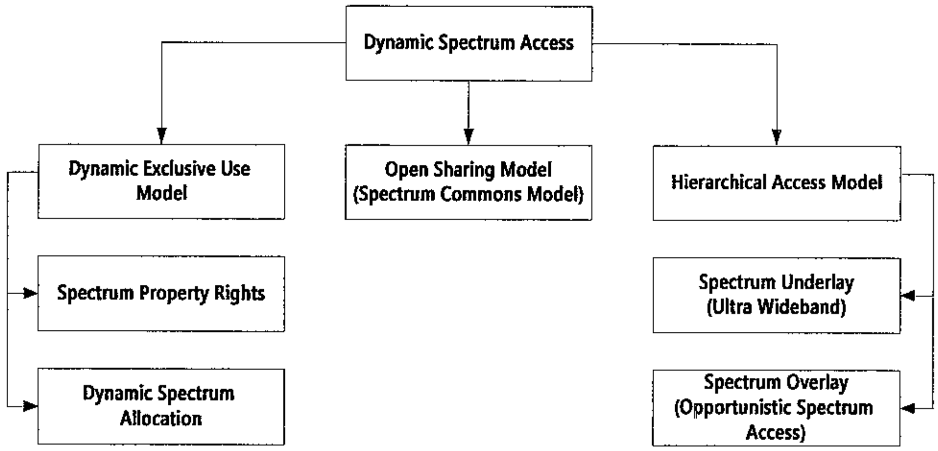

Figure 2.2 Taxonomy of DSA [26]

2.1.3.2 Open Sharing Model

The second category of DSA system is open sharing model, known as spectrum common model. It has 3 variants, uncontrolled, cooperative and managed, and private commons. In *uncontrolled model*, there is no entity who has an exclusive license to the spectrum band, which means that wireless user can access the spectrum band under the constraint of interference to other users (open spectrum access), such as the current ISM band (2.4 GHz) which bluetooth, WiMAX or WiFi, and microwave oven are assigned to this unlicensed band. The interferences is possibly occurrs by this model which comes from the communication and transmission among each users. Two kind of interference comes from the densely deployment of users, uncontrolled and controlled interferences. Uncontrolled interference come from users with the same frequency band but they do not participate in the MAC protocol, for example bluetooth device and microwave oven which are operated in 2.4 GHz bands interfere 802.11b or 802.11g wireless standards. Then, in controlled interference, the interferences come from user communication in one link. The interference depends on the network topology, congestion traffic, number of devices, etc.

The *managed model* or managed common is implemented to avoid much interference caused by many users exploit the respective spectrum band by limited to spectrum access. The existing resource should be controlled jointly by group and characterized by the restriction on who utilize the resources, then when and how it is used.

Furthermore, the concept of *private common* is aimed to allow multiple user to access and gradually utilize the existing license spectrum under the discretion of license holder. There are two ways this private commons can be implemented by *license holder offers private commons service* and *license holder offer spectrum access* [71].

2.1.3.3 Hierarchical Access Model

Hierarchical access model-based DSA implement licensed and unlicensed users. In this case, the holders of licenses or main users to those spectrums are known as primary users (PUs), which has an authority to access legal spectrum. There are two cases in this model, overlay and underlay cases, which is described on Fig. 2.3.

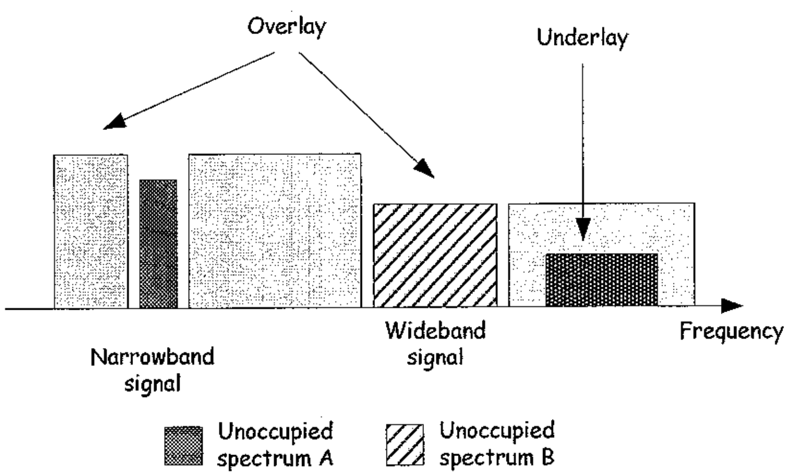

Figure 2.3 Overlay and underlay dynamic spectrum access [73]

The underlay case represents a conservative approach where secondary user transmit with low power and without interference to PU. In this case, SU device transmission is limited below the noise floor. Ultra wideband (UWB) is one of such application which has been implemented in underlay spectrum. The transmission of UWB spread over a wide spectrum band using low power, so it can coexist with current radio services with minimum or zero interference.

In overlay case, SU as unlicensed users can access legal spectrum when they are unoccupied by PU. However, user should have cognitive capability to detect white space and primary transmission. In order not to interfere primary transmission, SU perform the following step before access a licensed spectrum channels:

- *Spectrum sensing.* Secondary user continously senses the available spectrum and detect PU transmission. When unoccupied licensed spectrum is available and detected, SU immediately access and starting transmission.
- *Coordination.* SU competes each other to access the available spectrum, so it must coordinate their transmission.
- *Spectrum release.* SU must sense and seeking other vacant band during transmission. When PU return and will access their license band, then SU must vacate the band and continue their transmission on another unoccupied spectrum.

2.1.4 Opportunistic Spectrum Access

Opportunistic spectrum access (OSA) is referred to as DSA. It is part of the hierarchical DSA paradigm and categorized as spectrum overlay. It has emerged as a way to dramatically improve spectrum utilization. The basic concept is to allow SU to identify available spectrum and characterize the presence of PU. According to that information, the unlicensed devices identify communication opportunities (spectrum holes or white space) in frequency, time, or even code, and transmit using those opportunities in a manner that limits the interference perceived by PUs.

The requirement of OSA system is SU efficiently utilized unoccupied spectrum holes while avoiding harmful interference with PU. The spectrum model of primary networks vary over time, thus SU have dynamic spectrum holes and should intelligently adapts its channel. In OSA system, primary networks can be seen as idle and busy states. Idle states indicate channel is available and not in used by PU, while in busy states, SU cannot access them due to channel is underutilized by PU.

Spectrum opportunity is an opportunity of the existing license spectrum that can be accessed by two or more SUs without interference to PU communication. The interference should be below the maximum power level allowable by PU and may not exceed the interference level threshold.

The basic elements of OSA can be defined as follows:

- *Spectrum opportunity identification,* which tracking and scanning primary networks states dynamically. It can be performed by using the three primary signal detection methods, such as energy detector, cyclostationary feature detector, and matched filter. The selection of detector should be made to obtain the optimal sensing outcome. Matched filter detector can maximize signal to noise ratio (SNR), however it requires the prior knowledge of signal, such as modulation type, pulse shaping, packet format, etc. Energy detector performs suboptimal detection and simple implementation. It does not require the prior knowledge of signal. While the cyclostationary feature detector is better than energy detector, however it also requires the prior knowledge of primary signal

- *Spectrum opportunity exploitation.* Due to sensing for spectrum occupancy states is not free of error, therefore intelligent spectrum access strategies should be considered carefully. In other word, an optimal access strategy of the operating characteristics of spectrum detector such as probability of detection, probability of false alarm, and probability of miss detection must be taken into account.

- *Regulatory policy.* It establishes rules of cooperation and joint utilization between primary and secondary users. Estimation of power spectral, location, type of traffic, delay constraints, and other observable of the environment are specific parameter that must be considered in policy compliance.

2.1.5 Cognitive Radio

The term of cognitive radio was introduced by J.Mitola in 1998, and published later on by G.Q.Maguire in 1999 [72]. Cognitive radio (CR) is a form of wireless communication in which the device has a capability to intelligently detect which communication channel in use by PU and which are not, vacate the occupied channels and shift to other vacant bands when PU will access. The cognitive radio technology can provide reliable communication whenever and wherever we need as well as improve radio spectrum utilization. In its operation, CR observes and scans intelligently radio frequency environment for unoccupied license spectrum, and select the best available spectrum to be accessed and vacate them when PU return.

Cognitive radio itself is built on software-defined radio (SDR). This SDR is a wireless communication system, which has a capability to alter the communication parameters adaptively such as modulation, transmission power, etc. by software. Therefore, CR device should have three basic components as an adaptive communication; observe, decide and act as simply illustrated in Fig. 2.4.

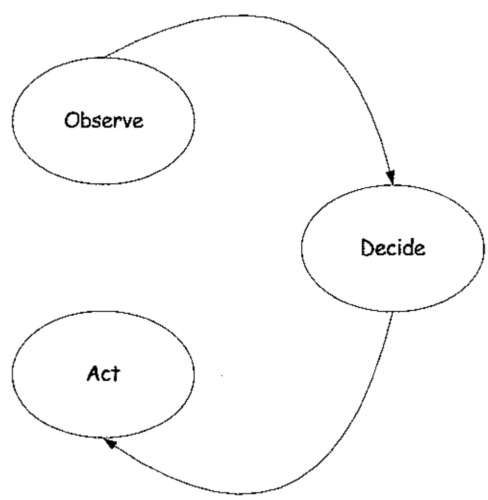

Figure 2.4 Basic components for CR communication [72]

Observe task has a function to sense and understand radio environment in which it operates and should be aware of the context in which it is operating to avoid interference to primary networks communication. CR devices have to *decide* by processing the signals it receives and make autonomous decisions on how to configure it to establish a communication. CR attempt to match action to requirements while at the same time should be aware to primary transmission or any constraints or conflicts that may exist. It should have the ability to learn from its actions and feed into any future actions. The detail illustration of cognition cycle of CR system is described in Fig. 2.5.

CR system as dynamic spectrum management has the following functions:

- *Spectrum sensing.* CR is designed to be aware its RF environment and must be sensitive to its surrounding. Spectrum sensing in CR has capability to explore the unoccupied license spectrum dynamically and adaptively. CR users should observe and monitor spectrum band activities before accessing the available channel spectrum (out of band sensing) or even when they are accessing channels and perform data transmission (in band sensing). It is performed to avoid the interference to PU. There are three methods to detect PU signal by energy detection, cyclostationary detection, and matched filter detection. These mentioned methods will be presented on detail in the following section.

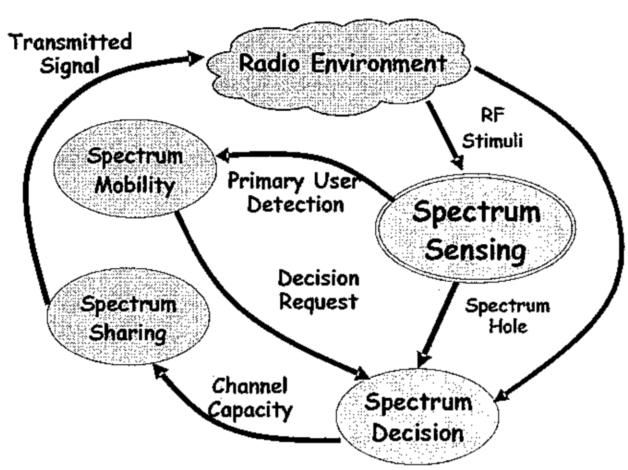

Figure 2.5 Cognition cycle by J.Mitola and Maguire [72]

- *Spectrum decision.* When the available spectrum is detected, CR users access it soon according to their QoS requirement (the best utilization). In spectrum decision, each spectrum band is characterized by both local sensing information and statistical primary network activity, and then based on this characterization the best available spectrum can be selected for transmission of CR user. The characterization must include radio environment, such as interference, path loss, wireless link errors, and link layer delay, as well as PU activity. Then, after spectrum is characterized, CR user select the available spectrum to be accessed according to the QoS requirements by reconfiguring the transmission parameters, such as power, type of modulation, etc.

- *Spectrum sharing.* The available spectrum is possibly to be accessed by multiple CR users. Therefore transmission coordination by spectrum sharing allocation should be performed among CR users to prevent collision with PU. Sharing among CR users will be presented clearly in the following MAC layer for opportunistic spectrum access section.

- *Spectrum mobility.* When PU is detected and return to use the spectrum, CR user must vacate the spectrum band immediately and seeking other vacant band to continue their transmission. Thus, it will cause handoff in CR networks, which occurred when PU activity is detected, CR communication is disconnected due to the mobility of users, and current accessed spectrum is out of QoS requirements. Therefore, spectrum handoff and connection management must be considered in CR system design.

2.2 Cognitive Radio Network

Currently, major spectrum for wireless user has been allocated and licensed users densely populate the existing spectrum. However, according to the real measurement conducted by FCC and BWRC, the spectrum utilization is around 15%-85% at one time. So, the practitioners and engineers were suggested the wireless spectrum to be utilized opportunistically (on demand), or in other word other users (illegal user or unlicensed user) can dynamically access the spectrum when it is unoccupied by licensed users. The term of listen before talk is adopted in cognitive radio system. The cognitive radio user has a capability to sense and observe the RF environment to convince available spectrum before they access and transmit data through channels. It must reconfigure the transmission parameters, such as power, modulation, etc to avoid interference to PU transmission.

Cognitive radio system is a new wireless technology paradigm where both user and networks changes transmission parameter to access channel and transmit amount of data without interference to licensed user communication. This parameter adaptation depends on some factors such as radio frequency spectrum, user behavior, and network states. Cognitive radio networks must have a capability to manage dynamically spectrum access in order to achieve a good quality of service (QoS) requirement through spectrum management. It also has capabilities to detect their RF environment while communication is being performed and maintaining seamless communication requirement during the transition to better spectrum through spectrum sensing and mobility. Then, CR network (CRN) can provide the spectrum scheduling method among coexisting users through spectrum sharing. Fig. 2.6 shows a simple of cognition cycle in cognitive radio networks.

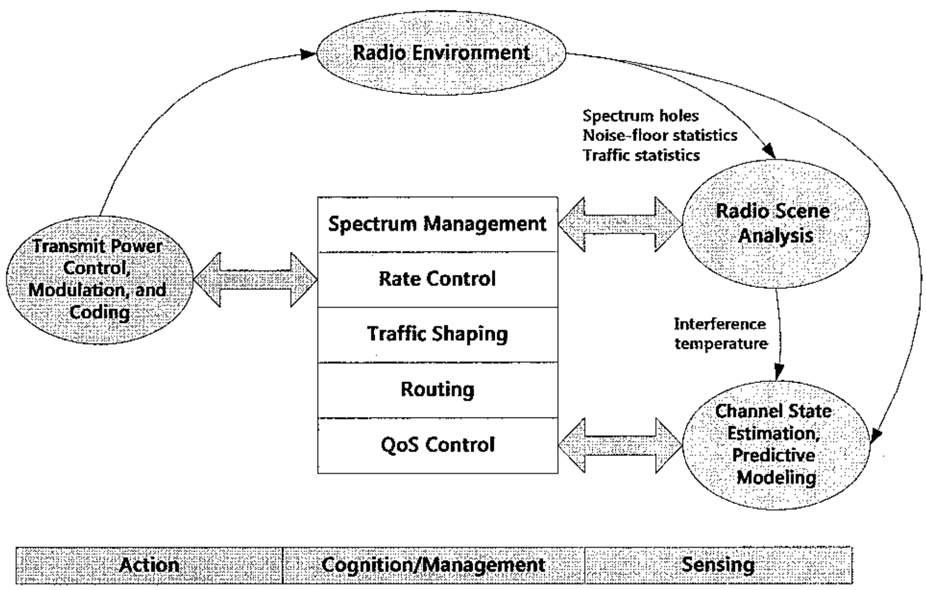

Figure 2.6 Basic concept of cognition cycle [73]

CRNs consist of set of software defined radio (SDR) devices that coordinate multiple information sources to dynamically adapt their transmission power, channel access method, and networking protocols to achieve as required for coexisting with PU and achieving a good performances. Some features of CRNs must include:

- *Sensing radio frequency environment*, which spectrum is available and in used by PU. These sensing results can be used to determine radio setting.

- *Policy and configuration database*, which can be used to determine which spectrum can be accessed and how user can access the available spectrums.

- *Self-configuration*. Radio may be assembled by any modules, such as frequency front end module, a digital signal processor and a control processor. Each module has a capability to self-reconfiguration automatically for communication and transmission.

- *Adaptive algorithm.* During the operation, cognitive radio user senses radio frequency environment, follows the regulation and policy with any constraints, and negotiate with peers to obtain the best utilization and performance.
- *Distributed collaboration.* Cognitive radio user has a possibility to exchange their local sensing and observation each other. Cognitive radio user inform to the neighbors and other users within its networks which spectrum is available.
- *Security.* Cognitive radio network requires authenticating, authorizing, and protecting information from users.

According to the network architecture, CRN can be classified into infrastructure based CRN (centralized) and CR ad hoc networks (CRAHNs, decentralized) [73]. The detail information of these two networks architecture will be presented in the following sub-section.

2.2.1 Infrastructure based Cognitive Radio

Infrastructure based CRNs or centralized network has a central coordinator, such as base station in cellular networks or access point in wireless LAN, while CRAHN or decentralized network does not have infrastructure backbone. Thus, CR user communicates with other users via ad hoc connection.

In infrastructure based CRN, sensing and observation are performed by each CR user and forward the results to the central coordinator (CR base station). Then, based on the sensing results, CR base station fix on which spectrum is available for final decision. According to this decision, CR user reconfigures its transmission parameters (power, modulation, etc) before accessing channel spectrum.

The structure of infrastructure based CR network is shown in Fig. 2.7 and it can be classified into primary network and CR network. The primary networks has the right for license spectrum band (i.e. cellular, TV broadcast networks, etc), while CR network can operate when the license band is not in use. The two elements of primary networks as follows:

- *Primary user*. This is the user who has a license to operate in license bands. Their activity is controlled by primary base station and unlicensed users are not allowed to interfere even they are coexisted by CR users.
- *Primary base station*. This is the network infrastructure that has a license spectrum. It behaves like base station to control communication among license users.

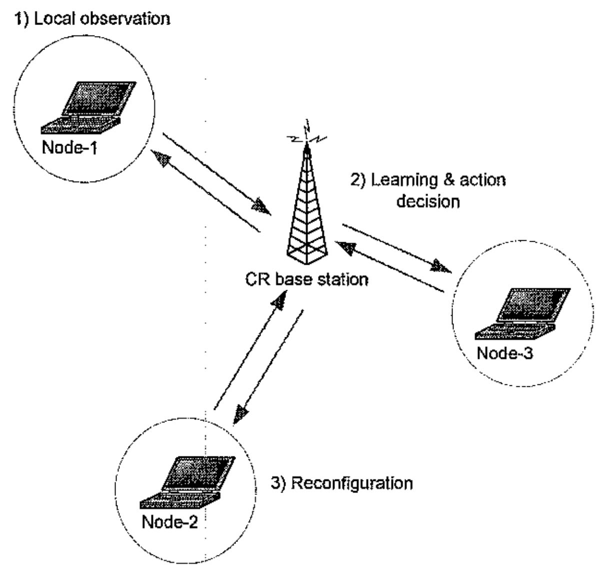

Figure 2.7 Infrastructure based CRNs architecture [43]

On the other hand, CR network is divided into 3 elements as follows:

- *CR user (SU or unlicensed user)*. The user who has a capability to intelligently sense unoccupied license spectrum and access it when it is available. In infrastructure based CRNs, local sensing of each CR user forward to the base station, then base station will decide which channel spectrum can be accessed by CR user.
- *CR base station (central coordinator)*. It provides single hop connection and has responsibilities to control channel access of each CR user within its transmission range and synchronize the sensing operation, which is performed by CR user.

- *Spectrum broker.* As known as scheduling server plays an important role to coordinate spectrum sharing. It also manage the use of spectrum resources among different networks based on sensing outcome of each CR networks

2.2.2 Cognitive Radio Ad Hoc Network

In CRAHN or decentralized network, CR user has a capability to decide which channel can be sensed and accessed independently. User reconfigures its transmission parameters before accessing the license channel. Cooperation among CR user is essential to exchange their local observation to know the wider network states. Model of decentralized network is described in Fig. 2.8.

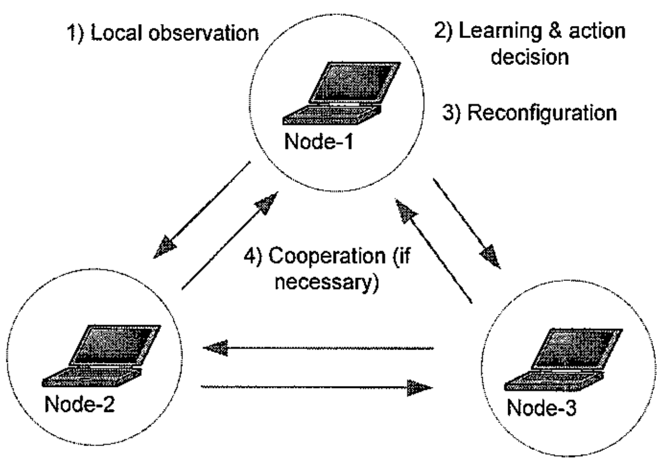

Figure 2.8 Cognitive radio ad hoc network (CRAHN) [43]

The two elements of CRAHN architecture are primary network and CR network as shown in Fig. 2.9. The primary network has a license to spectrum band utilization where PU can independently access a license spectrum, while CR network does not have the right to use the license spectrum. However, SU can access license channel when it is unoccupied by PU through prior sensing. Secondary user is able to communicate with each other in multi hop manner on both license and unlicensed bands.

As a dynamic spectrum access system, CRAHNs is required to adapt its environment. The same as infrastructure-based CRN, CRAHN must have some features of spectrum management, such as spectrum sensing, spectrum sharing, spectrum decision, and spectrum mobility. Spectrum sensing in CRAHNs has some functions as described in Fig. 2.10 sensing control enables SUs to adaptively sensing the dynamic radio environment. It coordinates sensing task of each SU in a distributed manner (without infrastructure), how long and frequently SU should sense the wide spectrum and how quickly they can find the unoccupied license spectrum.

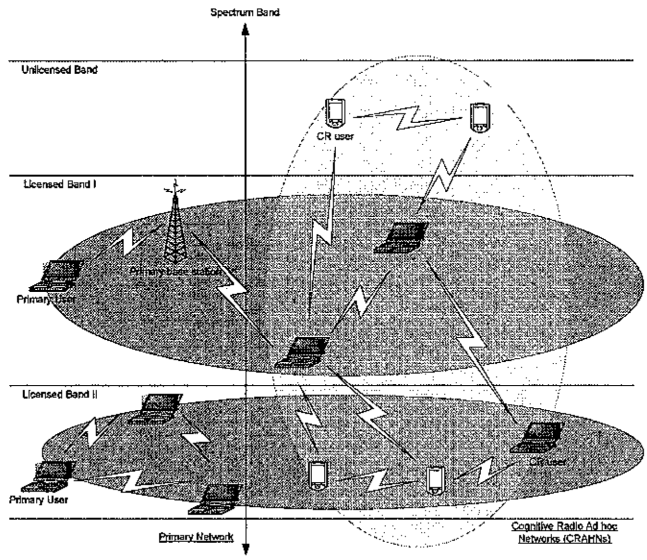

Figure 2.9 CRAHNs architecture [43]

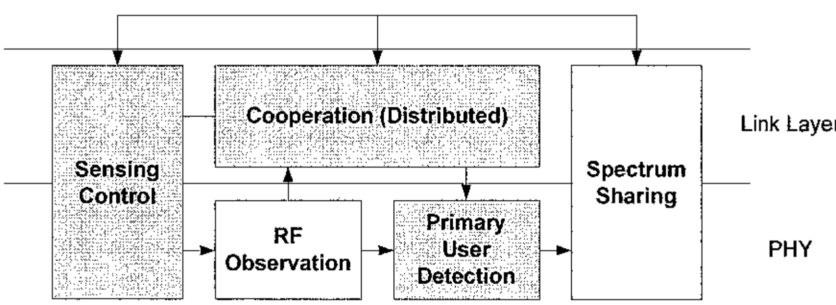

Figure 2.10 Spectrum sensing structure of CRAHNs [43]

2.3 Physical Layer of Cognitive Radio System

The successful operation of CR system is its capability to be aware of their surroundings through spectrum sensing. The main objective of spectrum sensing is to provide more spectrum access opportunities to SU under interference constraints to primary networks. CR devices should be able to opportunistically detect to the portion of spectrums continuously and use them for communication, then vacate those licensed bands when PUs is detected. Thus, accurate and fast sensing is the key of CR technology, which means that CR device must sense the spectrum opportunities as quickly as possible while maintaining the accuracy of sensing outcomes. These requirements are supported by physical layer of CR networks architecture and intelligent algorithms that are implemented in software.

2.3.1 Spectrum Sensing Algorithm

As previously mentioned, spectrum sensing is the main task of CR system to obtain the awareness of spectrum usage and primary networks activity in a geographical area. This awareness is obtained by using geo-location and database, beacon, and local spectrum sensing performed by CR transceiver [74]-[76].

CR networks as a visitor in license bands should have a capability to access unoccupied license spectrum without or with minimum interference to PU networks and vacate those frequency bands when PU activity is detected. The successful of this operation depends on the SU capability to be aware of its RF environment, which is accomplished through PU detection or spectrum sensing solution.

A number of different methods are proposed to detect primary signal transmission. In some approaches, characteristic and type of the signal is identified to obtain more accurate detection. For further detail, the mentioned signal detectors, which commonly used in CR system, will be presented in the following section.

2.3.1.1 Energy Detector

Energy detector is known as periodogram or radiometry. It is the most common method of spectrum sensing due to its low computational and implementation complexity [77]-[85] and more generic compared to others since it is no need of any knowledge on PU signal. Primary user signal is detected by comparing the energy detector output with the threshold which depends on the noise floor [86]. A simple block diagram of energy detector is shown in Fig. 2.11. The weaknesses of this energy detector are selection of the threshold to detect PU signal, inability to differentiate interference from main signals and noise, and poor performance under low signal to noise ratio (SNR) detection [87].

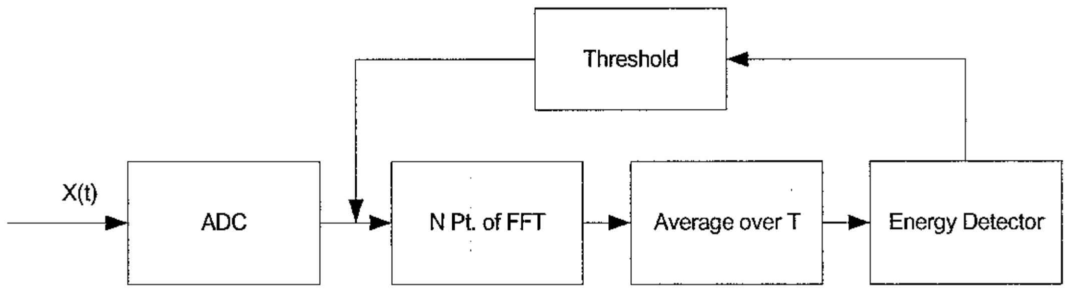

Figure 2.11 Block diagram of energy detector [86]

Let us assume that the received signal has the following simple form:

$$y(n) = s(n) + w(n) \quad (2.1)$$

Where $s(n)$ denotes signal to be detected and $w(n)$ is additive white Gaussian noise (AWGN). If the value of $s(n) = 0$, it means that there is no transmission from PUs. Then, the decision metric of energy detector can be written as

$$M = \sum_{n=0}^{N} |y(n)|^2 \quad (2.2)$$

where N is the size of observation vector. The final decision of channel occupancy state can be derived by comparing the decision metric M to the threshold value λ_E. Then, two hypothesis regarding to the primary signal detection can be written as follows:

$$H_0: y(n) = w(n) \quad (2.3)$$

$$H_1: y(n) = s(n) + w(n) \quad (2.4)$$

H_0 denotes that primary signal is not detected and merely include noise component $w(n)$ while primary signal can be detected in hypothesis H_1. Detection performance is defined by probability of detection (P_D) and probability of false alarm (P_F). The value of P_D is required to be as high as possible while P_F should keep as low as possible to prevent underutilization of transmission opportunities. Then, these two detection performances can be calculated by using the following formulas:

$$P_F = \varepsilon_n = 1 - \gamma\left(\frac{M}{2}, \frac{\lambda_T}{2{\sigma_0}^2}\right) \tag{2.5}$$

$$P_D = 1 - P_M = 1 - \delta_n = \gamma\left(\frac{M}{2}, \frac{\lambda_T}{2({\sigma_0}^2 + {\sigma_1}^2)}\right) \tag{2.6}$$

where $\gamma(m, a) = \frac{1}{\Gamma(m)}\int_0^a t^{m-1}e^{-t}dt$ is the incomplete gamma function and λ_T denotes signal detection threshold [88], ${\sigma_0}^2$ and ${\sigma_1}^2$ denote noise and primary signal power in channel n, respectively. Receiver operating curve (ROC) can be used to compare the performance under different threshold values. Subsequently, this curve is able evaluate and explore the performance of sensitivity (P_D) and specificity (P_F) of sensing method in order to obtain the optimal decision threshold.

Fig. 2.12 shows the ROC curve with different SNR values. This SNR is defined as ratio of PU signal to noise power. Therefore, the noise variance has an impact to the threshold used in energy detector, in which small noise power can cause significant performance loss of signal detection [89].

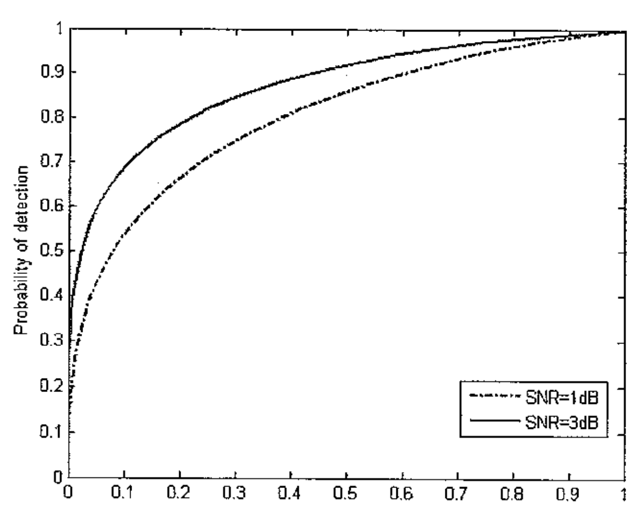

Figure 2.12 ROC curve for energy detector with different SNR

2.3.1.2 Cyclostationary Feature Detector

The cyclostationary feature detector is one technique to detect primary signal transmission by exploiting the cyclostationary features of received signal [90][91], in which the modulated signals are coupled with the sine wave carriers, pulse trains, repeated spreading, hopping sequences, or cyclic prefixes. The received signals are detected by analyzing a spectral correlation function. It has an ability to differentiate noise from the modulated signal energy.

The cyclic spectral density function of the received signal can be calculated as follows:

$$S(f,\alpha) = \sum_{\tau=-\infty}^{\infty} R_y{}^{a}(\tau)e^{-j2\pi f\tau} \tag{2.7}$$

where $R_y{}^{a} = E\left[y(n+\tau)y*(n-\tau)e^{j2\pi an}\right]$ and a are the cyclic autocorrelation function and cyclic frequency. The implementation of this detector is described in Fig. 2.13

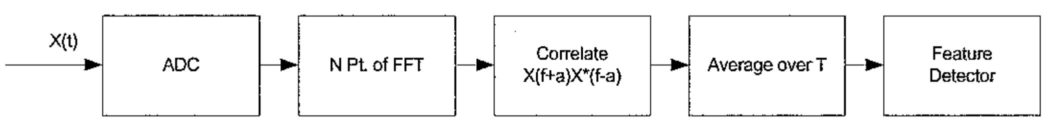

Figure 2.13 Implementation of cyclostationary feature detector [91]

2.3.1.3 Matched Filter

This filter requires less time to achieve high processing gain due to the coherency [92], so that it can be used to maximize signal to noise ratio (SNR). If input signal x(n) is known by the receiver, so the optimal detector can be calculated by the following formula:

$$S(Y) = \sum_{n=0}^{N-1} Y[n]X[n] \tag{2.8}$$

$$H_1 \; if \; S(Y) < \lambda \tag{2.9}$$

$$H_0 \; if \; T(Y) > \lambda \tag{2.10}$$

Where λ is the detection threshold. Number of samples which is required for optimal detection will be

$$N = [Q^{-1}(P_D) - Q^{-1}(P_F)]^2 (snr)^{-1} = O(snr)^{-1} \tag{2.11}$$

where P_D and P_F are probability of detection and probability of false alarm, respectively. However, this detector requires priori of knowledge such as modulation type, packet format, pulse shape, etc. with the perfect information. If the inaccurate information's are obtained or not coherent, so the signal detection can be poor. The main advantage of this detector is time requirement to achieve false detection probability and miss-detection probability is very short compared with other detectors. On the other hand, the disadvantage of matched filtering is large power consumption when various receiver algorithms must be executed for detection.

In this research work, we use energy detector due to its low computational and implementation complexity. This detector does not need prior knowledge of primary signal.

2.3.2 Physical Layer Constraint

It has been presented the type of signal detector that is commonly used in CR system, such as energy detector, cyclostationary feature detector, and matched detector. Cooperative detection is used as one solution for hidden node and shadowing problem. It concludes that spectrum sensing requires physical layer capabilities in term of wideband sensing and fast spectrum switching. Then, practically CR cannot perform sensing and transmission simultaneously, which can be considered in the design of spectrum sensing algorithms. Thus, it should schedule the transmission and sensing without degrading the system performance and sensing accuracy [93]. Furthermore, the effect of multiple radios usage was investigated in [94], where the two transceiver operation is implemented to listen the control channel for sensing. This scenario can improve the system performance, however, it will increase the complexity and device cost

Another constraint of CR is the limited spectrum sensing capability, where scanning the whole spectrum needs longer time and longer time requirement for sensing will impact to the energy consumption. Thus, it should be considered that sensing must be performed within a shorter time while maintaining the QoS of the system performance become higher. Due to this reason, this research work will focus on study and investigation of the performance for cognitive radio where SU has a limited sensing capability. POMDP model is used to model license spectrum behavior as Markov discrete process. Brief description of POMDP will be presented in the next section. POMDP as a method to assist SU for spectrum sensing and access is further discussed in the following section.

2.4 MAC Protocol for Dynamic Spectrum Access

There are a number of protocols standard on wireless spectrum over static spectrum allocation policy, which licensed users and applications are assigned to the specific licensed bands statically. Once licensed users assign a spectrum band, the determined allocation cannot be changed dynamically. Therefore, those protocols cannot be implemented over dynamic spectrum allocation.

As previously presented that static spectrum access policy can cause the scarcity of available spectrum due to the significant growth of wireless user. It is necessary to make a new concept for dynamic spectrum allocation to overcome critical spectrum availability.

Due to the mentioned problem, FCC has already suggested to a new concept of cognitive radio system, which has a capability to dynamically access the spectrum. This new system requires an enhancement of PHY and MAC protocols to be implemented in spectrum agile features. The concept of spectrum agility is by allowing unlicensed users to access licensed bands with the constraint of interference to PU. Secondary user has a responsibility to sense and monitor the activity of primary networks. When PU do not use the channel spectrum (spectrum hole or white space), SU has the right to access and utilize the licensed spectrum channel. However, SU should vacate the bands and utilize other vacant bands when PU returns to use the spectrum.

PHY layer detectors have already presented earlier, such as energy detector, cyclostationary detector, and matched filter detector. The three possibilities of detection results are provided, such as channels are available for unlicensed user; licensed user use the channels, but unlicensed users have possibility to access and transmit the packet data (spectrum sharing) without interfere to licensed user; and spectrum is not available for unlicensed user. On the other hand, MAC layer sensing is used as SU coordinator and it has a responsibility to determine which channel to sense and access and when and who can access the available spectrums. Fig. 2.14 describes the spectrum function in cognitive MAC.

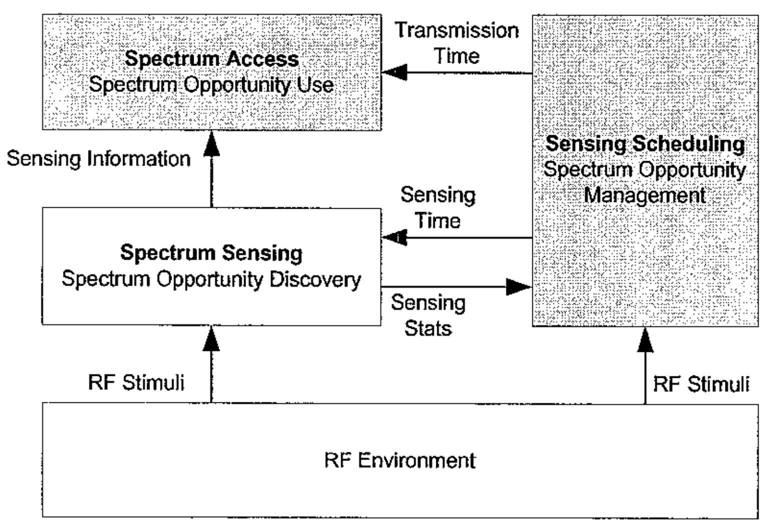

Figure 2.14 Spectrum function of cognitive MAC [42]

MAC protocol for dynamic spectrum access has some functions as follows:

- Unlicensed users have a responsibility to make a real time decision about spectrum occupancy states and determine which channels are available and possible to access based on the sensing outcome.

- Unlicensed user must coordinate to share the used spectrum among unlicensed users or with licensed users for better spectrum utilization

- Unlicensed user monitors their RF environment and seeking other spectrum holes. When primary signal is detected, unlicensed users should vacate the band as quickly as possible, and then attempt to access other vacant bands.

The spectrum allocation MAC protocol for opportunistic spectrum access (OSA) and a survey of MAC protocol for OSA which previously has been proposed by other researchers will be presented by detail in the following section.

2.4.1 Spectrum sharing

Spectrum sharing is a part of MAC functionality in CRN. It has responsibilities to maintain the QoS of SU by avoiding interference to PUs and coordinate multiple accesses of CR users by allocating the spectrum resources adaptively. Through spectrum sharing, SU can be coexisted and simultaneously perform transmission with licensed users. The structure of spectrum sharing is described in Fig. 2.15. According to the previous works, spectrum sharing in CRNs can be classified into 3 factors, type of architecture, spectrum allocation behavior, and spectrum access technique.

- Type of architecture

There are two assumptions of cognitive radio networks architecture, centralized and decentralized (distributed) spectrum sharing. In centralized spectrum sharing, central coordinator has responsibility to control spectrum allocation, while in decentralized spectrum sharing each node must responsible to control spectrum allocation and which spectrum can be accessed.

- The behaviours of spectrum allocation

Spectrum allocation behaviour can be divided into cooperative and non-cooperative spectrum sharing. In cooperative spectrum allocation, the effect of one user communication is shared among other users. The interference, which is generated by user communication, is shared to other users within the network coverage. On the other hand, in non-cooperative spectrum sharing, the generated interference by communication is compensated by only respective user.

- Spectrum Access technique

The two strategies can be considered in spectrum sharing, overlay and underlay. In overlay spectrum sharing, SU accesses the portion of the available licensed spectrum under the constraint of transmission power. So, interference to PU can be minimized. In underlay spectrum sharing, user can transmit independently due to the transmission power below the noise threshold. It exploits the spread spectrum developed for cellular networks. An example of underlay spectrum sharing is ultra wideband (UWB) technology.

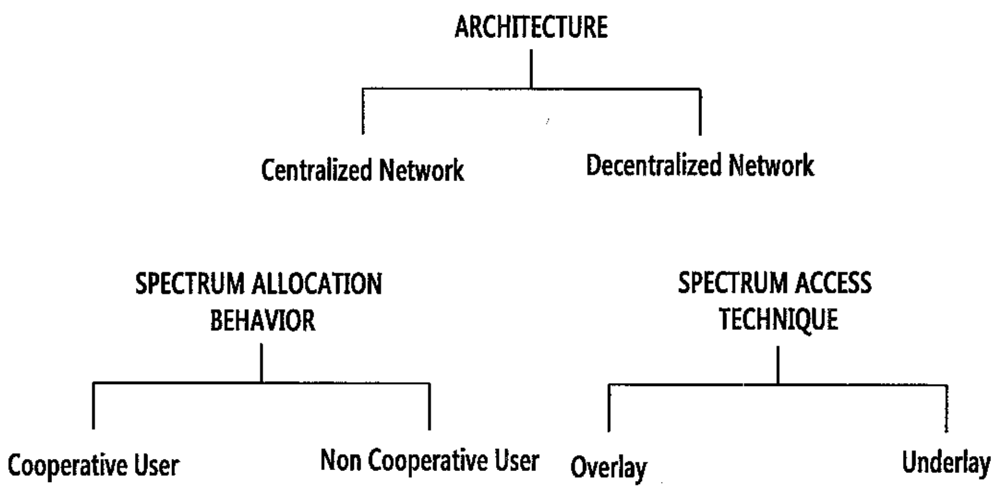

Figure 2.15 The structure of spectrum sharing [73]

2.4.2 Common Control Channel

The common control channel (CCC) supports spectrum sharing functionalities, such as transmitter handshaking [95], communication with central coordinator [96], facilitating to neighbor discovery, and exchanging local sensing and observation from each SU. Using CCC, CR can optimize the channel utilization with number of constraints such as channel quality, access time, network load and PUs activity. The CCC is also used as a control when SU will shift to other vacant channel since PU return and will access back the licensed channel. Fig. 2.16 shows the CCC classification with different design approach, in band and out of band CCC.

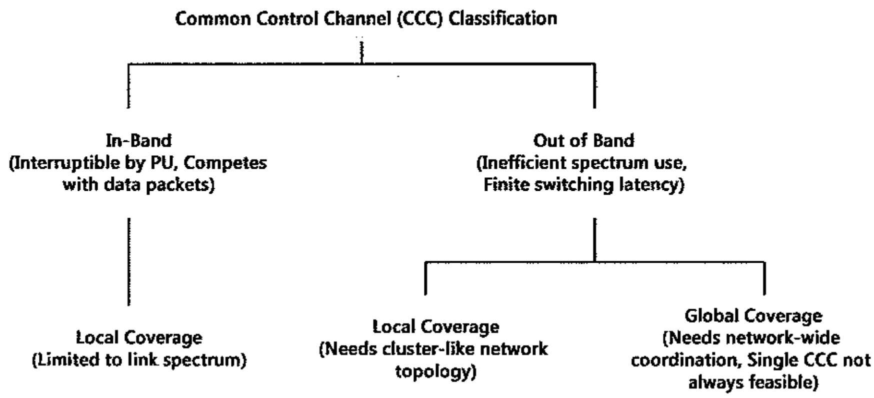

Figure 2.16 Classification of CCC [43]

2.5 Partially Observable Markov Decision Process (POMDP)

Decision-making is the cognitive process leading to the selection of action among variations. One-way to automate the decision making process is to provide a model of dynamics for the domain in which the machine will be making decisions. A reward structure can be used to motivate immediate decision that will maximize the future reward.

Partially Observable Markov Decision Process (POMDP) is an aid in the automated decision-making. POMDP policy informs SU what action to be executed. It can be a function or a mapping and typically depends upon the channel states. In this section, we provide detail formulation of policy strategy either optimal and sub optimal based on greedy approach for sensing decision. POMDP provides a framework to SU that learn how to act and access in primary license bands and seamlessly incorporates the uncertainty of perception, access action, and information. SU receiver will acknowledge and generate the reward for successful transmission bit at each time slot.

A decision process involves an agent that interacts synchronously with the environment. In dynamic spectrum access case, SU represent an agent that continuously monitor license spectrum band. The user's purpose is to maximize the reward or number of successful bit transmission by selecting appropriate access action.

Spectrum access and the history of spectrum states determine the probability distribution over the possible future states. Therefore, stochastic process can be represented as the sequence of spectrum states.

Markov decision process (MDP) is considered as an extension of Markov chains with a set of decisions (actions) and a state based on the reward structure. In each states, a decision should be made after sensing period of time whether SU transmit amount of data or refrain from transmission. An action made by SU affects both the transition probabilities and the reward. The MDP model has a purpose to select an optimal access in every state to increase the throughput performance by minimizing the interference to PU networks.

We assume that license spectrum of primary networks can be a finite number of states, and SU can select the access action based on the states. Let $S = \{S_0, S_1, \ldots, S_N\}$ be a finite set of states. Since the process is stochastic, a particular state at some discrete state, or time step $t \in T$, can be viewed as a random variable S^t whose domain is the state space S. The state should have sufficient information to estimate the future state. It means that the past history of spectrum states is irrelevant to predict the future of:

$$Pr(S^{t+1}|S^0, S^1, \ldots, S^t) = Pr(S^{t+1}|S^t) \quad (2.12)$$

At each stage, SU action to access the unutilized license spectrum can affect the transition probability states. The set of all actions denote by A. Thus, each action $a \in A$ is fully described by $|S|x|S|$ state transition matrix, whose entry in an i^{th} row and j^{th} column. It is the probability that channel state will shift from state s_i to s_j if action a gets executed:

$$P_{ij}^a = Pr\left(S^{t+1} = s_j | S^t = s_i, A^t = a\right) \quad (2.13)$$

It assumes that the processes are stationary, i.e., that the transition probabilities are independent to the current time step.

Access action on channel states can affect the transition function T(.). T: S x A → Δ(S) is a function that for each state and access relate on a probability distribution over the possible states (Δ(S) is set of all probability distribution over S). Thus, for each s, s'∈ S and a ∈ A, the function T define the probability of a transition from state s to s' after executing action a, as follow:

$$T(s,a,s') = Pr(S^{t+1} = s'|S^t = s, A^t = a) \quad (2.14)$$

2.5.1 POMDP Model

A POMDP is a generalization of MDPs to one condition where system states are not fully observable. In dynamic spectrum access case, POMDP frameworks is implemented due to hardware and energy constraints, so that only a part of the existing channel states can be observed by SU. In order to access optimally, SU must consider all the previous history of observation and access action, rather than just the current state. In this section, the description of POMDP model, belief states, value function, and other parameters used in POMDP are briefly presented.

2.5.1.1 Model Definition

A POMDP model generally consists of the following components:

a) A finite set of world states, *S*

The dynamic state of channel spectrum can be considered as a world state, which varies from idle and busy state. The 'idle' denote unoccupied channel state, while 'busy' is occupied channel state

b) A finite set of actions, *A*

Each user access unoccupied channel spectrum, and it is included into the finite set of access

c) A finite set of observations, *z*

SU performs sensing and observation before accessing unoccupied channel. It is intended to avoid collision to primary user activity and mitigate the interference.

d) A transition model.

When the state of channel is *s* from the set *S* and SU accesses the channel *a* from *A*, channel state will change to the nest state *s'* in *S* with the probability P(s'|s, a).

e) An observation model.

When the current channel state is s and at previous time SU accesses the channel, SU observe z from the set Z with the probability P(z|s,a).

f) A reward model R.

When SU is in state *s* and the current action performed is *a*, SU receives $r(s,a)$ units of reward for successful bit transmission. For example, R: S x $A \rightarrow \Re$ is a reward function where each state and action assign a numeric reward. The notation of $r(s,a)$ is an immediate reward that SU receive state *s* and access channel action a.

The process of SU accesses unoccupied spectrum dynamically by applying POMDP as follows: Initially, channel is in one state. Based on the information of channel states, SU access and transmit data on the unoccupied spectrum. This access action can cause two effects, SU receive an immediate reward and the access action changes the channel state into a new one probabilistically. This process repeats continuously and demonstrated in Fig 2.17. When SUs access the channel in state at certain time, it will receive an immediate reward. The objective is to maximize the expected total reward for some period of time.

In a finite horizon framework, SU maximizes the total reward over the next time slot *t*, i.e. $E[\sum_{n=0}^{t=1} r_n]$, while in an infinite horizon, SU maximizes the expected total reward in a long-term basis. It assumes that rewards received earlier have more value for SU than those received later. In this case, SU introduces discount factor to maximize the total rewards.

$$E\left[\sum_{n=0}^{\infty} \lambda^n r_n\right] \tag{2.15}$$

where λ is a discount factor and in the range of $0 \leq \lambda \leq 1$. When the reward function is in upper bounded by a constant, the discount factor convinces that the above total is finite. In this thesis, we will adopt POMDP frameworks under finite horizon that is implemented to model primary network as Markov discrete process CR system. The detail of POMDP implementation into OSA will be presented in the following section.

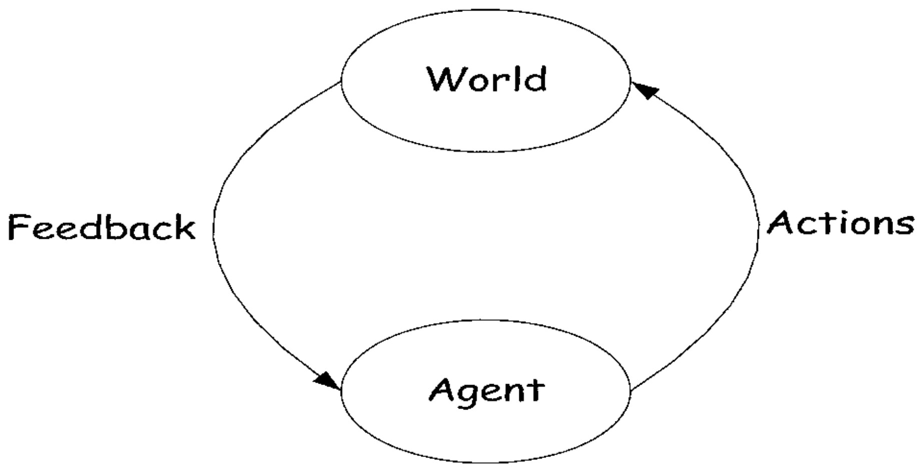

Figure 2.17 Interaction between CR user and channels using POMDP model [143]

2.5.1.2 Observation Function

In POMDP model, a set of observation, z, is added to the model so that after each state transition of the system, one of these observation is resulted by the system and it is accessible for final decision. The result of observation is correlated to the transition state; however it can completely determine the current state.

Let O is a set of observations that can be received by SU. In MDP, SU has full knowledge of the system state, so it can be considered that $O \triangleq S$. However, in partially observable environment, observations are only probabilistically dependent on the underlying environment state.

Z: S x A → Δ(O) is an observation function that specifies the relationship between system state and observations. $Z(s', a', o')$ is defined as the probability that observation *o'* will be recorded after SU access unoccupied channels and stay on state *s'*

$$Z(s', a', o') = Pr(O^{t+1} = o' | S^{t+1} = s', A^t = a) \quad (2.16)$$

A POMDP is determined by state (S), action (A), transition function, reward function, observation space (O), and observation function (Z). The relation between those parameters is shown in Fig. 2.18

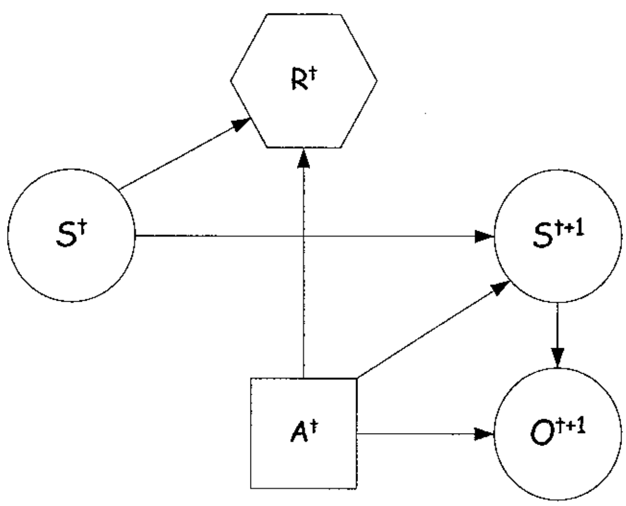

Figure 2.18 Relationships between POMDP states, actions, rewards, and observations [143]

2.5.1.3 Process History

A history in POMPD model is defined as a record of everything happened during the action process. A complete system history from the beginning until period of time, t, is considered as a sequence of state, observation and, action as bellows:

$$(S^0, O^0, A^0), (S^1, O^1, A^1)(S^t, O^t, A^t) \quad (2.17)$$

Then, the set of all complete histories can be denoted as H. Since rewards depend only on visited states and executed actions, a system history is sufficient to evaluate SU performance. Hence, a system history can be defined by only a sequence of state and action:

$$(S^0, A^0), (S^1, A^1)(S^t, A^t) \tag{2.18}$$

Dissimilar to fully observable, in POMDP, SU cannot fully observe the underlying spectrum state. It is only based on its decision of observable history. When SU has prior beliefs regarding to the spectrum states that are summarized by the probability distribution b_o over the system states, then SUs start to access unoccupied channel (a_0) based solely on b_o. The observable history until period of time t is a sequence of access actions and observations

$$(A^0, O^1), (A^1, O^2)(A^{t+1}, O^t) \tag{2.19}$$

The set of possible observable histories is denoted as H_o. When H_o is structured and represented by different ways will result different POMDP solution and policy access algorithm.

At each step in a sequential decision process, SU have to decide what action to be performed according to their observable history. A policy π: $H_o \rightarrow A$ is a rule that maps observable histories into action. A given policy causes a probability distribution over all possible sequences of states and actions. Therefore, SUs have to control statistical model of system histories. The purpose is to select a policy that maximizes the remaining rewards of the involved system. Such objective function is called a value function.

2.5.1.4 POMDP Parameter

Secondary user is able to know the channel states by identifying license spectrum of primary networks. However, incomplete information is obtained if users only refer to their observations. When user decides to access unoccupied license channel at one time, SU refer to all historical information including the initial states, observation, and access action.

A belief state is a probability distribution over all channel states in S. It is denoted by *b*. The belief of state *s* is *b(s)*. The total of beliefs over all channel state is 1.0 ($\sum s \in Sb(s) = 1.0$). If the current belief state of SU is *b*, the access action is *a* and the observation is *z*, then its belief state b_z^a is updated as follows:

$$b_z^a(s') = \frac{\sum_s P(s', z|s, a)b(s)}{\sum_s \sum_{s'} P(s', z|s, a)b(s)} \tag{2.20}$$

The notation of P(s',z|s,a) is the joint probability of state s', SU observing z if the previous state is s and channel access action is a. It equals to P(s'|s,a)P(z|a,s').

All the possible belief states of channel form a belief space and denoted by B. Formally,

$$B = \left\{ b: \sum_{x \in S} b(s) = 1.0, \forall s, b(s) \geq 0 \right\} \tag{2.21}$$

In POMDP model, a policy determines an access action for each belief state. A policy π is mapping from the belief space B to the action space A. A belief state *b*, π(b) is the channel access determined by π for *b*. A policy π is stationary when it is independent of time. At any time and each slot, a stationary policy determines the same channel access for the same belief state.

Given a policy π, if SU starts from a belief state *b*, it receives the expected reward can be stated by

$$E_{b,\pi}\left[\sum_{n=0}^{\infty} r(b_n, \pi(b_n))\right] \tag{2.22}$$

where b_n is the belief state and $\pi(b_n)$ is the channel access action at certain time n. This quantity is denotes by $V^{\pi}(b)$, where V^{π} is the value function π. Formally, a value function is a mapping from the set of system histories into real number, where V^{π}: $H_s \rightarrow R$. H_s is the set of history function.

The value function V^{π} is assumed to have a structure that makes it easier to represent and evaluate. It is the value of a particular system history, which can be accrued at each time slot. A finite horizon problem is defined if the decision process stops after a finite number of steps. Thus, the value function for system history of a certain length is the total reward that can be reached at each step [97].

$$V(h) = \sum_{t=0}^{t=H} R(S^t, a^t) \tag{2.23}$$

An optimal policy is denoted by π^*. The optimal value function is the value function of an optimal policy and denoted by V^*. For any b, $V^*(b)$ is the maximum expected total reward that can be accrued by SU if it starts from a belief state b. If value function of a policy π is optimal, it can say that the policy π is optimal. Hence, solving a POMDP model means that finding an optimal value function of the POMDP. In dynamic spectrum access case, it finds the optimal reward or number of bit transmitted by SU that can be accrued through adopting POMDP frameworks.

Regarding to the concept of belief state, a POMDP model M can be transformed into a belief space MDP *M'*. B is the state of M' and equal to the action space. The transition model is defined as given a belief state b and action a, it specifies the transition probability as

$$\left(P(b'|b,a) = \begin{cases} P(z|b,a) & if\ b' = b_z^a\ for\ some\ z, \\ 0 & otherwise \end{cases}\right) \tag{2.24}$$

while reward model is defined as given a belief state b and action a, it specifies immediate reward *r'(b,a)* as

$$r'(b,a) = \sum_{s \in S} b(s) r(s,a) \tag{2.25}$$

2.5.1.5 Value Iteration

Value iteration is a standard approach to find POMDP solution. One basic step to compute a near optimal value functions is dynamic programming. Using dynamic programming approach, a policy can be evaluated and we can simultaneously compute the optimal policy and values by working from time T-1 to time 0.

The optimal value function for a finite horizon can be calculated by using the following formula:

$$V_n^* = \max_{a \in A} \left[r(s,a) + \rho \sum_{s' \in S} r(s,a,s') V_{n-1}^*(s') \right] \tag{2.26}$$

where $V_n^*(s)$ represents the value of an optimal policy, π^*, when the starting state is s and there are n decision step remaining. The dynamic programming approach to find the optimal value is referred to value iteration. So, it is more convenient to write value function of above equation in term of value function as bellows:

$$V_n^*(s) = \max_{a \in A} V_n^{*,a}(s) \tag{2.27}$$

where

$$V_n^{*,a}(s) = r(s,a) + \rho \sum_{s' \in S} r(s,a,s') V_{n-1}^*(s') \tag{2.28}$$

The value $V_n^{*,a}$ means that the value of performing action a with n step remaining and performing optimally for the remaining n-1 steps.

2.5.2 POMDP Problem

The number of vector representing a step value function V_n will grow exponentially when n increases. Thus, it is very difficult to maintain every vector since the computational resource is limited. Some vectors can be removed without affecting the value function V_n, since not every vector is useful. However, this comes at the price of solving the same number of linear programs as the size of its representing set.

Regarding to the implementation of POMDP framework into dynamic spectrum access, the complexity of optimal solution will increase when number of channel increases. Thus, the greedy or myopic approach was introduced as a solution to reduce the complexity appears in POMDP as an optimal policy. This approach is presented in the separate section.

2.6 Related work

This section brings to light previous works and studies. It starts by listing types of MAC protocol for CR system, cross layer design, spectrum sensing and access under POMDP, and cooperative spectrum sensing.

2.6.1 MAC Protocol for Cognitive Radio System

A number of researches and studies related to MAC protocols of CR have been conducted. It is simply classified into 3 categories, random access protocol, time slotted protocol, and hybrid protocol. These protocols are clearly present by detail in the following sub-section.

2.6.1.1 Random Access Protocol

In random access protocol, SU can access channels without time synchronization and adopt the scheme of carries sense multiple access with collision avoidance (CSMA/CA). The secondary users keep monitoring channel utilization continuously, when it is not used by other SUs or licensed users, the relevant SUs will generate back off time until a certain time period to avoid simultaneous transmission among SUs or prevent interference to PUs.

In [98], the protocol based on CSMA was proposed. It has a capability to coexist between other SU and PU through adapting the transmission power to avoid interference to PUs. The authors considered infrastructure based cognitive radio networks with multiple users trying to transmit number of data packets to the base station and do it simultaneously with PU under the condition that interference to PU or transmission power of SU below the threshold value. PU sends request to send (RTS) signal to the base station before transmitting data packets with prior carrier sensing under certain period of time (T_{PU}). The base station will respond it by sending clear to send (CTS) signal to PU when it is available for data transmission. Subsequently, SU undertake carrier sensing with longer period of time (T_{SU}) than PU ($T_{SU}>T_{PU}$). This protocol is described in detail as Fig. 2.19.

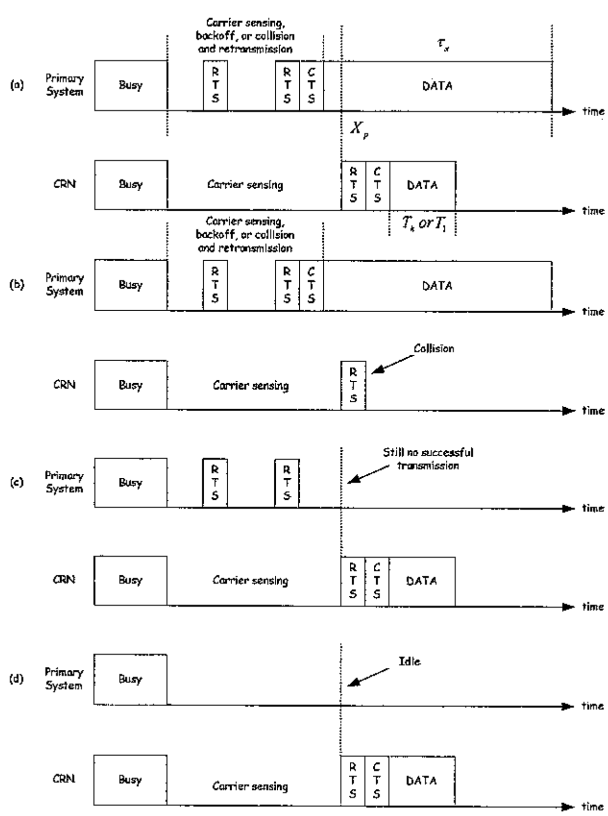

Figure 2.19 CSMA based protocol with 4 handshaking procedures coexist with PU [98]

According to that figure, CSMA based protocol behaves with 4 handshaking procedures to coexist with PU as follows:

- PU transmits the data packet after prior carrier sensing and backoff time. SU senses the channel with a longer period of time to find the available channel. After carrier sensing at certain time period, SU accesses the channel by sending RTS-CTS handshaking signal. When SU transmission occurs, the transmission power and rate are maintained below the threshold to avoid interference to PU.
- The RTS signal is sent by SU collide to PU transmission, so SU can transmit the data packet in the following transmission opportunities.
- The PU send RTS signal several times due to collision, so SU can start to transmit data packet independently by sending prior RTS-CTS signal.
- The is no data packet to be transmitted by PU, so SU can start to transmit its data packet independently by sending prior RTS-CTS signal as previous case.

Dynamic open spectrum sharing (DOSS) MAC protocol was proposed in [95]. This protocol properly implemented on ad hoc networks and provides solution to hidden and exposed terminal problems. The DOSS MAC protocol must follow the steps such as PU detection, divides bands into 3 operational frequency bands which have special function, spectrum mapping, spectrum negotiation, and data transfer. After successful packet transmission, receiver will send the acknowledgment signal.

Distributed channel assignment (DCA) based MAC as an extension of the IEEE 802.11 CSMA/CA protocol was proposed [99]. This protocol utilizes spectrum pooling to improve spectrum efficiency. Each user maintains the spectrum information, such as current usage channel list (CUL) and the free channel list (FCL). This information should be updated and recorded continuously, so that SU can transfer the data packet.

Single radio adaptive channel (SRAC) MAC is a protocol that adaptively combines spectrum bands according to SU requirements, namely dynamic channelization. In addition, this protocol enables SU to transmit packet on one spectrum band and transmit through another spectrum by using the scheme cross channel communication [100]. This scheme is intended to avoid frequency jamming and collision to PU transmission.

Another protocol that is included into random access scheme is hardware constrained MAC (HC-MAC) [101]. This protocol was proposed with the purpose to the efficiency of spectrum sensing and access by considering hardware constraint. This constraint makes SU must sense the available spectrum and limit the transmission time. The longer sensing time can obtain and explore the more data of spectrum occupancy state, however it will cause more complexity to the hardware implementation. The problem is how to sense and access the spectrum appropriately to obtain the optimal throughput performance. As described in Fig. 2.20, the HC-MAC protocol models the sensing process as an optimal stopping process.

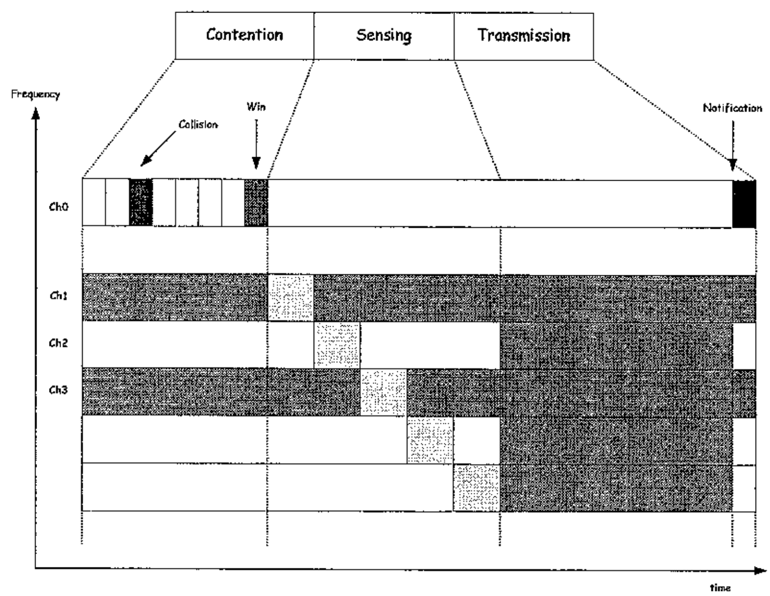

Figure 2.20 HC MAC protocol operation [101]

Cognitive MAC is divided into time frame and operation such as contention, sensing, and transmission phase. The three packet is introduce to this operation and sent over common control channel (CCC), C-RTS/C-CTS (contention phase), S-RTS/S-CTS (sensing phase), and T-RTS/T-CTS (transmission phase). In the contention phase, the packet pair C-RTS and C-CTS is sent to gain the channel access, and send the following packet S-RTS/S-CTS to send the available channel. Then, based on the sensing outcome, SU send the packet T-RTS/T-CTS by following the stopping rule.

2.6.1.2 Time Slotted Protocol

In these MAC protocols, time frame is divided into slot for both control channel and data transmission under time synchronization. The IEEE 802.22 standards for wireless regional area networks (WRAN) is one kind of these protocols which properly implemented in centralized networks [102]. The base station as central coordinator has a responsibility to manage the cell activities including consumer premise equipments (CPE). Subsequently, sensing mechanism of the IEEE 802.22 standard can be divided into 2 stages as described in Fig. 2.21, fast sensing and fine sensing. The fast sensing is performed very quickly (around 1 ms/channel), and intended to confirm whether the following stage is needed. The following stage, fine sensing, is performed to meet the quality of service requirement, so that longer sensing time should be performed to improve the throughput performance. The backup of channels is used to restore data communication when PU activity is detected since SU should vacate the bands and access other vacant bands.

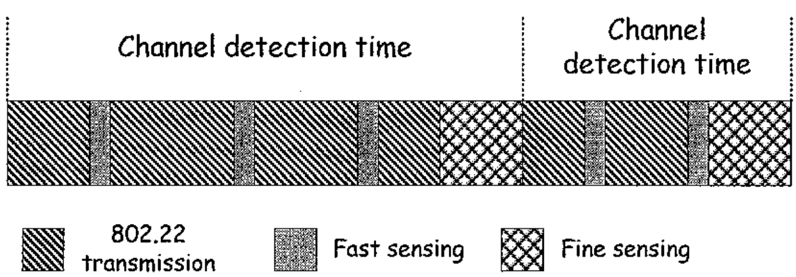

Figure 2.21 Sensing mechanisms in IEEE 802.22 standard [102]

Cognitive MAC (C-MAC) protocol [103] was proposed and implemented in ad hoc networks. The two of main keys in this protocol are rendezvous channel and backup channel. Rendezvous channel is used to manage the existing nodes, PU detection, and multi channel reservation. The selected channel can be used for long data transmission without interruption. Then, backup channel is used to provide alternative choices of available spectrum in case of SU detects primary signal.

It depends on how the CCC shares the channel information. For In band operation, the range of CCC is limited to local coverage, while out of band is intended into global coverage, which may have dedicated spectrum channel

2.6.1.3 Hybrid Protocol

These protocols are combination between random and time slotted protocol schemes. The protocols generally use control signaling over time slotted and random access channel for data transmission.

A game theoretic based dynamic spectrum access (DSA) is one example of hybrid protocol for centralized networks. It was proposed in [104] to obtain high spectrum utilization along with collision avoidance for spectrum access. Four important components are introduced in DSA driven MAC protocol as described in Fig. 2.22 as follows:

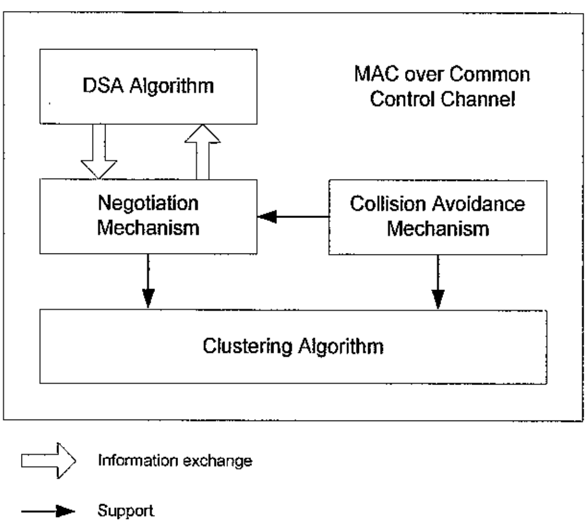

Figure 2.22 DSA-driven MAC protocol [104]

- DSA algorithm, which is an algorithm to prepare one strategy of each SU to give the information how to access available channels for data transmission.
- The negotiation mechanism, which is a mechanism to coordinate users to exchange the information and updating their strategies. The two phases should be

carried out, identify which SUs have data to transmit that will become user who considered in the formal negotiation stage. So, the formal negotiation phase has a responsibility to coordinate users who have data packets to be transmitted.

- The clustering algorithm, which has a responsibility to limit the negotiation of each user to solve scalability problems.
- The collision avoidance mechanism, which is a mechanism to mitigate collision among SU in different cluster during negotiation.

Furthermore, an efficient MAC protocol for wireless spectrum utilization as known as opportunistic spectrum MAC (OS-MAC) protocol was proposed in [105]. This protocol has capabilities to adaptively and dynamically seek the spectrum occupancy and explore the opportunities both licensed and unlicensed spectrum; shares those spectrum opportunities among SU or PU, and coordinate users for better spectrum utilization. The protocol operation can be described into 6 phases, network initialization, session initialization, data communication, update session, selection session, and delegation session. The network is divided into some cluster. SU can communicate each other within the same cluster or different cluster. One user within one cluster is directed as delegate user. The active delegate can select spectrum band for their communication, monitor spectrum continuously to inform all member within a cluster about the vacant spectrum. Each cluster delegate inform the traffic condition of data communication within their clusters even when changing which spectrum band will be utilized.

The synchronized MAC (SYN-MAC) was proposed [106] as a hybrid protocol. It does not need common control channel (CCC), but has a dedicated radio channel for control messages. A simple example of this protocol is described in Fig. 2.23. Suppose that sender want to transmit data to the receiver. First, sender select a channel to access, then after backoff time period and sending RTS-CTS signal, sender can independently transmit the data through the selected channel. The sender must inform to the receiver and its neighbor as well when PU is detected and it wants to shift to other vacant channels.

The opportunistic cognitive MAC protocol was proposed in [107]. It used two transceivers for each SU. One of the transceiver is used for dedicated CCC and the other is used for dynamically senses and identifies the available channels. The principle of the proposed MAC protocol is described in Fig. 2.24.

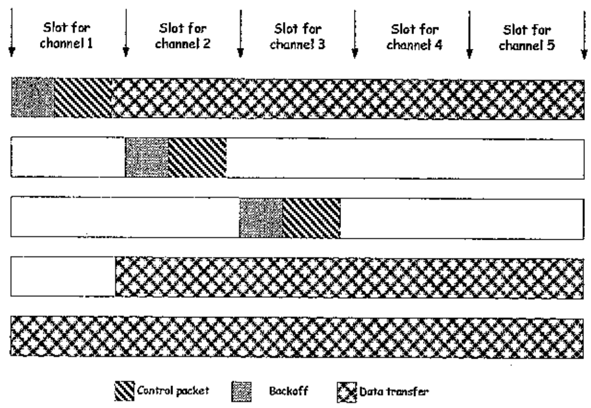

Figure 2.23 Control and data packet exchange in SYN-MAC [106]

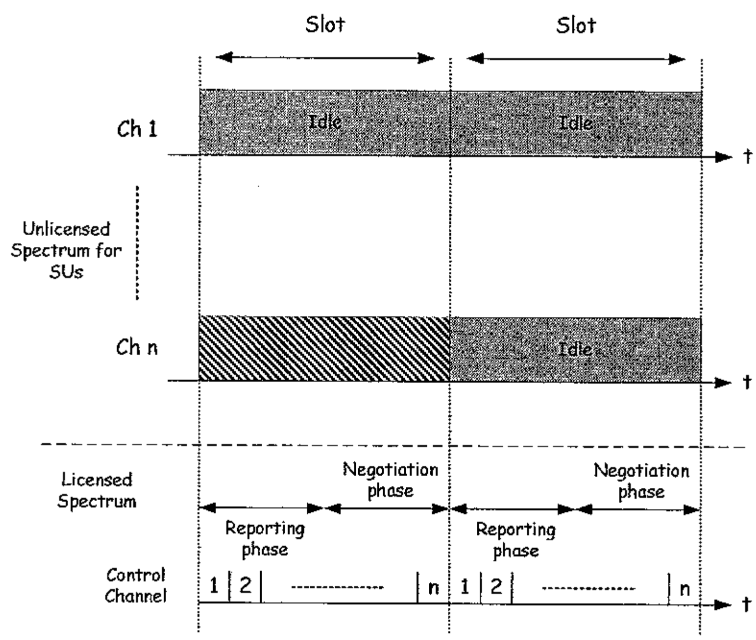

Figure 2.24 The principle of opportunistic MAC [107]

It has two phases, reporting and negotiation phases. The reporting phase is divided into n slot number. Before transmitting data, SU sense the available channel. If one channel is available, SU send a beacon signal over CCC and inform to the reporting phase, else SU will not send the beacon signal. In negotiation phase, SU negotiate with other SU through contention-based algorithm as IEEE 802.11 and p-persistent CSMA.

Q.Zhao et al proposed another hybrid protocol known as partially observable Markov decision process (POMDP) [128-131][108-112]. Due to the hardware constraint, SU merely select part of the channel to be sensed and accessed. In other word, SU has a limited sensing capability. Integration design between spectrum access protocol at the MAC layer and spectrum sensing in PHY layer are presented. It discussed cross layer design of spectrum sensing and spectrum access as well as transmitter-receiver synchronization. However, most of the works assume that single SU sense license channel without cooperation.

POMDP was proposed to avoid energy cost of full band sensing capability. Most of the existing works on full band sensing is used to find spatial spectrum opportunities that are static or slowly varying in time such as reuse of certain TV band that is not used for TV broadcast in particular region [82][89][113-118]

The term of partially comes from the fact that the network activity cannot be fully observed by SU. At the beginning of the slot, SU select channel to be sensed and set of channel to be accessed. The main purposes of this protocol are maximizing the throughput performance under the constraint of interference to PU and gain the reward of transceiver from the previous slot information.

This POMDP-based frameworks protocol provides which the available spectrum can be accessed by SU according to the sensing outcome. It is also introduced a new metric, reward, which is used to evaluate the system performance. The reward is defined as number of successful bit transmission over one slot and added when the transmission slot increases. The belief vector which is the distributed vector of networks state history based on all past sensing and observation is provided as well, so SU can access channel with the highest idle probabilities. Each SU senses the selected spectrum channel and decide which channels can be accessed by themselves.

The spectrum occupancy states are modeled into busy and idle. The busy spectrum channels are represented by 1, and the other hand, when spectrum channels are idle can be represented by 0. The simple model of spectrum occupancy state is described in the Fig. 2.25

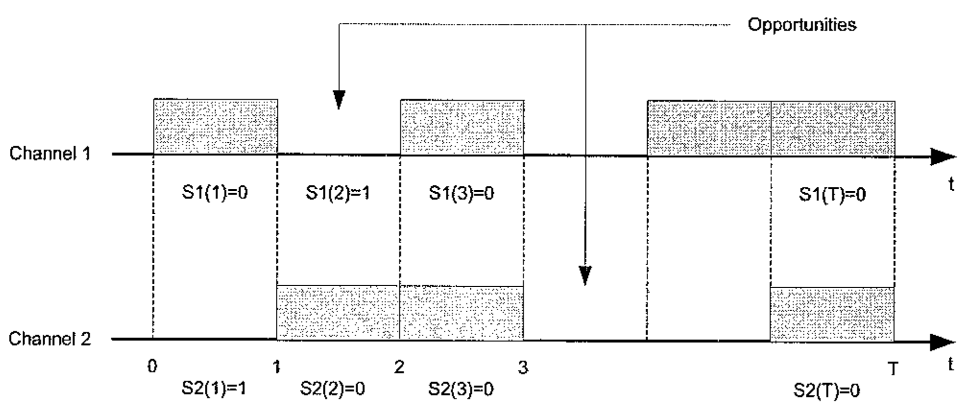

Figure 2.25 The simple model of spectrum occupancy under POMDP [128]

2.6.2 Cross Layer Design for Cognitive Radio System

The networking task is divided into layers that specify a service can be provided by each layer, like seven layers open system interconnection (OSI) model as described in Fig. 2.26. The service at layer is applied by designing protocols for each layer with respect to the rule of the reference architecture. The cross-layer design is defined as protocol design methodology and was introduced to increase and optimise the system performance by obtaining a global view of radio system and its performance.

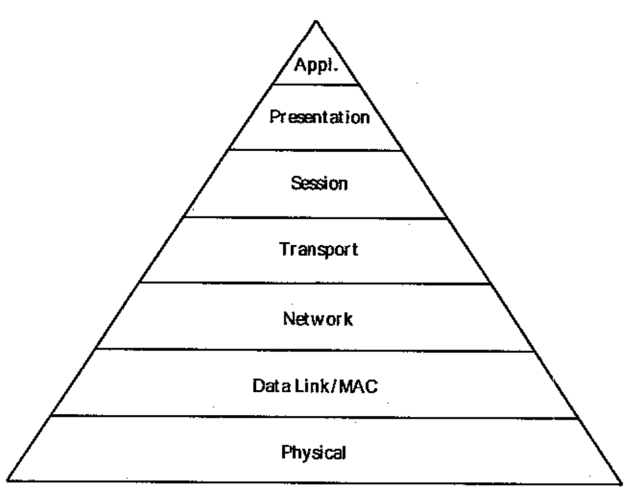

Figure 2.26 The seven layer OSI

The challenge of PHY layer such as rate, power, coding, etc, and QoS requirement for the applications should be taken into consideration.

Fig. 2.27 describe a new cross layer design frameworks by exchanging information through four layers. However, the cross layer approach in CR network will significantly increase the design complexity. Some procedures to be notified for cross layer design as belows:

- Which layers and which parameters will be selected for information exchange to optimize the system performance.
- How the cross layer interaction will be performed, as [119], classify it by three categories, direct communication between layers, a shared database among layers, and completely new abstraction.

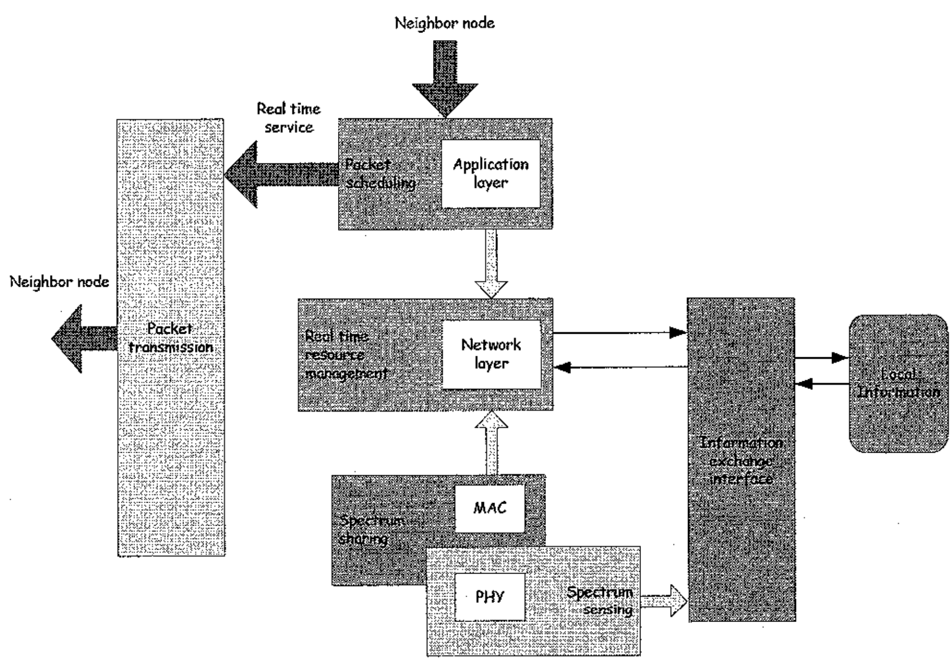

Figure 2.27 Cross-layer design framework over cognitive radio networks [119]

In PHY layer, adaptive strategies are applied to optimize the link rates under variation of channel state. Subsequently, MAC layer decide the capacity by assigning time slots, codes, or frequency bands for spectrum sharing. According to the transmission rate and packet loss rate, MAC layer jointly coordinates with the network layer to decrease the traffic congestion and application layer determines the packet scheduling within real time services.

Real time interaction between MAC layer and PHY layer is the most frequently perform compared with other layers. Hence, the design among these two layers is very crucial to improve CR system performance [120].

In CR system, the MAC layer has a capability to adapt the availability of communication resources i.e. channel spectrum, and manage the access of SU for mobility and performance optimization. Subsequently, PHY layer has a great performance to improve delay, throughput, and packet loss by implementing multiple coding, modulation shceme, advanced antenna technique, MIMO and OFDM technologies.

A lot of study in cross layer design of cognitive radio has been investigated and proposed. In [121], cross layer based opportunistic multi channel medium access control protocol was proposed. It integrates the spectrum sensing at PHY layer with the packet scheduling at MAC layer which is implemented in wireless ad hoc networks. Chen et al in [122] investegated joint coding and scheduling strategy for cognitive multiple access to overcome congestian on the traffic of packet transmission, which will cause large packet delay waiting and loss and result a poor quality of service as well. Then, a novel cross layer of opportunistic scheduling strategy with interference control at MAC layer for multiple cognitive radio users was proposed in [123]. In [124], Li et al presented cross layer design for joint scheduling and power control in cognitive radio networks to overcome the problem of throughput performance and power consumption, improve the throughput performance while maintaining power consumption low.

Q.Zhao and Y.Chen et.al investigated cross layer design of PHY layer and MAC layer [108]-[111]. The proposed algorithm improved the performance by considering spectrum sensor design at PHY layer and protocol design at MAC layer. It is able to maximize the spectrum utilization while limiting the interference to PU networks as well. However, they focused on single parameter setting. Exploration of the impact of spectrum sensing into throughput performance and time requirement for spectrum sensing against spectrum access should be further studied.

2.6.3 Cooperative Spectrum Sensing (CSS)

Cognitive radio can be viewed as an intelligent wireless communication system that must be aware of the radio frequency environment. It selects the communication parameters such as bandwidth, transmission power, and type of modulation, etc, in order to optimize the spectrum utilization. One of the critical issues in CR system is spectrum sensing. Through sensing and adapting to radio frequency environment, SU can access the unoccupied licensed spectrum without interference to PU transmission.

However, SU will have some problem when detect PU signal in severe multipath fading, inside building with high penetration loss, or detecting hidden terminal when SU is shadowed [85]. Regarding to these problems, cognitive radio can have fail detection or experiences any difficulties to sense the presence of PU, and causes interference occurs to PU, i.e. result a collision between SUs and PUs.

In order to overcome the aforementioned issues, multiple SUs can cooperate for sensing and detection. Each SU exchanges their local sensing and decides which channel can be accessed according to the sensing results. Theoretically, cooperative sensing can achieve the results more accurate than single one. The signal uncertainty in single user detection can be minimized through a sensing collaboration among SU. Multipath fading and shadowing effects can be reduced by cooperative sensing, so the detection probability can increase significantly. As illustrated in Fig. 2.28 SU-1, SU-3, and SU-4 receives a weak signal with low signal to noise ratio (SNR) due to multipath fading and obstacles.

Fortunately, SU-2 can detect PU signal correctly. By exchanging local sensing with SU-2, SU-1, SU-3 and SU-4 can detect PU signal even they are under fading and shadowing area. Furthermore, as a confirmation when we refer to [125]-[127], the results show that the cooperative algorithm can greatly improve the spectrum sensing performance when number of collaborated user increases.

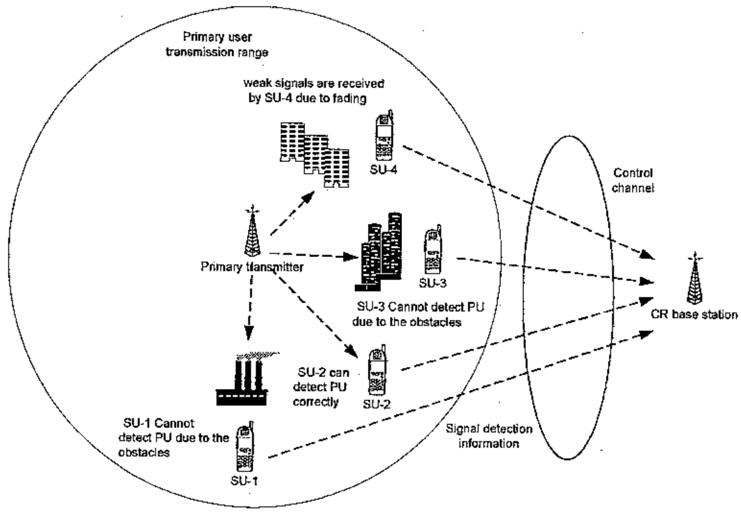

Figure 2.28 Cooperative detection in CR networks [127]

A lot of studies discuss cooperative spectrum sensing as in references [79-81][125-127], however, they mostly focus on physical layer without considering spectrum access. The presented results discuss sensing accuracy that was represented by probability of detection, probability of false detection, and probability of miss detection. Hence, spectrum sensing that influences spectrum access performance should further studied and investigated

2.6.4 Spectrum Sensing and Access under POMDP

POMDP is a framework that assist user to select one among variation. It is an aid to design environment into mathematic modeling.

The previous series of work in CR address this system into decision theoretic framework based on POMDP (Partially Observable Markov Decision Process) [128]-[131], which integrate spectrum sensing in physical layer, spectrum access at MAC layer and the traffic statistic determined by application layer together [132][133]. They investigated the limited sensing capability of each SU in cognitive radio system under POMDP as well as presented cross layer design approach to implement partial sensing results to optimise spectrum access. However, they considered only single SU senses either single or multiple channels. Multiuser CSS model is required to be further investigated.

Previous section discusses general theory of POMDP that commonly implemented to assist user selecting one among variation choices (e.q. robotic, etc). In this thesis, detail implementation of POMDP will be further studied. Decision theoretical approach of POMDP for CR system will be discussed by detail in the next chapter. The summary of related works is briefly indicated on Table. 1.

Table.1 Summary of related works

PUB. YEAR	AUTHOR	DEMERITS
2004-2008	Ghasemi et al; G. Ganesan et al; S. Kyperountas et al; J. Unnikrishnan et al; W. Zhang et al; S. M. Mishra et al; K. B Letaief et al [79]-[81], [125]-[127]	The authors investigated on cooperative spectrum sensing without considering access strategy. They focused on physical layer which discussed on the performance of physical layer (i.e. Pf, Pd, Pm)
2005-2011	Q. Zhao et al; Y. Chen et al; Tehrani et al [128]-[133]	The authors investigated the performance of opportunistic spectrum access under POMDP with single user sensing
2006-2008	A. Sahai et al; D. Cabric et al; K. Challapali et al; B. Wild et al; A. Ghasemi et al; H. Zheng et al; W. Wang et al; S. Sankaranarayanan et al; [23],[92], [113]-[118]	The authors investigated the performance of cognitive radio system with spatial spectrum opportunities that are static or slowly varying in time.

2.6.5 Research Challenges

According to extensive literature review on dynamic spectrum access, CR, and related works, the main points of research challenges are as follows

- It is required to further study and explore POMDP for CR system that maximized throughput during transmission slot time.
- It is a challenge to explore the performance of opportunistic spectrum access due to the bursty traffic of primary user activity

- It is required to investigate the performance of CR system by considering spectrum access in MAC protocol to explore further the impact of spectrum sensing to the throughput performance in case of time requirement for sensing (relationship between spectrum sensing and spectrum access)
- To mitigate fading, hidden node, and noise uncertainties, it is a challenge to design CSS model that captures dependence on the throughput performance improvement.

2.7 Summary

This chapter has presented the basic concept of static and dynamic spectrum access system. Cognitive radio as one of the enabling technology for DSA was presented as well, where unlicensed user enables to access license spectrum with prior sensing under the constraint of interference to PU. It must be noticed that interference should be below the threshold value.

Spectrum sensing is critical issue in CR system. It must be performed as quickly as possible with high degree of accuracy in order to avoid interference to PU. The types of PU signal detection was presented and each technique has advantages and disadvantages. Cooperative spectrum sensing is implemented in primary signal detection to mitigate the impacts of fading, shadowing, hidden terminal and uncertainty noises.

Furthermore, related works discussed the three categories of medium access protocol for CR system. POMDP as a hybrid protocol is used to further investigate optimal and sub optimal greedy sensing policy. It is used as an aid in decision making for which channel can be sensed and accessed by SU. It models license spectrum behavior as Markov discrete process where idle and busy channel states are denoted by number of 0 and 1. It also provides mathematical formulation for spectrum sensing and access that introduce reward function to stimulate user in successful transmission. Moreover, detection method that is commonly used in CR system was presented. Energy detector as a semi-accurate for PU signal detection is adopted to investigate CR performance.

Finally, the existing works of CSS model that assumes full band sensing capability has been presented along with literature references. However, full band CSS model is not efficient in term of energy constraint.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter discusses the methodology of research works. It explores POMDP as decision theoretic approach for optimal and sub optimal greedy sensing policies along with mathematic formulation. It begins with modeling of spectrum access under POMDP, Markov model for primary network traffic, and CR system model under POMDP. Optimal and sub optimal greedy sensing with perfect and imperfect propagation along with mathematic formulation is further discussed.

The following section discusses a basic concept of cross layer design principle through ROC to optimize throughput performance. The plot of ROC is divided into 2 regions, aggressive and conservative. Hence, it has 3 cases, when the point is laid on the best line of ROC, aggressive, and conservative regions, respectively. Finally, DMCSS model is proposed for optimization. The theory of binomial distribution statistic is introduced to derive probability of miss detection for DMCSS model. Finally, summary of this chapter is presented as a close section.

3.2 Spectrum Access Modeling under POMDP

Generally, a POMDP is used as an aid for making decision. It is adopted to assist the systems regarding to what action systems should take. Robotic field is one of the aforementioned systems that adopted POMDP framework. Robot must take an action based on the finite set of states and history. However, in this section, the description of dynamic spectrum access under POMDP and the mathematic modeling for opportunistic spectrum access is further discussed and presented.

Primary network activity can be viewed as world system in POMDP frameworks theory. It changes from idle and busy state and makes SUs possibly to access an idle license channel spectrum. SUs should sense and observe the spectrum occupancy state before accessing and transmitting data on the unoccupied license spectrum. If PU is supposed to return to use the channels back, SU should vacate the bands and seeking other vacant bands.

In the following section, OSA environment under POMDP frameworks will be briefly discussed. Spectrum utilization dynamically changes and it is modeled as "0" and "1" which denote idle (unoccupied spectrum channel) and busy (occupied spectrum channel) states, respectively. The objective of POMDP framework model implementation is maximizing the remaining reward or number of bit transmitted by SU during T slot transmission (total number of slot transmission)

3.2.1 Markov Model for Primary Network Traffic

Detection accuracy of PU activity is too crucial for SU since it determines how far SU interfere their communication and how successful is SU data transmission. Primary networks modeling are necessary to decide an access policy for SU in license bands. It requires very accurate traffic model that have a capability to capture the statistical characteristics of actual traffic on the primary networks.

If the traffic models do not efficiently capture the characteristics of the actual primary traffic, the result may be under estimation or over estimation and it can cause collision and make interference to primary user. Hence, it is a core element of SU to observe PU behavior and primary networks activity in order to have a good quality of service during transmission or co-exist with PU (spectrum sharing).

Primary traffic models are analyzed based on the number parameters required describing the model, tractability, and parameter estimation. SU must capture the actual traffic of primary network activity in order to avoid the interference and transmission collision. The assumption of primary traffic model makes SU can predict the current and future action of PU.

Markov model as one of the existing model attempts to represent the activities of a traffic source on a network by using finite number of states. The model increases accuracy linearly with the number of states used in the model. However, the complexity of the model also increases proportionally with increasing number of states. The future states depend on the current state and the probability of future states are determined by random variables.

Markovian model based multiple times scale hierarchical was proposed in [114][134]. In this model, network traffic is an aggregation of hierarchical Markovian ON-OFF process with different time scales. Fig. 3.1 shows one example of hierarchical ON-OFF process, where ON process denotes primary networks in busy state and packet is generated during performing communication. In this state, packet appears on the physical channel, some events at different time scales have to occur such as establishing a session, sending a message to the networks by a transport protocol, then sending the packet to the channel by MAC and physical layer. While OFF process means that primary networks in idle state and no message and packet sending to channel.

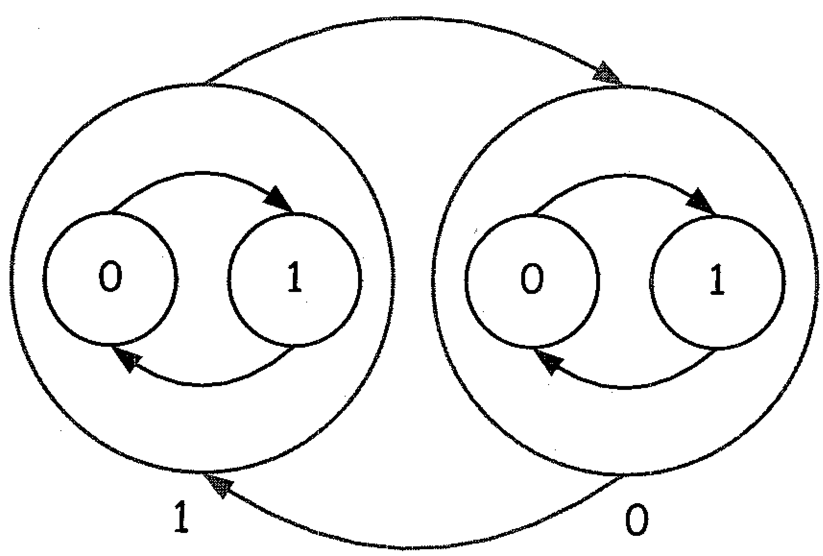

Figure 3.1 Markovian model for primary networks traffic

Shortly said that no primary user activity, such as generating and transmitting message and packet among transceiver during OFF process. The numeric number of

"1" represents ON states which denotes busy channel, while "0" represent OFF state, which denote idle state. These discrete Markov states are the key of POMDP formulation of spectrum opportunity tracking and exploitation that presented in the following section.

3.2.2 Cognitive Radio Networks Model

It was mentioned earlier that PU does not use the entire time to utilize the license spectrum. Spectrum occupancy states vary depending on time and region. Fig.3.2 describes the license networks such as WAP, TV channel, 4G, 3G, and mobile satellite communication which share their unutilized spectrum with SU. The infrastructure based cognitive radio network is considered in that illustration. Secondary user as unlicensed user can access the available license spectrum when it is not used.

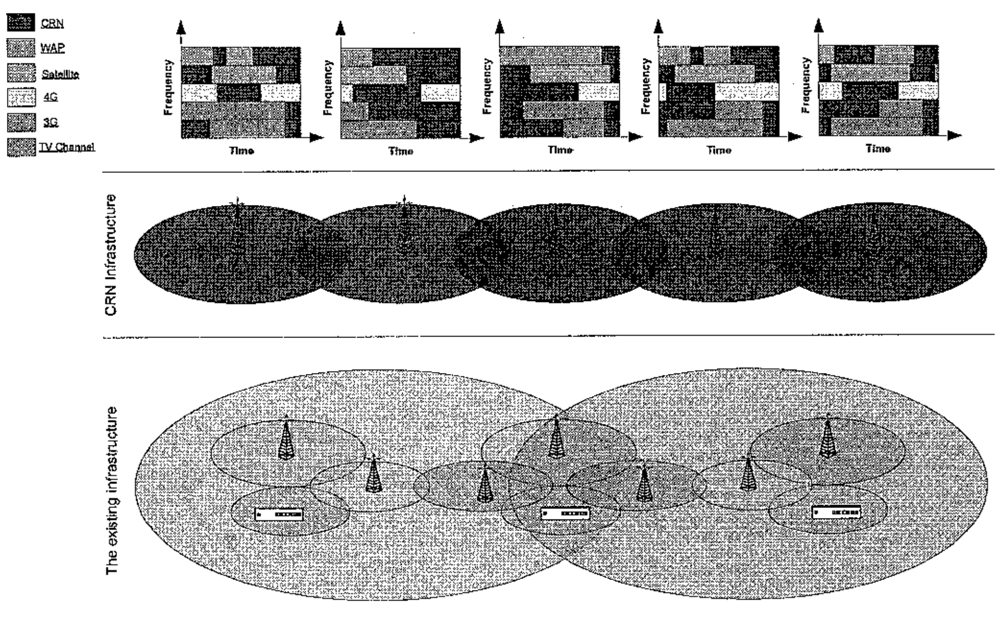

Figure 3.2 The example of spectrum utilization by SU

According to the illustration in that figure, primary channel contains number of spectrums that is licensed to PU. Primary user has an authority to use those channels. However, when channel is not used (i.e. unutilized or unused channel, spectrum holes), SUs is possible to utilize and access by prior observation to avoid interference to PUs activity. In this dissertation research, we consider a group of SUs that perform sensing and monitoring primary spectrum channels that change continuously, depend on the time step (time slot) and switch from occupied to unoccupied and vise versa according to Markov chain. The existing channels are shared among PUs and a large of number SUs.

Before accessing and transmitting data packet over the available channel spectrums, SU periodically monitors and checks them within short interval (sensing interval). Secondary user monitors the license spectrums and convincing that it is in used or not. When channel spectrum is not used, then SU starts to transmit data during a certain time interval (transmission interval). So, shortly we can say that SU have 2 tasks to be performed, sense the spectrum opportunities (sensing task) and transmit data when spectrum is available (transmission task). These tasks are divided into a certain time interval as described in Fig. 3. 3.

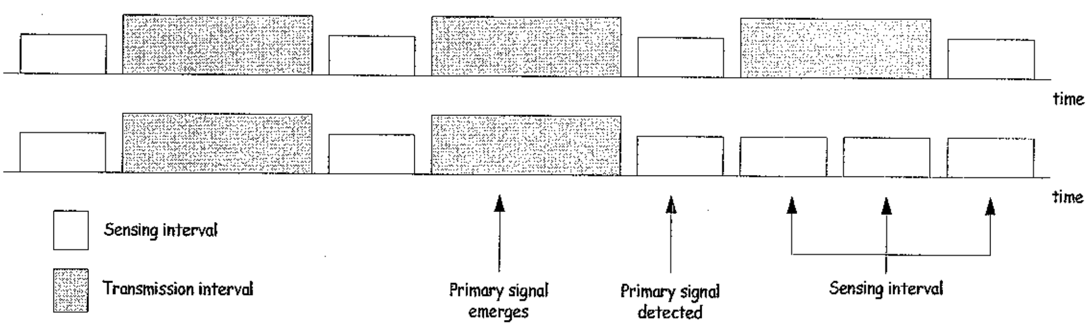

Figure 3.3 Sensing and transmission interval in CR networks

We must consider that SU monitors spectrum continuously until the end of the monitoring interval, which is able to detect primary signal even they are transmitting data packet. When PU returns and will use the spectrum, then SU should vacate the band immediately.

SU is possible to cooperate by sharing local sensing to improve the primary signal detection performance. The results of local spectrum sensing from each SU consist of hypothesis decision or collection of distributed statistic that must be sent for further processing. An example of cooperation procedure by two SUs is illustrated in Fig. 3. 4.

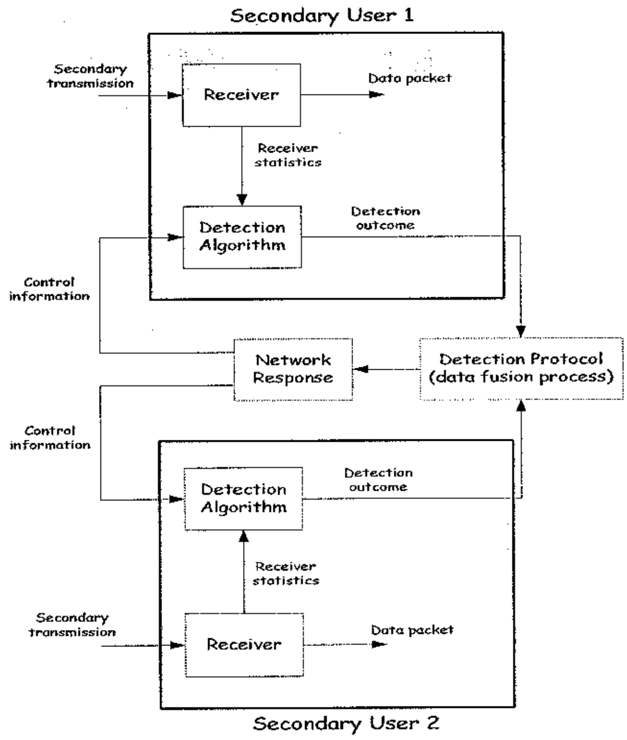

Figure 3.4 An example of cooperation between two SUs

The outcome of the detection algorithm is sent to central coordinator (centralized networks) or other SU (decentralized networks). In centralized networks, central coordinator has a responsibility to decide which channels are available and can be accessed by SU. Then, this available channel information will be sent back to SU. Meanwhile, in decentralized networks, SU decides as to which part of the channel can be accessed independently without forwarding to central coordinator after sharing local spectrum sensing among others.

As a central coordinator, it collects and processes data from multiple SUs and combines them for final decision. However, in decentralized networks, SU has a fusion function similar to central coordinator in centralized networks. They collect the data from other SUs and process further for final decision.

First, we consider that there are number of channels in this study. The state of these channels change independently. Each channel has the bandwidth Bi (I = 1,…,N). The state diagram and a sample path of the state evolution for N = 3 are illustrated in Fig. 3.5. The state of channel $S_n(T) = \{1,0\}$ indicates that channel is busy and idle.

In the CR system, cognitive MAC is divided into slots of equal length T, where slot k refers to the discrete time period [kT, (k+1)T]. The detail structure of the each slot is described in Fig. 3.6. At the beginning of each slot, SUs sense set of the channels (L_1). Based on the sensing outcome, SUs will decide which channel to be accessed (L_2), where $L_2 \leq L_1 \leq N$. At the end of the slot, SU will send the acknowledgement signal that indicates successful transmission. The traffic statistics of the primary network follows a discrete time Markov process with number of states. Furthermore, secondary network is seeking spectrum opportunity in these N channels. Ad hoc network is assumed in which SUs sense and access the spectrum channel independently without exchanging local information.

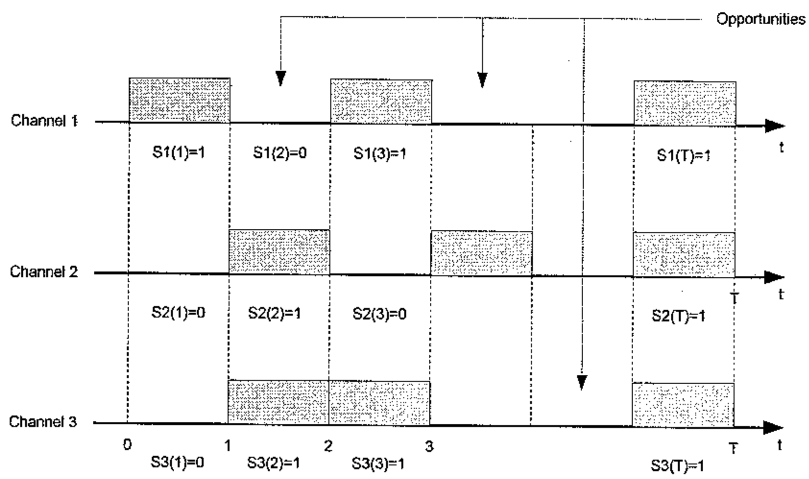

Figure 3.5 Spectrum occupancy for number of channel N = 3 [144]

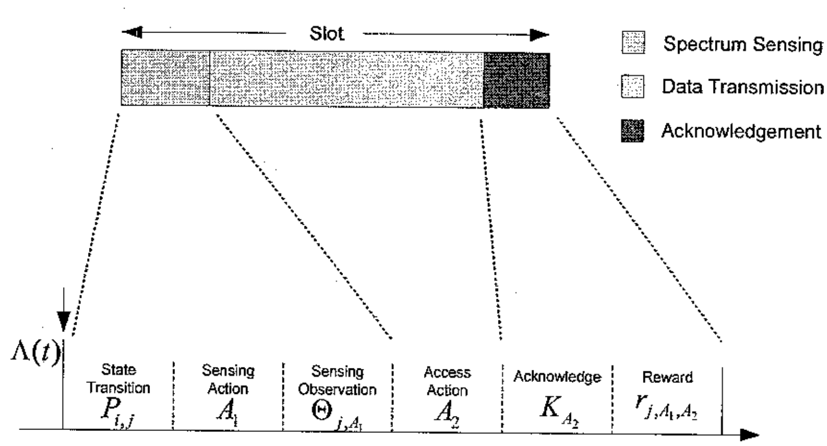

Figure 3. 6 The general slot structure of cognitive MAC [144]

As described in general POMDP model theory and algorithm, OSA model has transition probabilities of the k-th ($1 \leq k \leq L$) level for Markov discrete process for channel N, which is denoted by $\{p_{i,j}{}^{(n,k)}\}i,j = 0,1$. SUs in OSA networks transit from "0" to "1" state or vice versa, or keep staying on "0" and "1". The "0" and "1" denote as idle and busy channel states, respectively.

Then, consider that there is a pair of SU transmitter and receiver trying to find the spectrum opportunities in the number of license channels N. In each communication slot, SU select the existing license channel to sense. When the unoccupied channel spectrum is detected, then SU reconfigures their parameter transmission (i.e. transmission power, type of modulation, etc), and the transmitter starts to send the packet to the receiver through these unoccupied license channels. For successful bit transmission, SU receiver will give an acknowledgment and reward R(t). In the next chapter, we simulate the access protocol for OSA in CR system and studied the optimal sensing policy to maximize the remaining rewards of SU within a period of certain time slot.

3.3 Optimal Sensing Policy

To further study, this work adopts POMDP to model the channel opportunity of network system as discrete time Markov chain with number of channel state and formulate as $M = 2^N$ states, where N is number of channel. The state diagram for N = 2 is described in Fig. 3.7 where $\bar{\alpha_i} = 1 - \alpha_i$ and state (0, 1) indicates the first channel is available and the second channel is busy.

The term of partially observable mean that SU selects set of channels to be sensed and set of channels to be accessed based on sensing outcome. This objective is to maximize the throughput of SUs under the constraint of interference to PU by exploiting the sensing history and the spectrum occupancy statistics.

The design of CR protocol that maximizes the throughput of SU can be formulated as POMDP over finite horizon. It is defined by tuple {S,A,P,Θ,,R}, where S denotes a finite set of states with state i denoted by s_i, A denotes a finite set of actions with action i denoted by a_i, P denotes the transition probabilities $p_{i,j}$ for each action in each state as function of $\{\alpha_i, \beta_i\}_{i=1}^{N}$ which describes the channel availability of PU networks, R denotes the reward structure (r_{j,A_1,A_2}) which is defined as number of transmitted bits in one slot when CR user take an action, and Θ is observation where SUs observe the availability of channel at state j, $\Theta_{j,A_1} \in \{0, 1\}^{|A_1|}$.

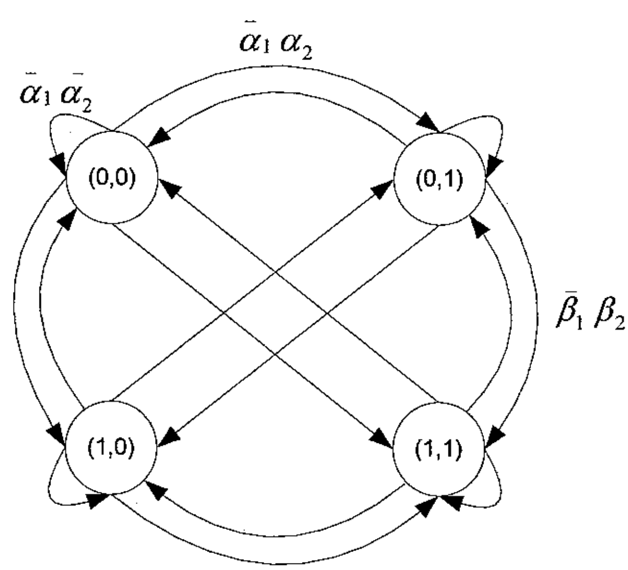

Figure 3.7 State diagram for N = 2 as Markov process model [144]

The reward is proportional to its bandwidth and formulated as follows:

$$r_{j,A_1,A_2}(t) = \sum_{i \in A_2} S_i(t) B_i \tag{3.1}$$

where $S_i(t) \in \{0, 1\}$ is the state of the channel *i* within slot t, where "0" denotes state of the idle channel and SU is possibly to access, while "1" defines a busy channel state and SU is not allowed to access. In the case of imperfect channel sensing, SU can experience detection error due to obstacles, shadowing, hidden node problem, fading, etc. Such errors can are known as false detection or miss-detection and cause collision to PUs or missing to access the available channels.

According to the Fig. 3.7, it has 4 number of states {(0,0), (0,1), (1,0), (1,1)} and number of transition states 2^N x 2^N = 16 states, which described in detail as bellows:

- $\bar{\alpha}_1\bar{\alpha}_2$ both channel (channel 1 and 2) keep on (0,0) state
- $\bar{\alpha}_1\alpha_2$ channel 1 and channel 2 transit from (0,0) to (0,1) state
- $\alpha_1\bar{\alpha}_2$ channel 1 and channel 2 transit from (0,1) to (0,0) state
- $\alpha_1\alpha_2$both channel (channel 1 and 2) keep on (1,1) state
- $\bar{\beta}_1\bar{\beta}_2$ both channel (channel 1 and 2) keep on (0,1) state
- $\bar{\beta}_1\beta_2$ channel 1 and channel 2 transit from (0,1) to (1,1) state
- $\beta_1\bar{\beta}_2$ channel 1 and channel 2 transit from (1,1) to (0,1) state
- $\beta_1\beta_2$ both channel (channel 1 and 2) keep on (1,0) state.
- $\bar{\alpha}_1\bar{\beta}_1$ channel 1 and channel transit from (1,1) to (0,0) state
- $\bar{\alpha}_1\beta_1$ channel 1 and channel 2 transit from (1,1) to (1,0) state
- $\alpha_1\bar{\beta}_1$ channel 1 and channel 2 transit from (1,0) to (1,1) state
- $\alpha_1\beta_1$ channel 1 and channel 2 transit from (0,0) to (1,1) state
- $\bar{\alpha}_1\bar{\beta}_2$ channel 1 and channel 2 to transit from (1,0) to (0,1) state
- $\bar{\alpha}_1\beta_2$ channel 1 and channel 2 to transit from (1,0) to (0,0) state
- $\alpha_1\bar{\beta}_2$ channel 1 and channel 2 to transit from (0,0) to (1,0) state
- $\alpha_1\beta_2$ channel 1 and channel 2 to transit from (0,1) to (1,0) state

In this simulation work, primary network contains number of channel spectrum that is licensed to PU and has an authority to access. However, when channel is unused, SU is allowed to access the channel with prior to sense and observe whether channel is available or not in order to avoid interference to PU activity. We consider group of SU sense and monitor primary channels that change depends on the time step and switch from occupied and unoccupied according to Markov chain. The existed channels are shared among PUs and a large number of SUs.

The illustration of SU is seeking the available channel spectrum by performing sensing is described in Fig. 3.8. Secondary user which is located in the range of PU network attempts to seek the possibility of accessing the primary channel.

The channel state is independently changed according to the time and location. It is not all SUs have an opportunity to access the same channel spectrum. There is a possibility that channel is available for SU, but not for others.

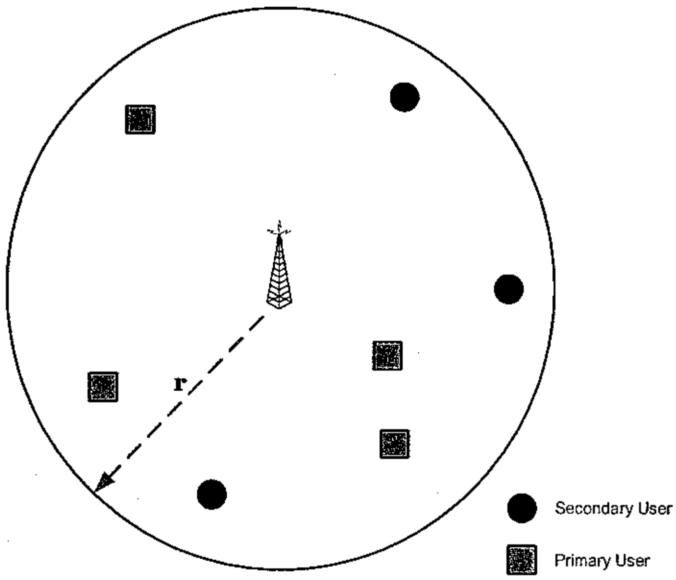

Figure 3.8 Secondary users are seeking for the access possibility

Due to the energy constraint, SU has a limited sensing capability where SU sense and access part of the existing channels. Fig. 3.9 shows the illustration how CR node senses only one channel of two existing one. The activity of PU and SU on channel spectrum is illustrated in Fig. 3.10.

This simulation considers number of channel with different frequency where state of these channels change independently. Each channel has the bandwidth B_i (i=1,...,N). State of the channel is denoted by symbol $S_n(T) = \{0,1\}$ that means an idle and busy channel.

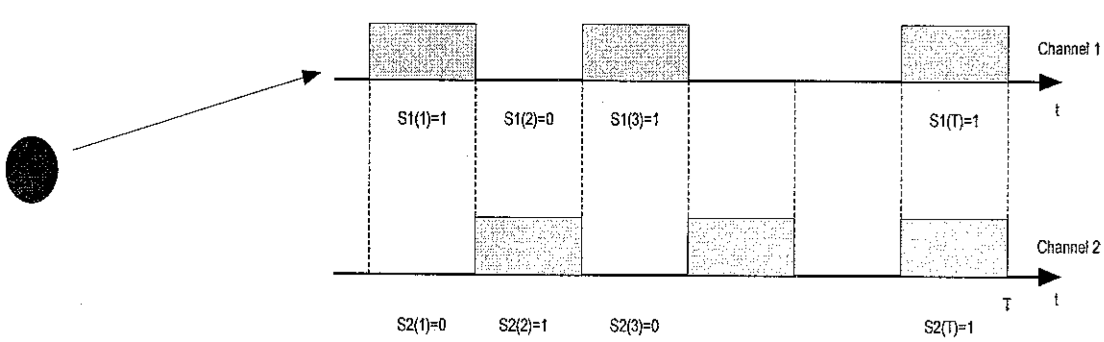

Figure 3.9 SU senses one channel of two existing one

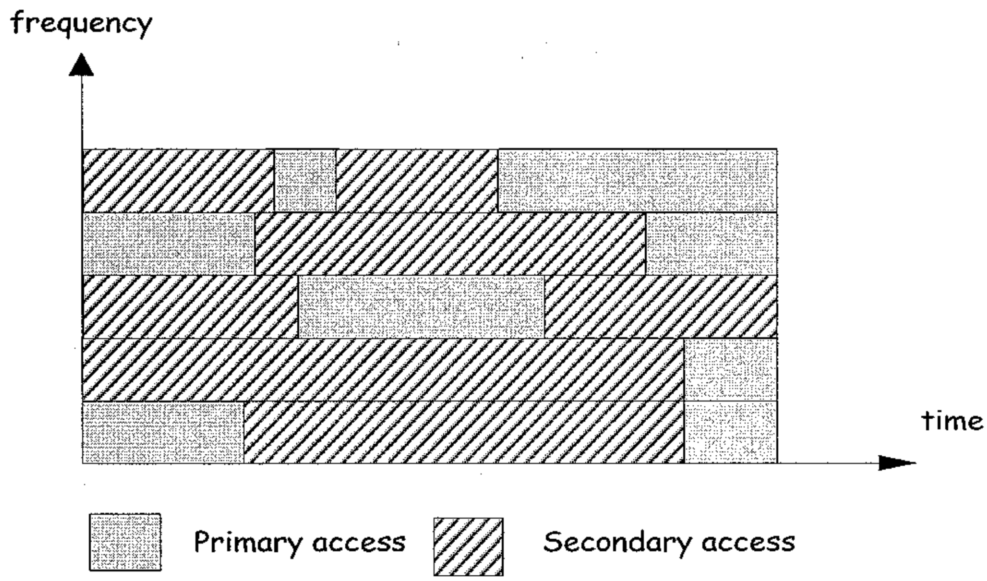

Figure 3.10 Primary and secondary spectrum access

Some of initial parameters are considered to investigate the performance of CR system. The number of channels (N) is sensed by SU with the varied bandwidth (B). Bandwidth B = 1 is used to ease the simulation, and then increase it with higher value. Reward is used as a standard metric to evaluate the performance of CR system. Since reward is defined as a number of successful transmitted bit over T slot, hence reward is also known as throughput (bit/slot).

Number of slot (T) is set into a certain value. Secondary user performs sensing, data transmission, and acknowledgement task during T slot time. The main objective of this work (investigation of CR performance under POMDP framework) is maximizing the remaining reward during T slot time, meaning that the throughput of SU must be improved when number of slot increases. In this simulation, we study the performance of CR system by drawing the plot of throughput performance as a function of slot number.

Transition probability $\{\alpha, \beta\}$ is defined as probability of SU transit from one state to another, or just keep active on the same state. This simulation assumes that the probabilities of transition state are known. However, practically that value is unknown. The notation of α denotes primary channel changes from idle state ("0") to busy state ("1"), while β indicates primary channel keep on the busy state.

In Markov dynamic process for opportunistic spectrum access system, observations are taken after channel access action, or equivalently observation could have been taken before channel access action. Fig.3.11 shows the description of how observation, sensing, and access work for dynamic access in opportunistic spectrum access. Information states are the collection of sensing and observation results and SU accesses the license spectrum channel. Reward and acknowledgement are sent to the SU transmitter for successful bit transmission. The looping system is performed continuously even SU is having transmission. When PU return and will access the channel back, then SU should vacate the channel soon and seeking other vacant bands.

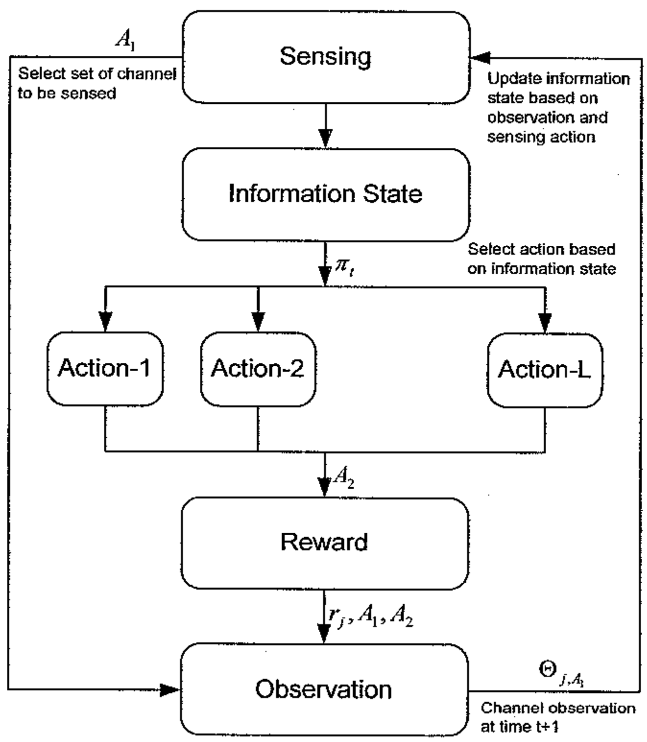

Figure 3.11 OSA under POMDP model [144]

An observation is made after taking one action. Equivalently, observation can also be made before actions. Sensing task is performed continuously even SU transmitter is having transmission amount of data to SU receiver. It is carried on in order to leave and provide the primary channel when PU returns back to use it. The flowchart of this algorithm for dynamic process in CR system is described in Fig. 3.12

Based on observation and sensing outcome performed by SU, information states will be updated continuously to provide the current state of the channel. The obtained information states are taken by SU as a standard to perform whether access the channel when channel spectrum is available or refrain from data transmission when channel is in use by PU.

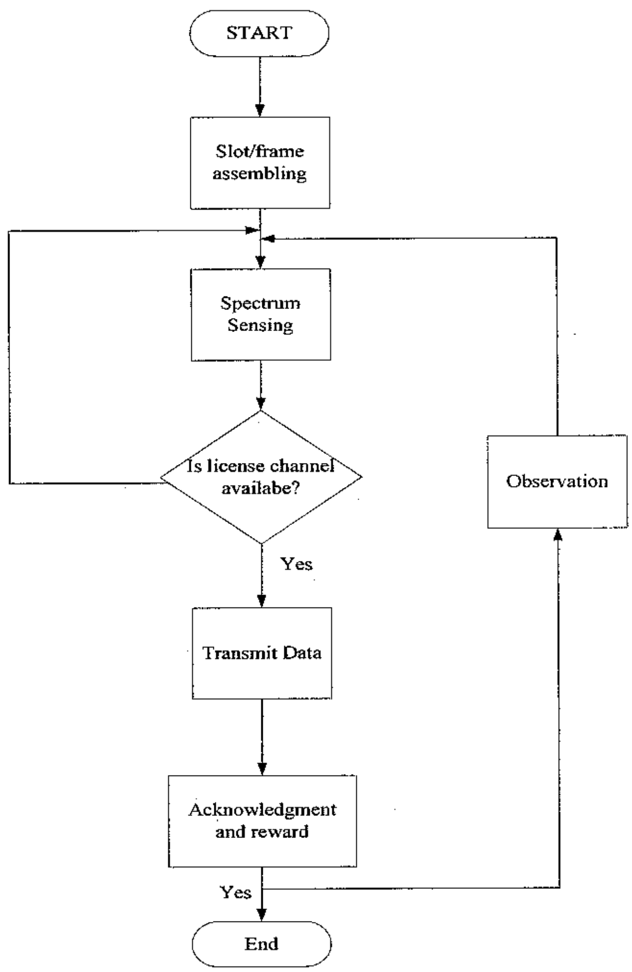

Figure 3.12 Algorithm of dynamic process model for OSA

The obtained information state is known as belief vector, which contains the statistic of primary network and define as the distribution probability of channel states based on the sensing, observation and previous actions. It is used as an aid by SU for final decision. This belief vector is updated after access action and observation as eq. (3.2). Then, after accessing available channel and having transmission, the distribution of statistic probability transform in π' according to eq. (3.3).

The action task performed by SU is required to maximize the expected total reward. It means that the number of transmitted bit within T slot transmission (i.e. throughput, bits/slot) must be maximized. The maximum value function within T slot transmission of SU is given by eq. (3.4), where V_{t+1} denotes the reward function after SU accessing channel.

In perfect channel sensing, the sensing outcome reflects the true channel state. It considers that there is no error when SU perform sensing on primary licensed channel. Hence, the decision of channel access can be directly transmit amount of data packet when the sensed channel is available. Since the error detection is not considered in perfect channel sensing, the constraint of maximum collision allowable in channel access is unrelated. SU concentrate on maximizing the expected total reward within T slots and determine the action, which channel to be sensed and access based on the belief vector.

In POMDP model, the system state is not directly known, however SU can observe to learn the most likely state. The observation yields the current system state. Then, the information state, also known as belief vector $\pi = (\pi_1, \dots, \pi_M)$, aids in determining the most likely state of primary network by storing all previous actions and observations in a summary statistic. The belief vector is probability distribution over state of the channels.

Belief vector π is a sufficient statistic for the optimal policy and behaves as a discrete time continuous state Markov process. The users observe with distribution probability under system channel states. The information state is updated after each action and observation with the application of Bayes' rule as follows:

$$\pi'_j = \frac{\sum_{i=1}^{M} \pi_i p_{i,j} Pr[\Theta_{j,a} = \theta]}{\sum_{i=1}^{M} \sum_{j=1}^{M} \pi_i p_{i,j} Pr[\Theta_{j,a} = \theta]} \qquad (3.2)$$

The resulting information state is vector of probabilities computed using the above formula and the information transformation function is given by

$$\pi' \cong [\pi'_1, \dots, \pi'_M] \cong \tau(\pi | a, \theta) \qquad (3.3)$$

In POMDP model, the policy maps the information states into action and maximizes the expected total reward. There are an infinite number of information states, since it is probability distribution over all states and stores the policy or value function in the form of tables. The maximum value function for all actions is given by the following formula:

$$V_t(\pi) = \max_{a=1,\ldots,N} \left\{ \sum_{i=1}^{M} \pi_i \sum_{j=1}^{M} p_{i,j} \sum_{\theta=0}^{1} Pr[\Theta_{j,a} = \theta](\theta B_a + V_{t+1}(\tau(\pi|a,\theta))) \right\} \quad (3.4)$$

where $V_t(\pi)$ denotes the maximum expected reward that can be accrued in the remaining t decision intervals when the current information vector is π. This formula shows that a selected access action at a certain slot will have an impact to the total reward, it achieves an immediate reward θB_a within one slot and transform the belief vector into $\tau(\pi|a,\theta)$ which determines the future reward $V_{t+1}(\tau(\pi|a,\theta))$. The optimal policy aims to gain the information within the slot for future use.

It is shown in [135] that $V_t(\pi)$ is piecewise linier and convex (PWLC) and can be written simply as

$$V_t(\pi) = \max_k \pi\gamma_k(t) \quad (3.5)$$

For some set of M dimensional column vectors {γk(t)}. The set of γ-vectors represents one of linier pieces coefficient for piecewise linier function. These piecewise linier functions can represent the value functions for each step in the finite horizon POMDP problem. The value function drawn over the information state is shown in Fig. 3.13.

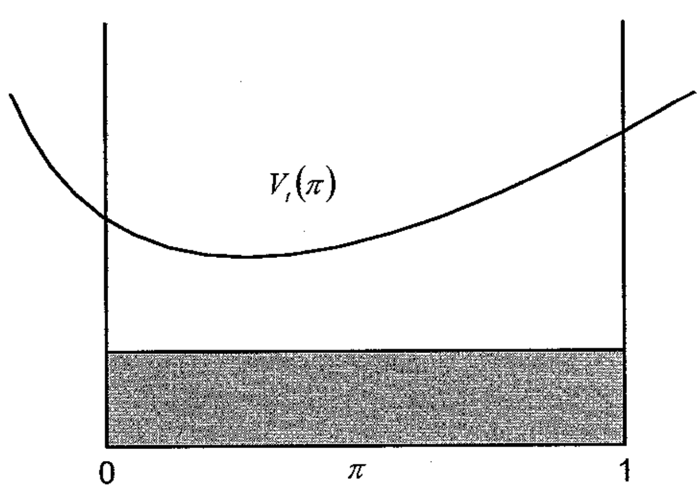

Figure 3.13 Value function drawn over information space [144]

3.4 Sub Optimal Greedy Sensing Policy

Due to the complexity of optimal policy computation when number of slot and channel increase, Q.Zhao *et al* in [128] proposes sub optimal protocol based on a greedy approach. They reduced the dimension of states from exponential to linear i.e. from $M = 2^N$ to N state as well as presented that the performance of greedy approach match and relatively close to optimal strategy. We will clearly discuss the theory of greedy approach and algorithm.

In optimal policy under POMDP framework, the belief vector grows exponentially when the number of channel N increases. It implies more complexity and as a result processing time become longer. A simple illustration is described in the Fig. 3.14. For example, we have number of channel N=5. Then, Markov process states become

$$M = 2^N = 2^5 = 32 \text{ States}$$

Subsequently, the number of transition probability will be 25 x 25 = 1024

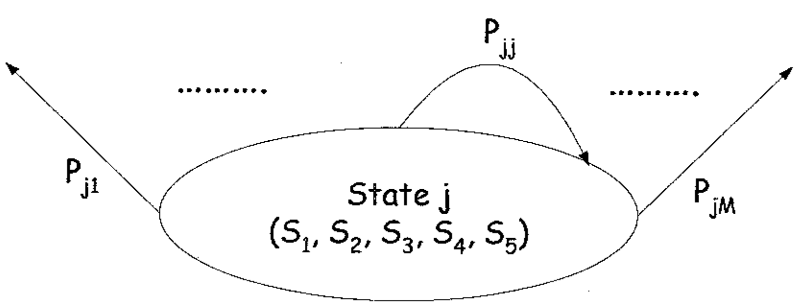

Figure 3.14 Number of states and transition probabilities when N = 5

This is the reason to find the sub-optimal strategy, which can decrease the complexity when number of channel increases, and it was proposed as greedy or myopic policy strategy.

The greedy policy does not consider the impact of the current action on the future reward. It solely considers maximizing the expected immediate reward $E\left[r_{j,A_1,A_2}(t)\right]$. Let us consider

$$\Omega = [\omega_1, \dots, \omega_N] \tag{3.6}$$

where ω_i is the probability of the available channel at the beginning of slot t according to sensing and observation history. Then Ω is a sufficient statistic for the optimal OSA protocol with N independent channels.

Based on the sufficient statistic Ω, the greedy strategy was proposed as a solution to the complexity appears on optimal strategy. It can maximize the expected reward and gain the information within T slot.

See the illustration of Markov channel model in Fig. 3.15, where those channels change independently from state "0" to "1" with the probability α_i and keep on the state "1" with the probability β_i. At the beginning of the slot t before these transition process is $\Omega(t)$.

So, the expected remaining reward when channel a is selected will be

$$\left[r_{j,A_1,A_2}(t)\right] = (\omega_a(t)\beta_a + (1 - \omega_a(t))\alpha_a)B_a \tag{3.7}$$

where $(\omega_a(t)\beta_a + (1 - \omega_a(t))\alpha_a)B_a$ equal to $S_n(t)$ in optimal policy and defined as probability of available channel in slot t.

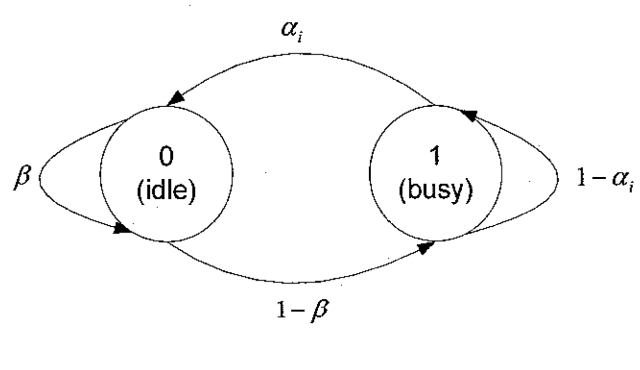

Figure 3.15 Markov channel model [144]

The greedy action $a^*(t)$ in slot t within current belief vector $\pi(t)$ which maximizes the expected immediate reward is given by

$$a_*(t) = \underset{a=1,\ldots,N}{\operatorname{argmax}}(\omega_a(t)\beta_a + (1 - \omega_a(t))\alpha_a)B_a \tag{3.8}$$

The belief vector of greedy policy (Ω) should be updated based on the spectrum action a*(t) and observation Θa*(t) with the following calculation:

$$\Omega(t+1) = [\omega_1(t+1), \dots, \omega_N(t+1) \cong \tau(\Omega(t)|a_*(t), \Theta_{a*}(t))] \tag{3.9}$$

$$\omega_i(t+1) = \begin{cases} 1, & if\ a_*(t) = i, \Theta_{a*}(t) = 1 \\ 0, & if\ a_*(t) = i, \Theta_{a*}(t) = 0 \\ \omega_i(t)\beta_i + (1-\omega_i(t))\alpha_{i,} & if\ a_*(t) \neq i \end{cases} \tag{3.10}$$

When the channel is not sensed (switch into sleep mode) since there is no data packet to be transmitted, the probability of available channel will be updated by following the Markov chain rule. Subsequently, after the existing license channel was sensed, then the state of the channel becomes the sensing outcome. The entire channel transitions and changes are recorded into belief vector.

Then, the recursive equation to maximize the expected reward based on the greedy policy is formulated as follows:

$$W_t(\Omega) = (\omega_{a*}\beta_{a*} + (1-\omega_{a*})\alpha_{a*})B_{a*} + \sum_{\theta=0}^{1} Pr[\Theta_{a*} = \theta|\Omega, a_*]W_{t+1}(\tau(\Omega|a_*, \theta))$$

$$\begin{aligned} &= (\omega_{a*}\beta_{a*} + (1-\omega_{a*})\alpha_{a*})B_{a*} \\ &\quad + [\omega_{a*}(1-\beta_{a*}) + (1-\omega_{a*})(1-\alpha_{a*})]W_{t+1}(\tau(\Omega|a_*, 0)) \\ &\quad + [\omega_{a*}\beta_{a*} + (1-\omega_{a*})\alpha_{a*}]W_{t+1}(\tau(\Omega|a_*, 1)) \end{aligned} \tag{3.11}$$

where $W_t(\Omega)$ denotes the expected remaining reward starting from slot t achieved by greedy approach, $\tau(\Omega|a_*, \theta)$ denotes the updated information on channel availability given the observation θ under action a and $\omega_{a*}\beta_{a*} + (1-\omega_{a*})\alpha_{a*}$ denotes the probability of availability for channel a in slot t.

3.5 Imperfect Spectrum Sensing

The formulation above does not take the sensing errors into account. The perfect channel sensing of primary user detection was assumed and probability of false detection, probability of miss-detection, and collision threshold, which define maximum allowable collision to PU were ignored. However, in real condition, we cannot ignore these sensing errors. SU experiences fading, shadowing, and noise uncertainties that will generate error in PU signal detection.

In case where sensing errors cannot be ignored, the design of spectrum sensor has an impact to the performance of OSA networks. It will generate the interference to the primary network as well. So that we need to design the optimal sensor for channel sensing and access strategy in order to obtain the optimal spectrum utilization by considering probability of false alarm, probability of miss-detection, and probability of detection in receiver operating curve (ROC).

As we know that fading, noise, and any obstacles cannot be ignored in wireless communication link. These imperfect conditions can cause some errors in PU signal detection and spectrum sensing. False detection senses idle states as a busy channel and CR users refrain from data transmission. On the other hand, miss-identification senses busy states as an idle channel and cause CR users collide to primary user transmission.

Spectrum sensor design determines binary hypotheses, which are H_0 and H_1. As mentioned earlier if SU detector makes mistakes in detection H_0 for H_1, then SU in false detection. The consequence is SU should refrain from data transmission. On the other hand, if SU detects H_1 for H_0, then collision occurred between SU and PU. An example of the ROC curve is described in Fig. 3.16 with different sample of measurement.

Suppose that number of channel is sensed and SU perform binary hypothesis as follows:

$H_0=S_n(t)=0$ (idle) (3.12)

$H_1=S_n(t)=1$ (busy) (3.13)

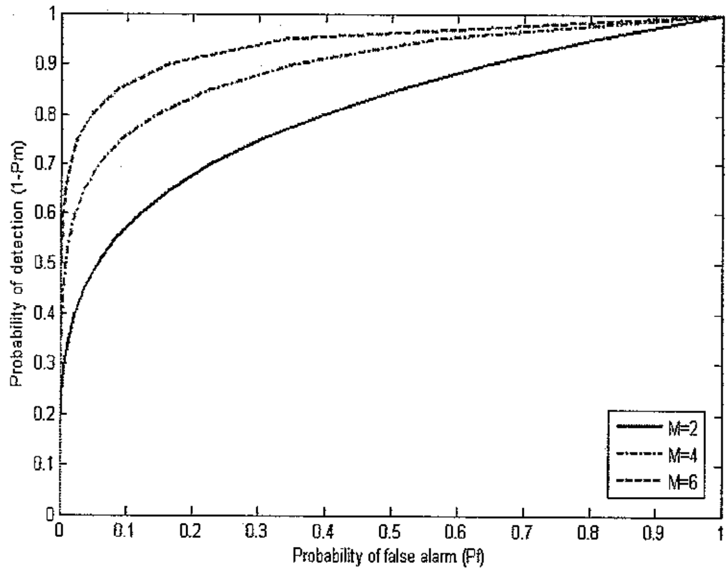

Figure 3.16 ROC curve for signal detector

Let $\Theta_n(t) \in \{0 \text{ (idle)}, 1 \text{ (busy)}\}$ denote the sensing outcome of binary hypothesis. The performance of spectrum sensing is characterized by probability of false alarm (P_F) $\varepsilon_n(t)$, and probability of miss-detection (P_M) $\delta_n(t)$. The design objective is obtaining the optimal policy for spectrum sensing and access strategy by considering the operating point of ROC as formulated bellows

$$\{\pi * \delta *\} = arg \max E_\pi \left[\sum_{t=1}^{T} r_j(t), A_1(t), A_2(t) | \Lambda(1) \right], \quad P_c \leq \zeta \tag{3.14}$$

The channel a_* selected by greedy approach is thus given by

$$a_*(t) = arg \max_{a=1,\dots,N} \left(\omega_a(t)\beta_a + \left(1 - \omega_a(t)\right)\alpha_a \right)(1 - \varepsilon) B_a \tag{3.15}$$

The decision (a_*) and the observation (Θ_{a*}, K_{a*}) will be gained by SU. $K_{a*} \in \{0,1\}$ is sent at the end of the slot, which denotes an acknowledgement for successful bit transmission. Furthermore, SU transmitter and receiver should have the same sensing outcome by updating their belief vector $\Omega(t+1)$. It will make sure that both transmitter and receiver with the same channel in the next slot as the formulation bellows:

$$a_*(t) = arg \max_{a=1,\dots,N} E\,[U_a|\Omega] = arg \max_{a=1,\dots,N} \{B_a Pr[S_a = 1, \Theta = 1|\Omega]\}$$

$$a_*(t) = arg \max_{a=1,\dots,N} \big(\omega_a(t)\beta_a + \big(1-\omega_a(t)\big)\alpha_a\big)(1-\varepsilon)B_a \tag{3.16}$$

Thus, the belief vector becomes

$$\Omega(t+1) \triangleq \tau(\Omega(t)|a_*, K_{a*}) = [\omega_1(t+1), \dots, \omega_N(t+1)] \tag{3.17}$$

$$\omega_i(t+1) \triangleq Pr[S_i(t) = 1|\Omega(t), a_*, K_{a*}] \tag{3.18}$$

$$\omega_i(t+1) = \begin{cases} \dfrac{\varepsilon(\omega_{a*}\beta_{a*} + (1-\omega_{a*})\alpha_{a*})}{\varepsilon(\omega_{a*}\beta_{a*} + (1-\omega_{a*})\alpha_{a*}) + (\omega_{a*}(1-\beta_{a*}) + (1-\omega_{a*})(1-\alpha_{a*}))}, & if\ a_*(t) = i,\ \Theta_{a*}(\\ 1, & if\ a_*(t) = i,\ \Theta_{a*}(\\ \omega_i(t)\beta_i + \big(1-\omega_i(t)\big)\alpha_i, & if\ a_*(t) \neq \end{cases} \tag{3.19}$$

The formulation above comes from the calculation as bellows

$$Pr[S_{a*}(t) = 1|\Omega(t), K_{a*} = 0] = \frac{Pr[S_{a*}(t) = 1, \Theta_{a*} = 0|\Omega(t)] + Pr[S_{a*}(t) = 1, \Theta_{a*} = 1, K_{a*} = 0|\Omega(t)]}{Pr[K_{a*} = 0|\Omega(t)]}$$

$$= \frac{Pr[\Theta_{a*} = 0|S_{a*}(t) = 1]Pr[S_{a*}(t) = 1|\Omega(t)]}{Pr[K_{a*} = 0|S_{a*}(t) = 1]Pr\left[S_{a*}(t) = 1|\Omega(t) + Pr[K_{a*} = 0|S_{a*}(t) = 0]Pr[S_{a*}(t) = 0|\Omega_{(t)}]\right]} \tag{3.20}$$

$$= \frac{Pr[\Theta_{a*} = 0|S_{a*}(t) = 1]Pr[S_{a*}(t) = 1|\Omega(t)]}{Pr[\Phi_{a*} = 0|S_{a*}(t) = 1]Pr\left[S_{a*}(t) = 1|\Omega(t) + Pr[S_{a*}(t) = 0|\Omega_{(t)}]\right]} \tag{3.21}$$

Equation (3.20) is resulted when there is no acknowledgment received over available channels, while formula (3.21) is used if there is no acknowledgement received over unavailable channels.

The following section will discuss implementation study of POMDP framework into opportunistic spectrum access system including simulation and results. The discussions covers study of optimal and sub optimal Greedy sensing strategy, how this framework implemented into perfect and imperfect channel propagation as well as selection of sensor operating point for sensing in PHY layer by considering access decision in MAC layer. Finally we investigate this framework into collaboration sensing where each SU who has a limited sensing capability exchange their sensing results in order to increase PU signal detection and improve the throughput performance.

3.6 Cross Layer Design Principle in Cognitive Radio System

Separation principle was presented in [129]. They formulated PHY-MAC design of OSA as a constrained POMDP. It generally requires policies to achieve optimality by selecting spectrum sensor point and access strategy to maximize the instantaneous throughput under a collision constraint and then decide access strategy to maximized overall throughput. This chapter discusses simulation on how sensing error (i.e probability of false detection and probability of miss-detection), number of measurement sample (L), ROC curve, and SNR have an impact to the optimal design of spectrum sensor point and throughput performance.

In CR system, spectrum sensing determines which channel must be sensed while spectrum access decides which channel SU can access based on the sensing outcome under imperfect propagation channel. The design requirement is maximizing the throughput performance while maintaining the sensing time as quickly as possible, under the constraint of collision to PU below the threshold. The optimal policy for OSA in CR system formulates the reward as equation (3.18). This equation determines immediate reward when select the sensing operating point (π_δ), spectrum sensing (π_s) and access (π_c) policies. Meanwhile, the probability of collision can be defined as follows:

$$P_n(t) \triangleq Pr\{\phi_n(t) = 1 | S_n(t) = 0\} \leq \zeta \tag{3.22}$$

This equation means that probability of the accessed channel on busy states should be below the collision allowable by PU ($\zeta = collision\ threshold$).

Spectrum sensing implies to the throughput performance in CR system. The purpose of spectrum sensing is finding the available channel for immediate access and to gain statistical information on the spectrum opportunities for better available channel tracking. These two purposes must be balanced in order to obtain the throughput performance while maintaining the fidelity of sensing outcome.

3.6.1 Spectrum Sensing and Throughput Performance

According to the general slot structure of cognitive MAC, spectrum sensing is the first task of cognitive cycle in CR system. It has a responsibility to check the availability of primary channel whether the sensed channels are possible to access or not by SU. Secondary user immediately accesses the unused spectrum when it is available by prior adapting its parameter such as transmission power, type of modulation, etc. The features of CR system can be defined as follows:

- *Frequency agility*; CR system has a capability to change its frequency operation to optimise the use.
- *Dynamic frequency selection*; SU has a capability to sense an available spectrum from nearby transmitter
- *Adaptive modulation*; SU access an idle primary channel with prior adapting of its modulation
- *Transmit Power Control (TPC)*; the transmission power of SU is adapted to full power limit when necessary on the one hand and to lower level on the other hand to allow greater sharing and reuse of spectrum.

Although spectrum sensing is performed as quickly as possible, however it is required to concern the fidelity of sensing outcome as well. Fast sensing lead to the throughput improvement, unfortunately it has a possibility to achieve less fidelity of sensing outcome. Longer sensing time to the existing channels can increase the fidelity of sensing outcome. However it degrades the throughput performance. Hence, the fundamental design related to sensing and throughput performance is too crucial. The design of optimal sensor operating point by considering the impact of the throughput performance of SU must be addressed.

Fig. 3.6 illustrates the slot structure in cognitive MAC. At the beginning of slot, SU performs sensing action during a certain period of time. The sensed channel should be less and equal than number of channel, $L_1 \leq N$, where L_1 denotes number of sensed channel and N is number of channel. SU immediately access the channel when it is unoccupied by PU. Number of accessed channels (L_2) is less and equal than L_1. It is simply denoted that $L_2 \leq L_1 \leq N$. In the end of slot, SU receiver acknowledge SU transmitter for successful bit transmission.

We adopt POMDP to further investigate the relation function between spectrum sensing and access in term of throughput. Firstly, SU select subset of the channel to sense and access the available channel. According to Markov discrete process, SU observe the channel states, which are represented by "0" and "1". For example, the state of channel spectrum ($S_1, S_2, S_3, \ldots, S_N$) are denoted by (1, 0, 0,..., 1). Fig. 3.17 is the illustration of license channel spectrum where CR user sense and access part of the existing channels.

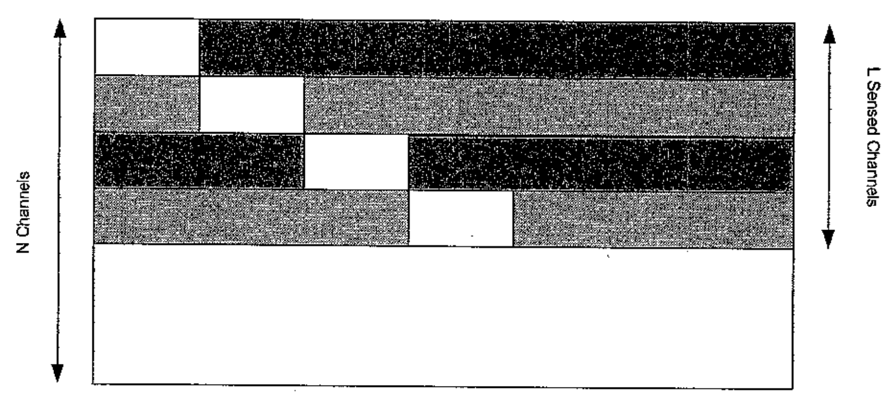

Figure 3.17 Illustration of sensed channel

3.6.2 *Characteristic of Receiver Operating Curve (ROC)*

The characteristic of ROC curve can be used to design how to achieve an optimal throughput performance through spectrum sensing. The receiver-operating curve

(ROC) between probability of false detection (ε) and probability of miss-detection (δ) has an impact to the optimal access strategy. Selection of sensor operating point in ROC determines how SU can achieve the optimality of throughput performance. False detection denotes the sensed channel as a busy state, hence SU refraining from data transmission. Unfortunately, the actual channel condition is in idle state. In this case, SU wastes the opportunities of channel access. Furthermore, miss-detection denotes busy state as an idle state; hence it collides to PU when SU access the channel and drop the throughput performance due to the frequent collision. Sensor operating point has a responsibility to identify the opportunities of accessible channels through detecting the presence of primary signal.

The spectrum sensor performance is characterized by probability of false detection $\varepsilon_n(t)$ and probability of miss detection $\delta_n(t)$ where optimal detection probability can be achieved by Newman-Pearson (NP) detector or Bayesian detector. Fig. 3.18 is illustration of the best ROC characteristic achieved by NP detector. All possible operating points of the spectrum sensor can be denoted by

$$\{(\varepsilon,\delta): 0 \leq \varepsilon \leq 1-\delta \leq P_{Dmax}(\varepsilon)\} \tag{3.23}$$

where P_{Dmax} is the best ROC line. The other sensor operating points $(\varepsilon_n, \delta_n)$ may lie below the best curve line of ROC. It is located on line that connects two boundary points, $(\varepsilon_{n1}, \delta_{n1})$ and $(\varepsilon_{n2}, \delta_{n2})$.

SU is required to select the license channel (i.e. channel a) to sense in each slot, a possible sensor operating point $(\varepsilon_a, \delta_a)$, and transmission probabilities $(f_a(0), f_a(1))$, where $f_a(\theta) \triangleq Pr\{\phi_a = 1|\Theta = \theta\} = [0,1]$ is defined as the probability of channel access with given sensing outcome $\Theta = \theta \in \{0, 1\}$. The notation of $f_a(0)$ is probability of SU access the channel on a busy state, while $f_a(1)$ defines the probability of channel access on idle state.

Spectrum sensing is performed by SU in physical layer by taking number L of channel measurement $Y_n \triangleq [Y_{1,\dots,}Y_L]$ from the chosen channel and performs binary hypothesis as presented eq. (4.1) and (4. 2). Then, detector optimal under Newman and Pearson (NP) criteria is determined by eq. (4.3), probability of miss-detection

(P_M) and probability of false alarm (P_F) are incomplete gamma function and given by eq. (4.4) and (4.5).

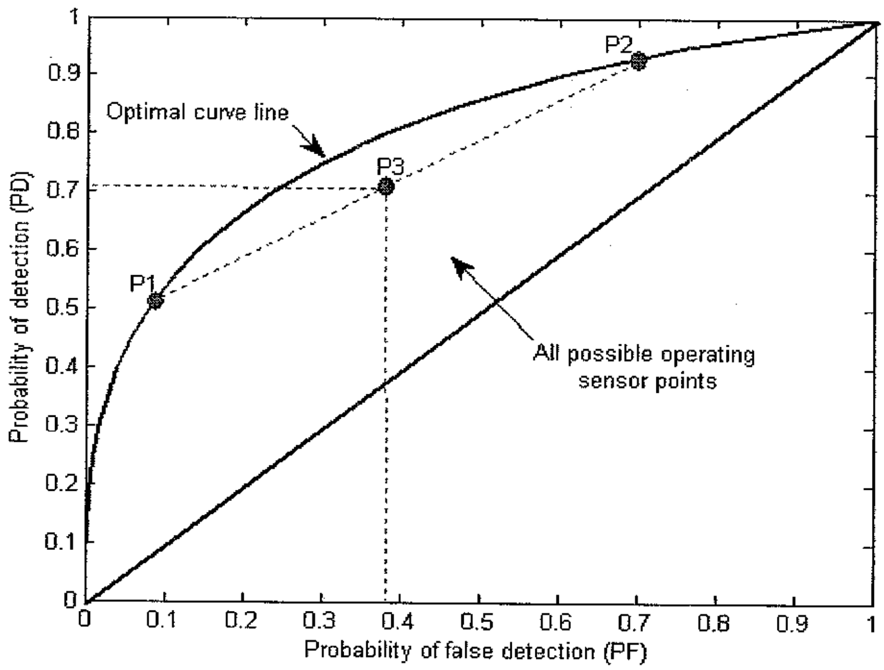

Figure 3.18 ROC with feasible sensor operating points, SNR = 1dB, L = 5

3.6.3 Fundamental Design of Sensor Operating Point

The design requirement for sensing and throughput performance is maximizing the number of transmitted bits during T slot while maintaining sensing time period low under the collision constraint. Sensing time relates to number of measurement sample (L). Longer sensing time can achieve high number of measurement sample and lead to high fidelity of sensing outcome, but consequently the throughput performance becomes low. On the other hand, short sensing time lead to low fidelity of sensing outcome but it implies to improve the throughput performance.

Probability of collision is defined as how frequently SU collides to PU. To obtain an optimal performance, number of collision is limited below the threshold value (ζ). Collision threshold is defined as maximum collision allowable by primary network. The probability of collision is determined by sensor operating point and transmission probabilities. It is calculated by the following formula:

$$P_a(t) \triangleq Pr\{\phi_a(t) = 1 | S_a(t) = 0\}$$

$$= \sum_{\theta=0}^{1} Pr\{\Theta_a = \theta | S_a = 0\} Pr\{\phi_a = 1 | \Theta_a = \theta, S_a = 0\}$$

$$= (1 - \delta_a) f_a(0) + \delta_a f_a(1) \leq \zeta \qquad (3.24)$$

The probability of collision should be maintained below the threshold value; otherwise it can result to the excessive collision. Sensor operating point $(\varepsilon_a, \delta_a)$ and transmission probabilities $(f_a(0), f_a(1))$ have a strong impact to the probability of collision. Thus, in the design procedure, it is required to select the sensor operating point of ROC curve and the access policy to maximize the number of transmitted bit under collision constraint. For example, the selected channel a, an optimal sensor operating point $(\varepsilon_a, \delta_a)$ and transmission probabilities $(f_a(0), f_a(1))$ under the collision constraint are given by

$$r_{j,A_1,A_2}(t) = \underset{\pi_\delta, \pi_s, \pi_c}{argmax} \sum_{i \in A_2} S_i(t) B_i$$

$$= \max_{(\varepsilon_a, \delta_a); (f_a(0), f_a(1))} \varepsilon_a f_a(0) + (1 - \varepsilon_a) f_a(1)$$

$$P_a(t) = (1 - \delta_a) f_a(0) + \delta_a f_a(1) \leq \zeta \qquad (3.25)$$

where $f_a(0)$ is defined as transmission probability on busy channel, while $f_a(1)$ is transmission probability on idle channel.

Fig. 3.15 shows the ROC for selection of sensor operating points. It must convince that the selection of sensor operating point is lied down in the line of the curve.

Optimal selection is derived when sensor operating point located on the best line of ROC curve, where probability of miss detection equals to collision threshold (maximum collision allowed by PU), and denoted that $\delta = \zeta$. The other sensor operating points that lied out of this optimal location are known as aggressive $(\delta < \zeta)$ and conservative region $(\delta > \zeta)$. For selected channel a with a certain sensor operating point $(\varepsilon_a, \delta_a)$, the optimal transmission probabilities are given as follows:

$$
(f_a(0), f_a(1)) = \begin{cases} \left(\dfrac{\zeta - \delta_a}{1 - \delta_a}, 1\right), & \delta_a < \zeta \\ (0,1), & \delta_a = \zeta \\ \left(0, \dfrac{\zeta}{\delta_a}\right), & \delta_a > \zeta \end{cases} \tag{3.26}
$$

where the conditions of $\delta_a < \zeta$ and $\delta_a > \zeta$ are aggressive and conservative access policy, respectively. It is more clearly shown on Fig. 3.19 which describes conservative and aggressive region.

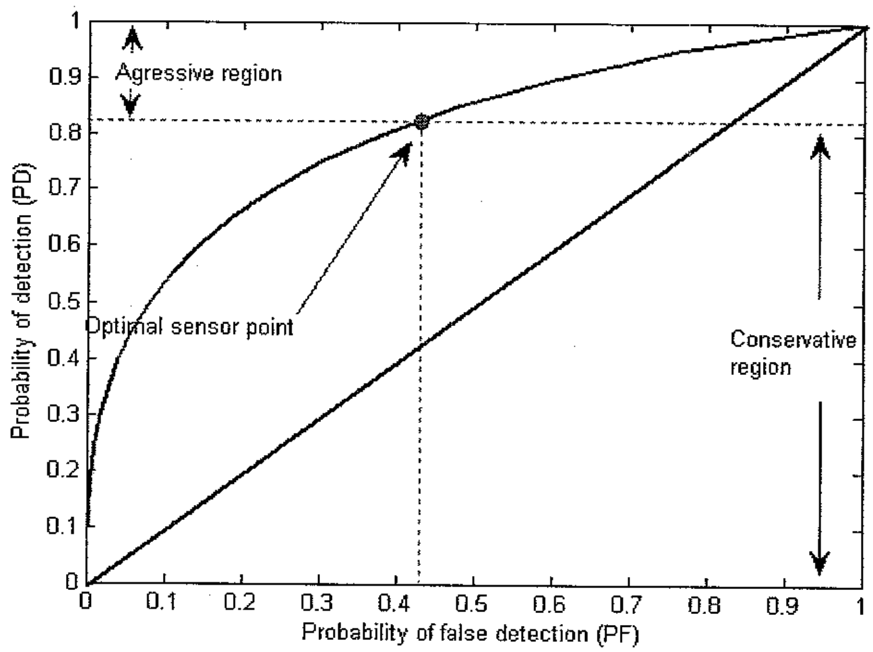

Figure 3.19 Selection of sensor points on ROC

The proof of condition above can be stated as follows. When simulation sets probability of miss detection $\delta_a = 1$, the value of false detection probability should be $\varepsilon_a = 0$. The function of $\varepsilon_a f_a(0) + (1 - \varepsilon_a) f_a(1)$ can be maximized when $f_a(1) = 1$. If $\varepsilon_a = (0,1)$, the collision constraint can be written as below:

$$
0 \le f_a(0) \le \frac{\zeta - \delta_a f_a(1)}{1 - \delta_a} \tag{3.27}
$$

by substituting the equation (5 - 4) into (5 – 6), we derive the formulation as below:

$$
\varepsilon_a f_a(0) + (1 - \varepsilon_a) f_a(1) \le f_a(1) \left[1 - \frac{\varepsilon_a}{1 - \delta_a}\right] + \frac{\varepsilon_a \zeta}{1 - \delta_a} \tag{3.28}
$$

Hence, to maximize the function of $\varepsilon_a f_a(0) + (1 - \varepsilon_a) f_a(1)$, we must select the largest $f_a(1)$, such as $f_a(0) = \frac{\zeta - \delta_a f_a(1)}{1-\delta_a} \geq 0$. Therefore, when $\delta_a < \zeta$, $f_a(1) = 1$, and $f_a(0) = \frac{\zeta-\delta_a}{1-\delta_a}$. Subsequently, when $\delta_a > \zeta$, $f_a(1) = \frac{\zeta}{\delta_a}$ and $f_a(0) = 0$.

Suppose that the selected channel and transmission probabilities have the following criteria:

- If $f_a(0) \leq f_a(1)$ and $f_a(0) \leq \zeta$, then the optimal spectrum sensor is given by detector should be $(\varepsilon_a, \delta_a) = arg \min \varepsilon_a$ under the constraint $\delta_a \leq \frac{\zeta - f_a(0)}{f_a(1) - f_a(0)}$
- If $f_a(0) \geq f_a(1)$ and $f_a(0) \geq \zeta$, the optimal spectrum sensor is given by detector should be $(\varepsilon_a, \delta_a) = arg \max \varepsilon_a$ under the constraint $\frac{\zeta - f_a(1)}{f_a(0) - f_a(1)}$

Those condition and constrain is implemented in order to obtain the optimal sensing and access strategy that can lead to optimal throughput performance.

Furthermore, in aggressive region ($\delta_a < \zeta$) case, it is the condition where SU senses an idle state, as a busy state (probability of false detection) is high, so that SU wastes the opportunity and misses data transmission. In this region, SU adopts aggressive access policy. It means that SU always transmit when the sensed channel is idle state, and transmit with the probability $\frac{\zeta-\delta_a}{1-\delta_a} > 0$ even the sensed channel is in busy state.

While in conservative region ($\delta_a > \zeta$) case, the condition of SU senses a busy state as an idle state (probability of miss detection) is high, so that SU collides to PU. In this region, SU adopts conservative access policy to convince that collision probability is below the threshold value (ζ). If the sensed channel is in idle state, SU transmits with the probability $\frac{\zeta}{\delta_a} < 1$, and when the sensed channel is in busy state, SU must refrain from data transmission. In condition of $\delta_a = \zeta$, SU trust on sensing outcome, which means SU accesses the primary channel if it is available, and refrain from data transmission when it is on busy states.

Regarding to the condition where SU trust the sensing outcome ($\delta_a = \zeta$), false alarm can waste the access opportunities, while miss detection may lead to the collision with primary users. To optimise the throughput performance while minimize the interference to the primary network, it must consider the impact of spectrum sensor in physical layer to MAC layer in terms of throughput and collision probability.

According to the mentioned theory, for some selected channels within one slot, the optimal sensor adopt the condition where SU trusts to the sensing outcome ($\delta_a = \zeta$), in order to obtain the optimal throughput performance. It means that SU transmit when the sensed channel is available and refraining from data transmission when the sensed channel is busy. Suppose that the optimal transmission probabilities $f_a(0)$ and $f_a(1)$ substitute to the equation (5.7), we derived that:

$$\varepsilon_a f_a(0) + (1-\varepsilon_a) f_a(1) = \begin{cases} 1 - \dfrac{\varepsilon_a}{1-\delta_a}(1-\zeta) & for\ \delta_a \leq \zeta \\ \dfrac{1-\varepsilon_a}{\delta_a}\zeta & for\ \delta_a \geq \zeta \end{cases} \tag{3.29}$$

Both $\frac{\varepsilon_a}{1-\delta_a}$ and $\frac{1-\varepsilon_a}{\delta_a}$ can increase when the value of ε_a increases, and can decrease when it decreases. Regarding to the function of $\varepsilon_a f_a(0) + (1-\varepsilon_a) f_a(1)$, it can increase when the value of δ_a increases for $\delta_a \leq \zeta$ and decreases when $\delta_a \geq \zeta$. It can reach the maximum value when $\delta_a = \zeta$ and the condition of transmission probabilities $\{f_a(0), f_a(1)\} = (0,1)$.

3.7 Decentralized Multiuser Cooperative Spectrum Sensing

This section discusses the proposed decentralized CSS model under POMDP framework. In this model, SU senses and accesses part of license channel spectrum and exchange their sensing result and observation among others. Collaboration of SU aims to improve detection probability and decrease time requirement for sensing that implies to improve the throughput performance. It is also used to mitigate hidden and exposed terminal as well as noise uncertainties that appear in primary signal detection. Number of SUs is considered for sensing and each SU competes to access the available channels. Sensing result is exchanged amongst them and SU independently decides which channel can be accessed at one time based on sensing outcome and observation.

It is different from the previous works, where CSS assumes full band sensing capability and focused on the series of sensing capability (i.e. probability of detection, probability of false alarm, and probability of miss-detection). This section will further investigate cooperative spectrum sensing where SU has limited sensing capability under POMDP. Secondary user accesses license channels with higher probability of idle states. The information of channel state is achieved from spectrum sensing (belief vector) and observation. We also introduce binomial distribution theory to derive probability of miss-detection (local sensing and CSS model). To validate the proposed model, we make some comparisons with single user sensing, full band random sensing strategy where SU access license channels randomly, and centralized CSS where central coordinator is used to coordinate spectrum access. It will be presented by detail in the following section.

Two types of CSS are considered in this investigation, centralized (with central coordinator) and decentralized (without central coordinator, and known as ad hoc network) cognitive radio. In centralized CSS, SU senses the license channel spectrum and forward their sensing results to central coordinator. Central coordinator has a responsibility to decide which available channel SU has possibility to access. It is performed by sending back the final decision to SU. Unlike centralized CSS model, in decentralized CSS model, SU independently senses and accesses license channel. Secondary user has responsibilities to sense spectrum, exchanges local sensing results, and decides which channel can be accessed. CSS model with limited sensing capability under POMDP will be discussed further in the following section. Throughput is used as a metric to evaluate SU performance.

3.7.1 Multiuser CSS Model

The goal of dynamic spectrum access is to increase spectrum utilization within 3 dimensions such as time, frequency, and space. Spectrum sensor design must detect the unoccupied spectrum quickly and accurately to such dimensions in order to guarantee that license spectrum access by SU without interference to PU activity.

This simulation consider number of channels where state of these channels change independently. Each channel has a certain bandwidth Bi (i=1,...,N) and state of the channel spectrum can be illustrated as Markov discrete process which is denoted by idle and busy.

In CR system, a single or multiple SU sense either single or multiple channel availability. Fig. 3.9 shows a single user senses spectrum availability without cooperation with other users and access when it is unoccupied by PU.

Secondary user accesses license channel and transmits data based on the sensing outcome. When SU is accessing channel, SU still seeks other available channels and make spectrum sensing continuously to guarantee continuous communication when PU will use its channel back. Secondary user must vacate license channel quickly to access another vacant band when PU signal is detected

Unlike single user sensing, CSS model senses spectrum opportunities by multiple SUs. According to each belief vector, SU compete to sense an unoccupied channel and access based on the sensing outcome. SU accesses channel spectrum state with the highest probability to be idle with prior to exchange their local sensing results. Final decision is made by SU through combining all local sensing results from each SU. If license channel is available, then SU is allowed to access. The illustration of 2 SUs sense 3 channels is described in Fig. 3.20.

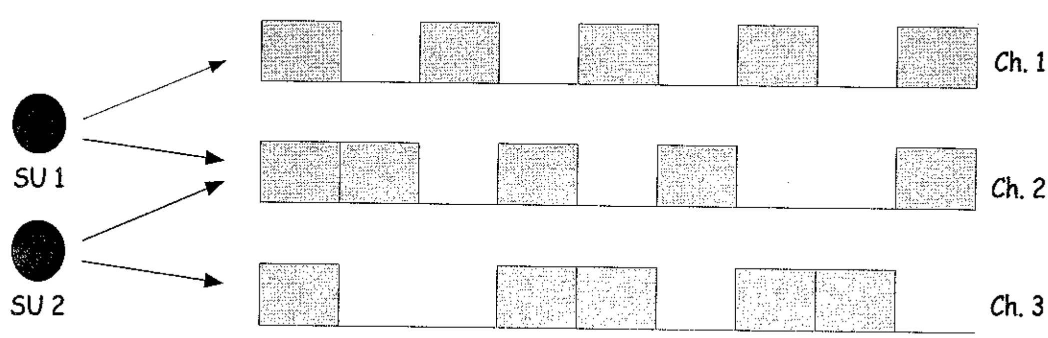

Figure 3.20 Multiple SU sensing

Due to the cost to achieve wideband spectrum sensing is quite high, only part of license channel can be sensed and accessed by SU. One solution to achieve wideband spectrum sensing is collaboration among SU as known as CSS. This simulation models decentralized CSS under POMDP framework, which provides mathematical modeling for channel spectrum behavior.

Previously, it has already presented and discussed CR system with single user sensing. This chapter will be discussed decentralized multiuser CSS model that can increase the fidelity of sensing outcome. Secondary user partially selects license channel to sense and access, and exchange local sensing result among SU to increase fidelity of sensing outcome.

There are two types of CSS model, Centralized Multiuser Cooperative Spectrum Sensing (CMCSS) and Decentralized Multiuser Cooperative Spectrum Sensing (DMCSS). It will be clearly presented by detail in the following sub section.

3.7.2 Cooperative Spectrum Sensing (CSS)

In non-cooperative spectrum sensing (single user sensing), SU independently detects PU signal. Secondary user determines the presence and absence of PU individually and acts accordingly. As shown in Fig. 3.21, SU detects primary signal and individually decides whether license channel is available or unavailable. However, this technique cannot detect primary signal properly due to fading and shadowing. As shown in that figure, SU-2 can detect primary signal more accurately than the other SUs since SU-2 detects signal in condition of line of sight (LOS) propagation while others detect primary signal with obstacles.

There are number of the proposed techniques to identify the presence of PU signal transmissions such as matched filter, cyclostationary and energy detector as describe in chapter II. Energy detector requires no prior knowledge of the signal and is less complex than the other detectors. However, it has a limit on the required amount of signal SNR (SNR wall) [141]. A matched filter requires prior knowledge of the signal that it is used to detect the primary user signal. It can be obtained by correlating the sensed signal with an already known signal. Furthermore, the cyclostationarity based detection algorithms can differentiate noise from primary users' signals. This is a result of the fact that noise is wide-sense stationary (WSS) with no correlation while modulated signals are cyclostationary with spectral correlation due to the redundancy of signal periodicities. However, it also requires prior knowledge of signal.

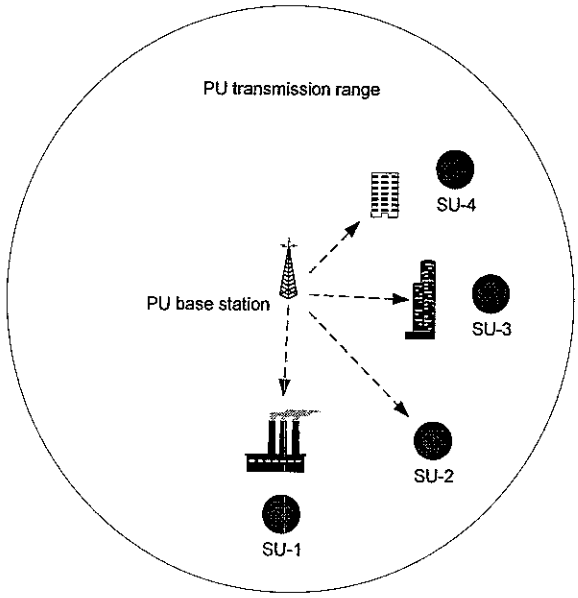

Figure 3.21 Model of non-cooperative technique [139]

This simulation uses energy detector for primary signal detection due to its low complexity and easier to implement. The simplified block diagram of signal detector is shown in Fig. 2.11. The detail information of this detector can be referred to chapter II.

Cooperative spectrum sensing has been proposed to overcome noise uncertainties, fading and shadowing in PU signal detection. It can be used as a solution for hidden and exposed terminal problem that is source of sensing errors in PU signal detection. CSS technique is possibly to decrease sensing time as well [142]. It maps radio spectrum environment and provide spectrum opportunity with higher fidelity of sensing outcome than single user. In CSS model, SUs are collaborated to sense spectrum and detect PU signal. In this technique, SUs are populated in the range of primary transmitter to perform its individual signal detection using some detection methods and determine the reliability of its own detection results. Subsequently, SU exchanges their local sensing results and decides which channel SU can access.

3.7.3 Centralized Multiuser Cooperative Spectrum Sensing (CMCSS)

It is similar to cellular system that dynamic spectrum access (DSA) can implement centralized networks with central coordinator. The central coordinator has responsibility to arrange and collect the sensing results from SU. Based on the sensing outcome and observation of SU, central coordinator decides which possible channels SU can access, establish communication among SU transceiver, and transmit data packet. Normally, central coordinator is a base station system. However SU itself is possibly to become a central coordinator as a cluster head to coordinate each user in one cluster within one DSA system.

As described in Fig. 3.22, in centralized CSS model, SU senses spectrum opportunities and a central coordinator allocates one of the N numbers of channels at the sensing stage. Then, at the report stage, each SU forwards the sensing results to the central coordinator for final decision.

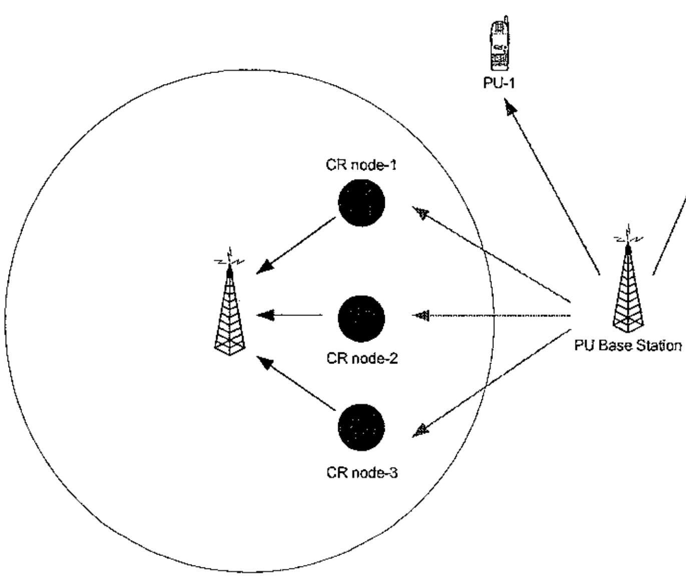

Figure 3. 22 Centralized multiuser cooperative spectrum sensing [145]

The central coordinator as a fusion center decides which channels are idle and busy based on the sensing results and forwards it back to the users.

In order to realize cooperative detection among SU, spectrum sensing and signal detection information over individual users should be sent to a fusion center for further process. Fusion center makes a final decision whether PU signal is present or absent. This work discusses centralized CSS model under communication bandwidth constraints, so it is assumed that all SU send their one-bit decision on spectrum sensing to fusion center based on their local sensing and observations.

As described in Fig. 3.23, in centralized CSS model, information of local signal observation from all SUs transmits to data fusion center. They forward 1-bit local detection to avoid communication overhead when CR users increased. Then, the final decision is performed whether signal is present (H_1) or absent (H_0) by regarding to decision rule.

There are two decision fusions that commonly used in cooperative spectrum sensing, hard and soft decision. Hard decision is fusion method that individual cognitive radios make one-bit decisions regarding to the existence of the primary user. The bit-1 indicates that primary user uses spectrum channel, so that SU cannot access. Spectrum channel is available to access if it is indicated by bit 0. After observing PU signal, each SU forwards local sensing result to data fusion centre for further process. Then, final decision for channel access is made by combining all local sensing results and observation.

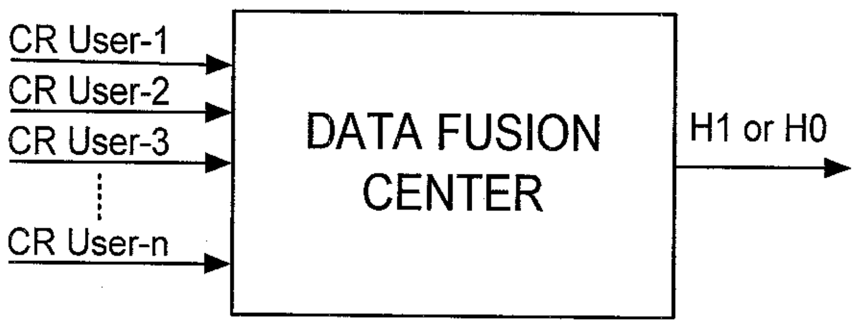

Figure 3.23 Data fusion centre [139]

The two simple rules of hard decision are OR and AND rule. OR rule determines that at least one of CR users involved in sensing decide that PU is present. Whereas AND rule decides available license channel when primary signal is detected by all SUs or in other word that all local decision of SU is H_1. In case of soft decision, the decision is taken by correlating the measurement made by individual users in signal detection. Such detection is more accurate than hard decision. However, it will cause data transmission overhead when number of SUs increase.

This simulation will focus on hard decision combining where individual users forward their one bit decision to fusion center. Specifically, it uses OR rule for centralized CSS model.

According to decision fusion rule, the results presented in [136][137] show that soft decision combining outperforms hard decision combining in terms of the probability of miss-detection. On the other hand, hard decisions combining obtain as good results as soft decisions when the number of collaborated users is increased [126].

This simulation work uses hard decision fusion to combine local sensing results from each SU. Fig. 6.4 shows the system model of centralized CSS where only one SU could be able to detect the primary signal accurately. The other SUs are not able to distinguish existence of the primary signal by fading and shadowing effect. The users are populated in the range of primary transmitter. Under this condition, it is expected to improve probability of signal detection. Cooperative spectrum sensing model is theoretically more accurate and convenient. The simplified diagram of centralized CSS model is described in Fig. 3.24.

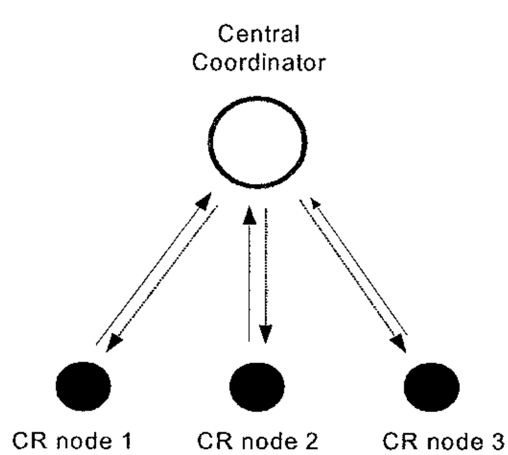

Figure 3.24 The simplified diagram of CMCSS model

Hard decision fusion shares their final binary bit to minimize communication overhead. The data fusion centre receives local decision from number of users and decides that signal is present (H_1) when total sum of user number decision is H_1. It means that at least one SU detect the primary transmitter signal and forward 1-bit local detection. This fusion rule is known as OR rule. The AND rule decides primary signal is present when all local detection of SUs are H_1.

PU signal detection based on hard decision fusion, the probability of detection (C_D), probability of miss detection (C_M), and probability of false alarm (C_F), for OR rule in centralized case can be calculated by using the following formulas [138]:

$$C_D = 1 - \prod_1^n (1 - P_{D,k}) \tag{3.30}$$

$$C_M = 1 - C_D = \left\{1 - \left(1 - \prod_1^n (1 - P_{D,k})\right)\right\} = \prod_1^n (1 - P_{D,k}) \tag{3.31}$$

$$C_F = 1 - \prod_1^n (1 - P_{F,k}) \tag{3.32}$$

Furthermore, detection probability and false alarm probability by employing AND rule is given as bellows:

$$C_D = \prod_1^n P_{D,k} \tag{3.33}$$

$$C_F = \prod_1^n P_{F,k} \tag{3.34}$$

where n is a number of collaborated user, $P_{D,k}$, and $P_{F,k}$ are detection probability and false detection probability for k-th SU. Probability of false detection, $P_{F,k}$ can be calculated by using eq. (4.5) as a function of an incomplete and gamma function. In energy detector, this function is represented by the following operation [82]:

1) Sampling the received signal and passing through an FFT device to obtain the signal spectrum.
2) The peak of the spectrum is then located and windowed.
3) The signal energy is then collected in the frequency domain and binary decision is created by comparing this energy to threshold value. Then, N is degrees of freedom, σ^2 is noise variance of communication, Y is a decision statistic, λ is the decision threshold, and H_0 stand for the hypothesis: no signal transmitted.

On the other hand, probability of detection, $P_{D,k}$, can be calculated by calculating probability of miss detection (P_M), where P_D as a function of P_M as bellows:

$$P_M = \delta_n = \gamma\left(\frac{M}{2}, \frac{\lambda_T}{2({\sigma_0}^2 + {\sigma_1}^2)}\right) \tag{3.35}$$

$$P_D = 1 - P_M = 1 - \gamma\left(\frac{M}{2}, \frac{\lambda_T}{2({\sigma_0}^2 + {\sigma_1}^2)}\right) \tag{3.36}$$

According to [139], the performance of signal detection between OR and AND rule is shown through the simulation. The authors assume 2 SUs are collaborated for PU signal detection. It is described on Fig. 3.25 that OR rule has better performance for probability of detection than AND rule.

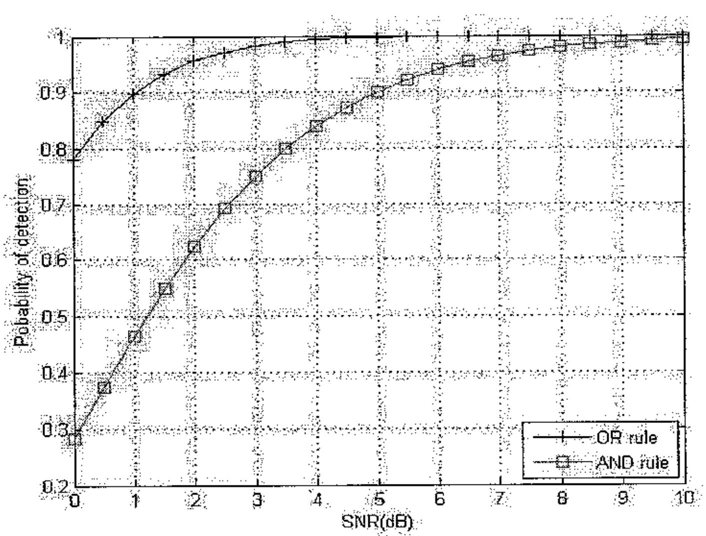

Figure 3.25 Probability of detection for OR and AND rule

The data fusion centre decides H_1 when at least there is one CR user detects primary user signal for OR rule while in AND rule, all local detection of CR users must be H_1 to decide the presence of primary user signal. However, when the figure shows when SNR value is greater than 10 dB, both of the rules has an optimal performance.

In this research work, in order to investigate multiuser cooperative signal detection with limited sensing capability, we concentrate on OR rule of energy detector for centralized network.

3.7.4 Decentralized Multiuser Cooperative Spectrum Sensing (DMCSS)

Unlike CMCSS model that has a central coordinator to collect sensing result from all SU, each SU in DMCSS distribute local sensing results among others and independently make their own decision as to which part of channel can be accessed.

In DMCSS model, SU senses and selects channel without central coordinator as illustrated in Fig. 3.26. In such case, SU does not need to forward their sensing results to central coordinator for final decision. Decision on which and when channel can be accessed is made by themselves through combining all local sensing results. In decentralized CSS model SU performs sensing, observation, exchange and distribute their local sensing and observation among others, make a final decision, and reconfigure their parameter (environment adaptation), i.e. power, modulation, etc., before accessing the available channel. Unlike centralized CSS, in decentralized CSS model SU independently senses and accesses channel without forwarding to CR base station. Channel access is taken by considering local sensing exchange from other SUs.

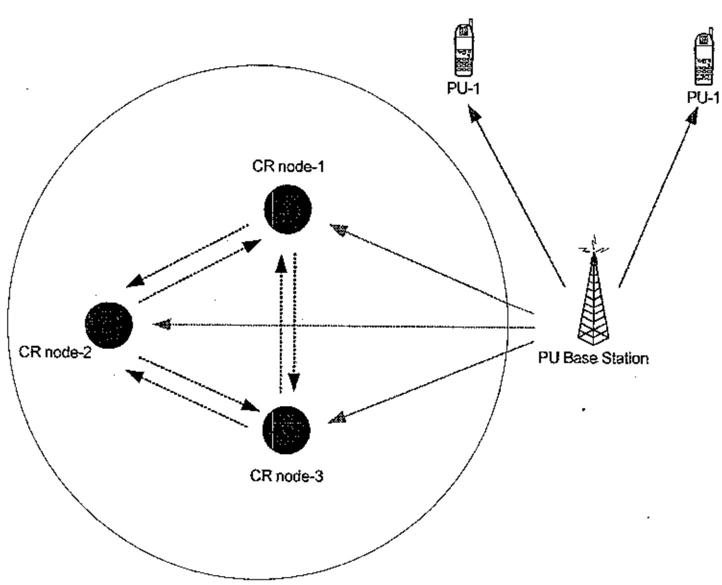

Figure 3.26 Decentralized multiuser cooperative spectrum sensing (DMCSS) [145]

Decentralized CSS model follows the procedure as single user sensing model. At the beginning of slot, each SU selects channel to sense. Then, each SU cooperatively exchange its local sensing result and observation among others. Secondary user makes a final decision as to which part of the channel can be accessed based on the exchange of sensing outcome. Data transmission is the next task to be performed when channel is available. Secondary send an acknowledgement signal to SU transmitter for successful data transmission.

Furthermore, to derive formulation of local and cooperative miss-detection probability, it cannot use equation (6. 2) and (6. 6) as presented in centralized CSS model. We introduced binomial distribution theory to derive probability of miss detection for decentralized CSS model.

In probability and statistic theory, binomial distribution theory can be defined as discrete probability distribution for a sequence number of independence experiment with probability of successful selection p. Hence, this statistic theory is applied to derive local and cooperative miss-detection probability for decentralized CSS model in CR system.

Let us assume that SU i select L channels to sense with probability $P_{i,L}$ at each time slot, and the expected miss detection probability for local sensing is P_M.

According to the binomial distribution theory, the probability that users i select L channels can be calculated as below:

$$\binom{n}{i} p^i (1-p)^{n-i} \qquad i = 1, 2, \ldots, n \tag{3.37}$$

where n, i, *and* p denote number of SU, number of user that select channel L, and probability of user i to sense channel L, respectively. The average of miss detection probability, C_M, for DCU can be calculated as the following formula

$$C_M = \frac{P_M \; x \; Prob. \; of \; user \; select \; channel \; to \; sense}{\sum_{i=1}^{n} Prob. of \; user \; select \; channel}$$

$$= \frac{\sum_{i=1}^{n} {P_M}^i \binom{n}{i} p^i (1-p)^{n-i}}{1-(1-p)^n} \tag{3.38}$$

The optimal strategy can be derived when the probability of miss detection is equal to maximum collision probability allowed by PUs $(C_M = \zeta)$. Thus, the probability of miss detection for the local sensing result, P_M, can be calculated as bellows:

$$\zeta = \frac{(P_M\, x\, p + 1 - p)^n - (1-p)^n}{1-(1-p)^n} \qquad (3.39)$$

$$P_M = \frac{(\zeta(1-(1-p)^n) + (1-p)^n)^{\frac{1}{n}} + (p-1)}{p} \qquad (3.40)$$

where ζ denotes a collision threshold or a maximum collision probability allowed by PUs. Thus, the chosen action in slot t to maximize the expected immediate reward can be given by

$$a_*(t) = arg \max_{a=1,\dots,N} \left(\omega_a(t)\beta_a + \left(1-\omega_a(t)\right)\alpha_a\right)(1-\varepsilon_{DMCSS})\,\beta_a \qquad (3.41)$$

The notation of ε_{DMCSS} is defined as probability of false detection for decentralized cooperative system. Its value is affected by decentralized probability of miss detection ($P_M = \delta$), which is derived by eq. (6.9).

Furthermore, by considering the derived equation above, detail protocol description of DMCSS model can be presented as follows:

- For each SU, transmitter and receiver select a certain channel for sensing based on initial probability of channel state or belief vector, with the probability p
- Each SU transmitter senses channel and obtain the sensing outcome.
- SUs which do not have data to transmit can turn on to sleep mode and should not participate on channel sensing
- In case of channel state is affected by different PU activity (spatially varying spectrum opportunity), each SU transceiver sense channel for the opportunity to access.
- Probability of miss detection, P_M is calculated based on the value of p by using equation (6.11).
- The derived probability of miss detection is used as reference for local spectrum sensing on each SU.

- Each SU distributes their local sensing and observation results to others independently for final decision whether sending data packet is possible.
- Based on the exchange of sensing outcome, SU make a final decision whether transmit or refraining from data transmission.
- If channel spectrum is available, SU transmitter send the data packet to receiver over license channel quickly.
- SU receiver will send acknowledgement signal to SU transmitter for successful data packet transmission.
- SUs update channel states or belief vector after accessing channel

The following section will present the performance of proposed DMCSS model along with comparison. To validate the works, we compare DMCSS model with single user sensing, full band random CSS, and centralized CSS model in term of probability of false detection, probability of miss detection and throughput performance. The methodology of those mentioned validation technique was discussed in earlier section.

3.8 Summary

This chapter discussed POMDP framework which is used as an aid in decision making for CR system. This framework assists SU to decide which channel can be sensed and accessed. It models license spectrum behavior as Markov discrete process where idle and busy channel states can be denoted by number of 0 and 1. It also provides mathematic formulation of POMDP that introduces reward function to stimulate user for successful transmission. This reward is sent by SU receiver at the end of each slot.

POMDP is used as a basic reference for our method to further investigate the performance of CR system. Mathematic modeling for optimal and sub optimal greedy sensing policy was presented. Sub optimal greedy sensing policy is used to simplify the complexity of calculation when number of channel increases. Through exploiting greedy sensing policy and adopting binomial distribution statistical theory, DMCSS model was proposed.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter presents MATLAB simulation results along with discussion related to the performance of CR system. Through dynamic programming and heuristic simulation, we present simulation results as follows

1. Optimal and sub optimal greedy sensing policy under perfect and imperfect propagation channel with different initial parameter setting

2. Cross layer design principle that aims to optimise throughput performance

3. The proposed DMCSS model is compared with single user sensing, CMCSS model, and full band random CSS model.

Firstly, simulation models primary network behaviour as Markov discrete process. The values 0 of primary network indicate that PU is not accessing the channel and it is available for SU. In this case, SU is allowed to access using licensed channels and transmit data. While the values of 1 indicate license channel is in busy state, meaning that PU is using the channel for transmission. In this state, SU is not allowed to use the channel; otherwise it will collide to PU transmission.

The implementation of POMDP in CR was proposed under the constraints of fewer disturbances to PU transmission and avoids the collision to PU. Fig. 4.1 describes the example of channel spectrum occupancy state, which follows Markov discrete process. Channel spectrum is divided into number of states from S_1 (1) that is varied depending on time and location.

As described in the figure, there is 3 channels example, where the states of the channel spectrum are not identical. Spectrum opportunities are indicated by values of 0. Channel 1, for example, there are 3 spectrum opportunities, S_1 (2), S_1 (4), and S_1 (n). In these spectrum states, SU is allowed to access until certain period of time. Then, in the states of S_1 (1), S_1 (3), and S_1 (T) indicate channel spectrum that is not available (busy state), thus SU is not allowed to access in order to avoid collision to PU activity.

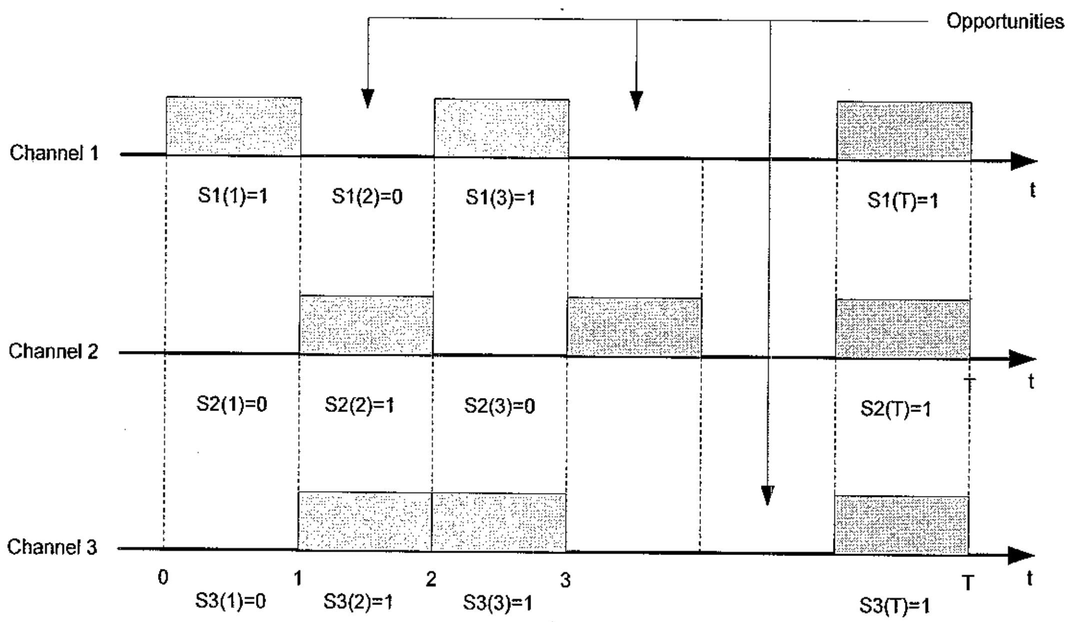

Figure 4.1 Spectrum occupancy state with number of channel N = 3

POMDP framework is implemented as an aid for spectrum sensing and access decision. Such framework enables SU to sense a part of the existing channel and access the available one under the condition of $L_2 \leq L_1 \leq L$, where L_2, L_1, and L are number of accessed channels, number of sensed channels, and number of existing channels, respectively. The following sub section discusses optimal and sub optimal greedy sensing policy followed by simulation over perfect and imperfect channel condition. This simulation mostly uses throughput or reward performance as a metric as a function of number of slot. However, it also presents the performance of spectrum efficiency, primary signal detection, etc. Detail discussion for the obtained results will be clearly presented in the following section.

4.2 Optimal Spectrum Sensing Policy

POMDP framework is a generalization of Markov Decision Process (MDP) which provides a mathematical framework to model decision making where outcomes are partly random and partly under the control of decision maker. Hence, this research work implements such framework as an aid for SU to decide which channel can be sensed and possibly to be accessed by mapping of the channel spectrum state. A dynamic model is presented where SU select an action among number of variations.

In this section, computer simulation results are presented to evaluate the performance of optimal policy under POMDP with throughput of SU (bit/slot) as a function of slot number (T) as a metric. The numerical simulation set up some of certain parameters such as transition probabilities (α,β), bandwidth (B), and number of channel (N).

At first done, sensing errors is not considered in this simulation, meaning that SU senses license channel over perfect propagation. Parameter includes 3 channels (N = 3) of primary network with the same bandwidth B = 1 and number of slots T = 25. Simulation of 3 cases with different transition probabilities (α, β) is performed. In case 1, probability of channel transition from busy (1) to idle (0), $\alpha = 0.1$, whereas channel remains unchanged, $\beta = 0.9$. The term of remain unchanged means busy traffic occurred on the primary network activity. The message length and inter-arrival time are large relatively. It leads to stationary of channel state. Case 2 is the opposite of case 1, where the probability of channel remains unchanged ($\beta = 0.1$) is lower than probability of channel transition from busy to idle state ($\alpha = 0.9$). In case 3, each probability of channel state where remain unchanged and the change of channel states are equal ($\alpha = \beta = 0.5$)

The result is presented in Fig. 4.2. The obtained results show that throughput of SU increases over time in both case 1 and 2. Due to the probability of channel remains unchanged in case 1 greater than case 2, the throughput of SU in case 1 is higher than case 2. Higher probability of channel remain unchanged cause case 1 has more time of data transmission. The congestion of data traffic for primary network in case 1 is higher than case 2. It concludes that CR can be more effective when it is over layered by primary network with a great message length and inter arrival time.

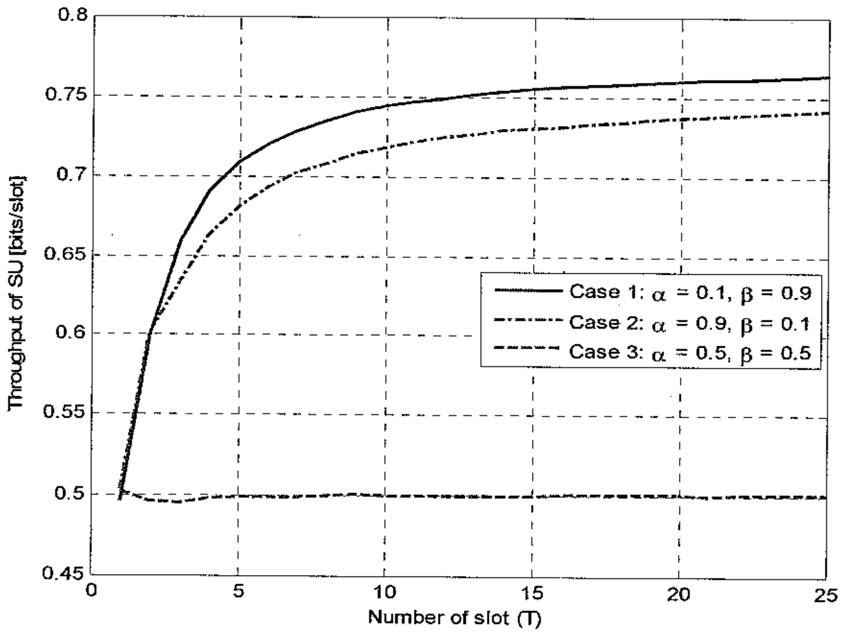

Figure 4.2 Throughput performance with B = 1, N = 3, T = 25

According to the results, SU improves the reward or throughput during T slot transmission time. Secondary user is able to gain the information and observation from previous slots. However, in case 3, SU cannot gain the information from the past observation and lead to the static reward that achieved during T slot transmission time. In such case, optimal strategy reduces to a random selection channels.

Then, we observe the impact of changing transition probabilities and make some comparisons. The other parameters remain unchanged as a previous setting. The throughput achievement is presented in Fig. 4.3.

According to the result, it is concluded that when probability of remain unchanged (β) for channel state is set higher than probability of channel state transition (α), the achievable throughput is improved significantly with number of slot increases. In such cases, information from previous slot and past observation can gain the reward since number of bit transmitted over T slot is improved. Parameter setting of $\alpha = 0.1$ and $\beta = 0.9$ has higher throughput performance compared with others.

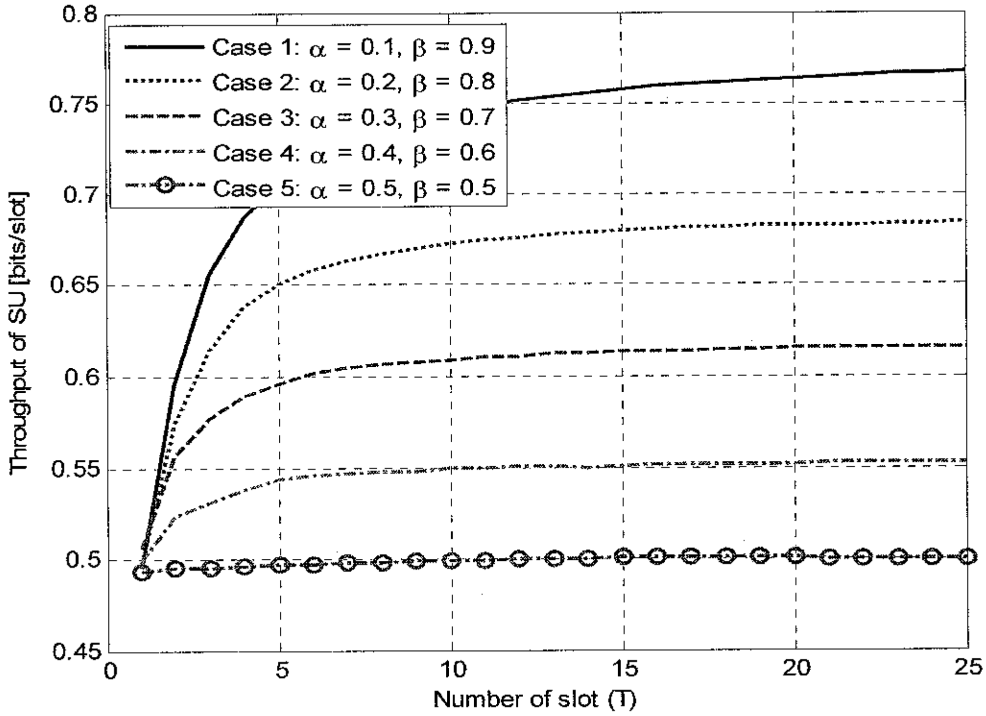

Figure 4.3 Throughput performance with B = 1, N = 3, T = 25 and different transition probabilities

The result shows that in all cases, at the beginning of the slot, channel has the same stationary distribution, where probability that channel can be accessed is 0.5. Although the traffic load of primary network is the same, however it will result the different performance of secondary network. As stated earlier, when setting of transition probabilities $\alpha = 0.5$ and $\beta = 0.5$, the throughput performance seems to be constant relatively, meaning that no information can be gained from previous slots and past observation. In such case, reward cannot increase and the throughput performance seems to be constant relatively.

In the following simulation, we set different value of channel bandwidth, $B_1 = 5$, $B_2 = 10$, $B_3 = 15$, and $B_4 = 20$, respectively, transition probabilities $\alpha = 0.1$ and $\beta = 0.9$, and keep the other parameter setting remain unchanged. According to the result as described in Fig. 4.4 shows that increasing bandwidth lead to improve the throughput performance significantly.

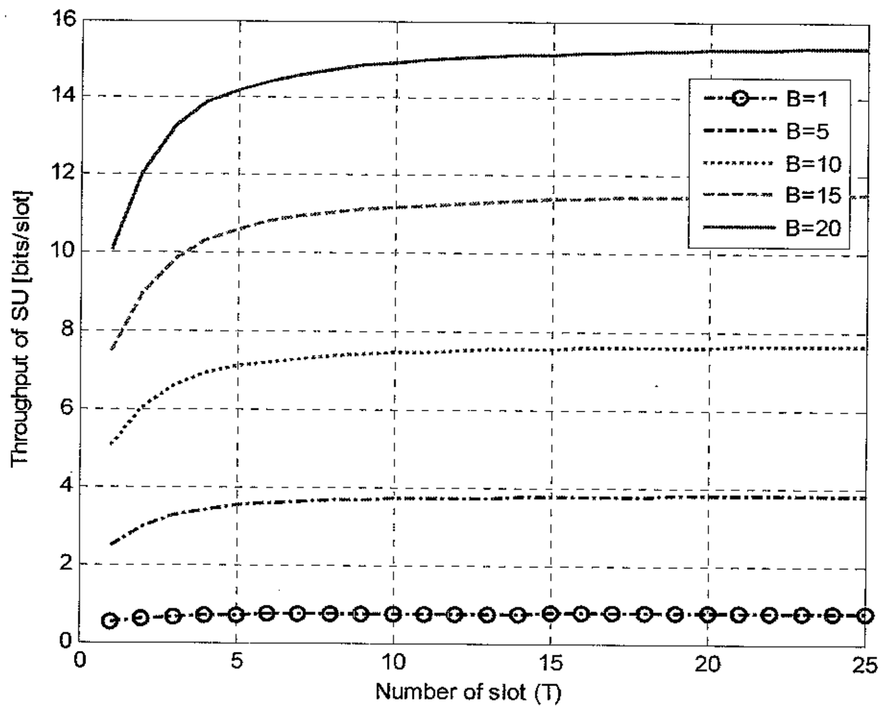

Figure 4.4 Throughput performance with N = 3, T = 25, transition probabilities {0.1, 0.9}, and different bandwidth B

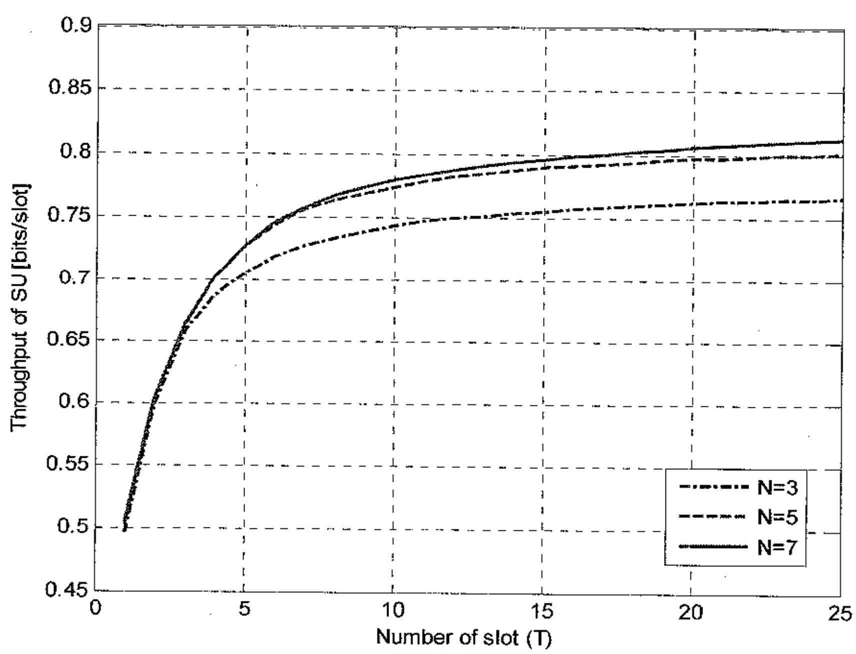

Figure 4.5 Throughput performance with B = 1, T = 25, transition probabilities {0.1, 0.9}, and different number of channel N.

Fig. 4.5 describes the throughput performance for different channel while keeping other parameter setting unchanged. Number of channel is set to $N_1 = 3$, $N_2 = 5$, and $N_3 = 7$ respectively, B = 1, $(\alpha, \beta) = \{0.1, 0.9\}$, and number of slot T = 25. According to the achievable result shows that number of channel has an impact to the throughput performance. When number of channel increases, the possibility of SU to access and transmit data becomes larger. The more number of channels the more achievable throughput. Increasing number of channel is able to improve the throughput performance significantly.

4.3 Sub Optimal Greedy Sensing Policy

By modifying previous model, we investigate the performance of CR system through sub-optimal greedy sensing policy. Greedy sensing policy was proposed in order to reduce the complexity of calculation and process in optimal sensing policy when number of channel increases. Belief vector is defined as information state of channels based on sensing and observation for optimal sensing policy. Its dimension of sufficient statistic grows exponentially when number of N channel increases. In chapter III, it has been presented an example of how number of channel can increase exponentially to number of states. For this reason, it is too crucial to represent innovative strategy, which reduces the complexity one.

The decision theoretic approach of sub optimal greedy sensing can be referred to Chapter III. This sub-section presents the simulation results of greedy sensing policy and compared with the optimal sensing policy. Simulation sets the same initial parameters as previous setting. Sensing error is not considered into account, channel bandwidth B = 1, number of slots T = 25, and transition probabilities $(\alpha, \beta) = (0.2, 0.8)$.

According to Fig. 4.6, the performance of sub optimal greedy sensing policy matches to optimal sensing. The obtained result shows that in each point of slot number, the values place at the same point, relatively. A significant gain is achieved for both optimal and greedy sensing policy over random channel selection strategy during T slot transmission time. Meanwhile, random sensing strategy curve remains unchanged. Its result is constantly obtained during T slot time.

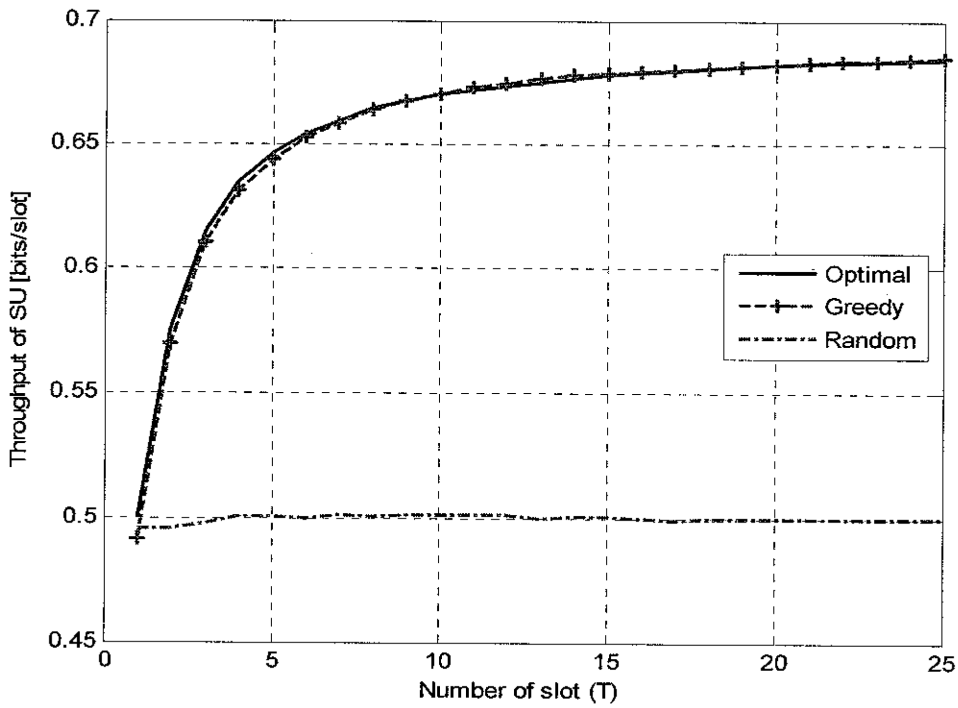

Figure 4.6 Throughput performance for optimal and greedy sensing policies with B = 1, N = 3, T = 25, and transition probabilities (0.2, 0.8)

This simulation sets channels with the same values of bandwidth and transition probabilities, meaning that the three channels have an equal bandwidth B = 1 and transition probabilities (α, β) of channels are (0.2, 0.8). This result can be used as reference that greedy policy can be adopted to investigate further works in the following sections in order to reduce the complexity of implementation works.

Then, simulation sets to the condition in case of primary channels have different bandwidth (B) and transition probabilities (α, β). Primary channel is set to multiple bandwidths and multiple transition probabilities as follows:

- Bandwidth channels $B = [B_1, B_2, B_3] = [0.75, 1, 1.5]$
- Transition probabilities $\alpha = [\alpha_1, \alpha_2, \alpha_3] = [0.8, 0.6, 0.4]$
- Transition probabilities $\beta = [\beta_1, \beta_2, \beta_3] = [0.6, 0.4, 0.2]$

The obtained result is presented in Fig. 4.7. It can be seen that conversion into multiple bandwidth and multiple transition probabilities with different values causes loss of throughput performance (around 2% loss) and less performance than optimal sensing policy.

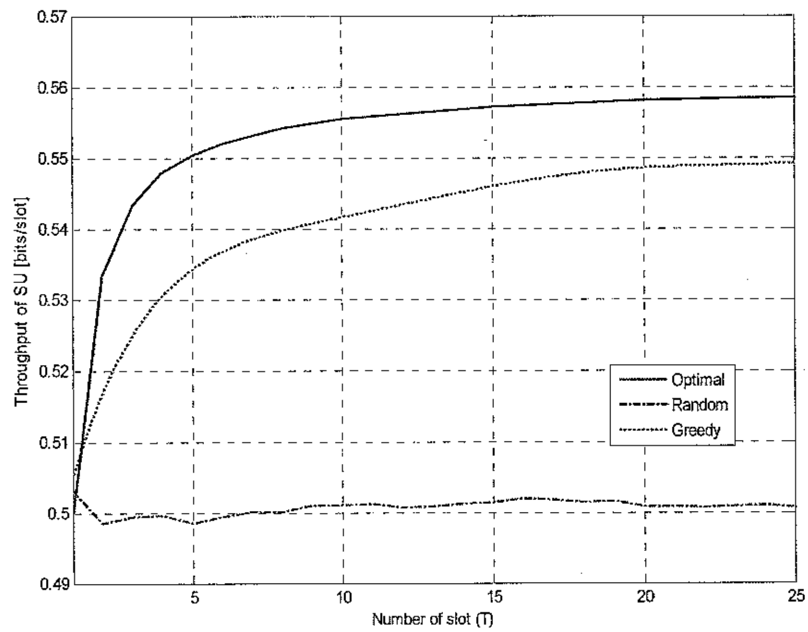

Figure 4.7 Throughput performance for optimal and greedy sensing policies with multiple bandwidths and transition probabilities

For further investigation, setting of transition probability parameters is changed and keep the bandwidth values remain unchanged as follows:

Bandwidth channels $B = [B_1, B_2, B_3] = [0.75, 1, 1.5]$

Transition probabilities $\alpha = [\alpha_1, \alpha_2, \alpha_3] = [0.8, 0.5, 0.4]$

Transition probabilities $\beta = [\beta_1, \beta_2, \beta_3] = [0.5, 0.4, 0.2]$

The result is shown in Fig. 4.8. Such setting generates loss that implies to the throughput performance of greedy sensing policy.

Likewise, when simulation set transition probabilities into different values while keep bandwidth remain unchanged as below:

Bandwidth channels $B = [B_1, B_2, B_3] = [0.75, 1, 1.5]$

Transition probabilities $\alpha = [\alpha_1, \alpha_2, \alpha_3] = [0.7, 0.5, 0.3]$

Transition probabilities $\beta = [\beta_1, \beta_2, \beta_3] = [0.5, 0.3, 0.2]$

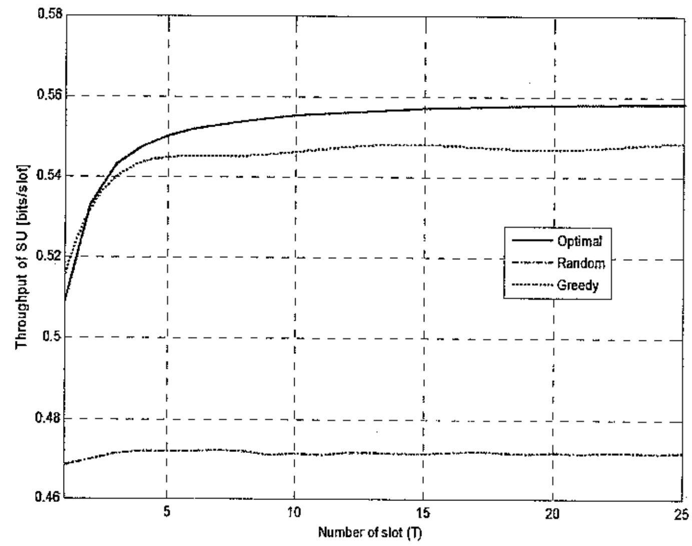

Figure 4.8 Throughput performance for optimal and greedy sensing policies with multiple bandwidths

Throughput performance of sub-optimal greedy sensing policy obtains larger loss as presented in Fig. 4.9.

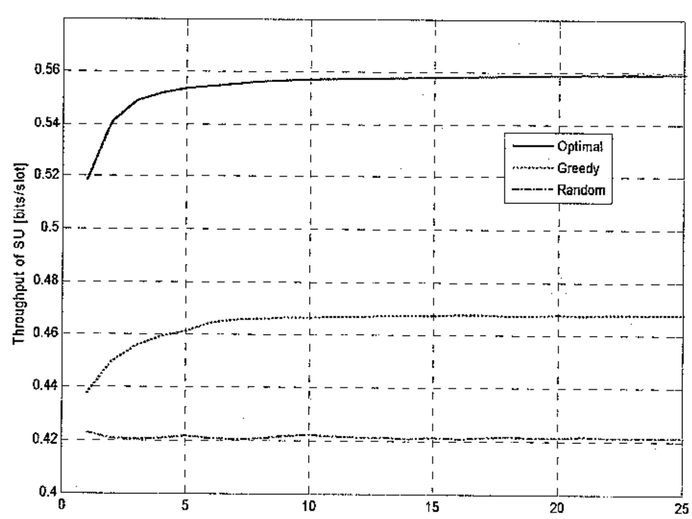

Figure 4.9 The performance for optimal and greedy with multiple bandwidths and transition probabilities

4.4 Imperfect Spectrum Sensing

In this section, the performance of CR system by considering sensing error where SU senses channel over imperfect propagation is further discussed. As we know that in real condition, fading, shadowing, hidden terminal problem and uncertainty noises cannot be ignored in wireless communication link. This imperfect propagation case can generate errors in PU signal detection, such as false detection and miss detection. False detection senses idle states as a busy channel, hence SU refrain from data transmission. On the other hand, miss-identification senses busy states as an idle that will lead to collision to PU activity. Such errors can decrease the throughput performance, in which CR user refrains from data transmission and makes collision between primary and secondary user.

Fig. 4.10 shows PU signal detection by SU where there are 3 SUs that detect primary signal over imperfect propagation channel condition.

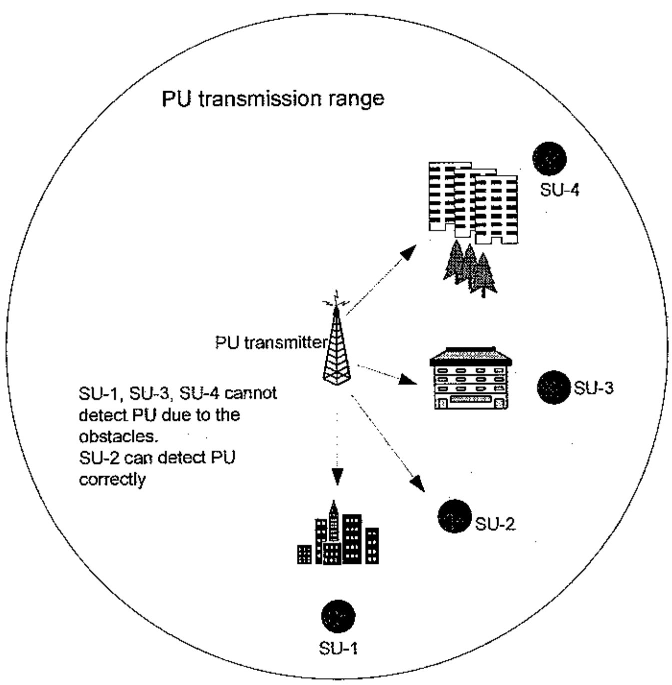

Figure 4.10 Perfect and imperfect primary signal detection

As described in that figure, SU-2 senses primary signal over perfect channel or line of sight (LOS) condition. However, SU-1, SU-3, and SU-4 sense channel over imperfect channel condition. There are some obstacles such as building, trees, etc, that obstructs the primary signal detection. These obstacles cause error detection, i.e. false detection and miss detection.

False detection and miss detection is not only generated by obstacles. Hidden and exposed nodes also become the cause of sensing error on primary signal detection. These two problems is critical design on MAC especially in CR system. As illustrated in Fig. 4.11, hidden node is defined as SU which is located in SU receiver range but outside the SU transmitter range (node 4), while exposed terminal is defined as SU which is located in SU transmitter range but outside the SU receiver range (node 3). Both hidden and exposed terminal has possibility to generate errors in primary signal detection and decrease the throughput performance. Hidden node cause collision (i.e. miss detection) with PU while exposed node can lead to waste the opportunities (i.e. false detection).

Hidden and exposed node case is known as CR network in spatially varying spectrum opportunity, where SU is influenced by some of PU and the state of spectrum occupancy depends on their location. In this spatially varying spectrum opportunity, idle spectrum channel for SU transmitter does not mean spectrum channel will be idle state in SU receiver.

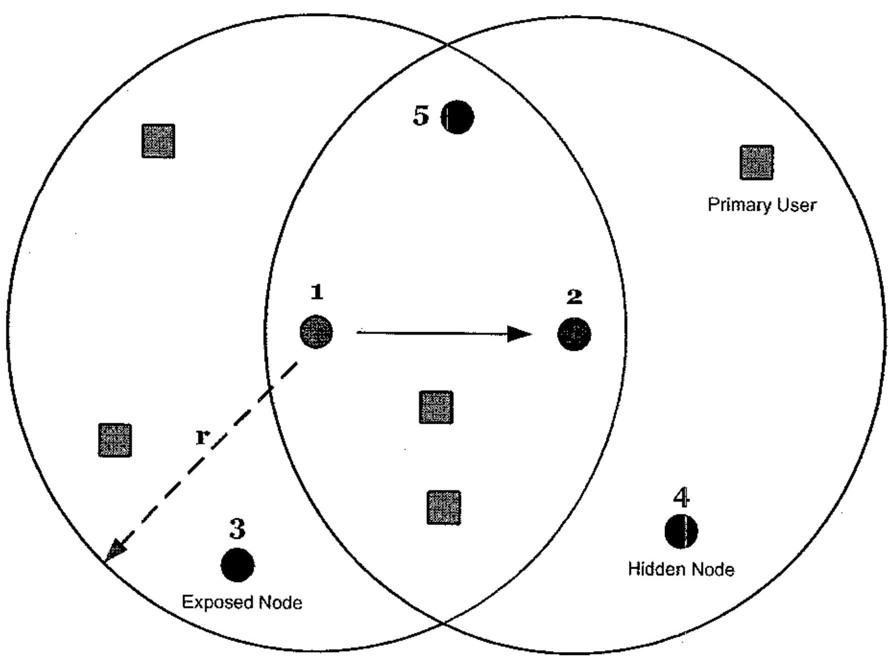

Figure 4.11 Hidden and exposed terminal in OSA networks

To solve this problem, the basic slot of cognitive MAC in Fig. 3.6 can be modified by adding RTS-CTS (request to send, clear to send) signal and backoff time as shown in Fig. 4.12.

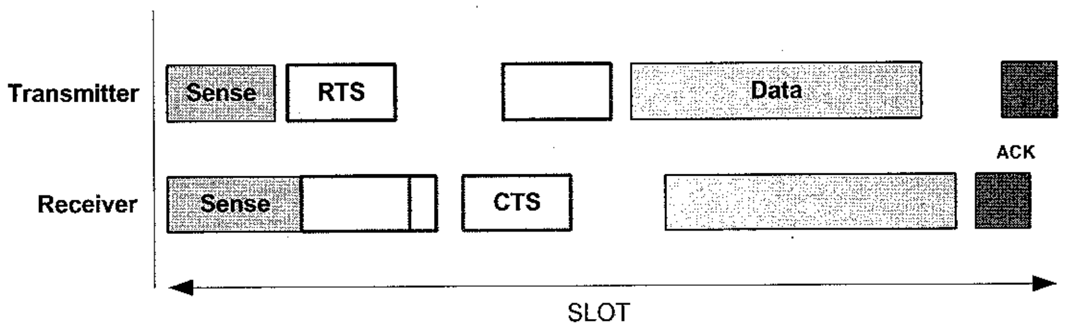

Figure 4.12 Protocol in spatially varying spectrum opportunity

It is clearly stated that at the beginning of slot, SU transmitter and receiver perform sensing until certain period of time. When SU transmitter senses an idle channel state, it generates random backoff time, and send RTS signal. If spectrum channel is also available in SU receiver, it will send the signal of CTS after generated random backoff time, indicates that receiver is ready to establish communication and receive data from SU transmitter. Secondary user receiver will send the acknowledgment signal for successful data transmission,, which informs to SU transmitter that data is successfully received. The flowchart of algorithm for this case is shown in Fig. 3.12.

During spectrum sensing, SU performs binary hypothesis for idle and busy states as eq. (3.29) and (3.30). Then, sensing outcome is denoted by Θ_n. The performance of spectrum sensing depends on ROC curve that is characterized by P_F (ε) and P_M (δ). The selected channel is thus given by eq. (3.32).

The belief vector should be updated both at transmitter and receiver. Information at the transmitter in one slot included the decision $\{a_*, \Phi_{a*}\}$ and the observation $\{\Theta_{a*}, K_{a*}\}$ where $K_{a*} \in \{0,1\}$ denotes an acknowledgement in the end of the slot. However, information at the receiver only covers a_* and K_{a*} since SU receiver does not have the sensing outcome Θ_{a*} and cannot distinguish an unsuccessful transmission from no access decision $\Phi_{a_*} = 0$. Then, modification of belief vector can be updated by following eq. (3.36).

We adopted greedy sensing strategy to evaluate the performance of OSA in CR system. At the beginning of the slot, SU take L number measurement samples $Y_n \equiv [Y_1,...,Y_M]$ from the selected channels and perform binary hypothesis as follows:

$$H_0(S_n = 0) = idle = Y_n \approx N(0_M, \sigma_0^2) \tag{4.1}$$

$$H_1(S_n = 1) = busy = Y_n \approx N(0_M, \sigma_1^2) \tag{4.2}$$

where $N(0_M, \sigma_0^2)$ denotes the M-dimensional Gaussian distribution with identical mean 0 and variance σ^2 in each dimension, σ_0^2 and σ_1^2 denote noise and primary signal power in channel n, respectively. Detector optimal under Newman and Pearson (NP) criteria is as follow [128]

$$||Y||^2 = \sum_{i=1}^{M} Y_i^2 \begin{matrix} > H_1 \\ < H_0 \end{matrix} T \tag{4.3}$$

Probability of miss-detection (P_M) and probability of false alarm (P_F) are incomplete gamma function and given by [140] as follows:

$$P_M = \delta_n = \gamma\left(\frac{M}{2}, \frac{\lambda}{2(\sigma_0^2 + \sigma_1^2)}\right) \tag{4.4}$$

$$P_F = \varepsilon_n = 1 - \gamma\left(\frac{M}{2}, \frac{\lambda}{2\sigma_0^2}\right) \tag{4.5}$$

where $\gamma(m, a) = \frac{1}{\Gamma(m)} \int_0^a t^{m-1} e^{-t} dt$ is the incomplete gamma function and λ denotes signal detection threshold. The receiver-operating curve (ROC) between false detection (ε) and miss-identification (δ) affect the optimal access strategy. The separation principle is clearly presented in chapter V, in which the partition of ROC curve is divided into conservative and aggressive access strategy. Hence, the optimal decision can be achieved when $\delta_n{}^* = \zeta$, where ζ is collision threshold.

4.4.1 Performance of throughput

This sub-section discusses the performance of throughput as a function of some parameter such as collision threshold, number of slot, SNR, and probability of false detection.

Fig. 4.13 shows the throughput performance with different SNR values (1dB and 3dB) and draw the plot as a function of collision threshold (maximum collision probability ζ allowed by PU network) with sensing errors. The simulation sets number of channel, N = 3, slot number, T = 25, and transition probabilities $\alpha = 1$, $\beta = 9$. According to the derived result, the throughput performance improves with maximum collision probability allowed by PU network ζ increases. It is because probability of false alarm becomes small and lead to increase the throughput of SU when ζ increases. Then, Fig. 4.14 shows the relation curve between probabilities of false detection as function of collision threshold. The derived curve shows that increasing signal to noise ratio (SNR) decreases the probability of false detection and lead to the throughput improvement. This curve confirms the obtained results on Fig. 4.13.

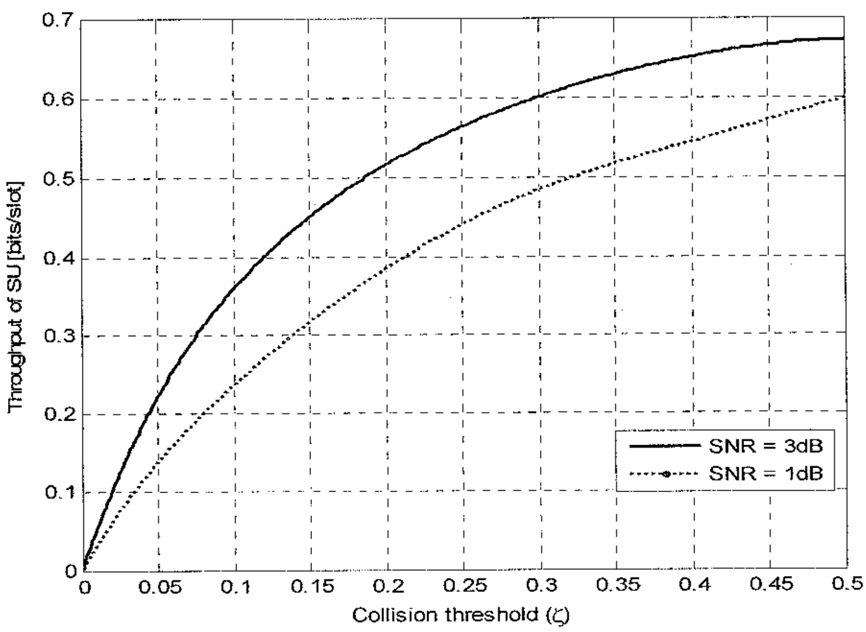

Figure 4.13 Throughput performance over imperfect channel sensing based on greedy sensing policy with B = 1, N = 3, T = 25, $\alpha = 0.1$ and β=0.9

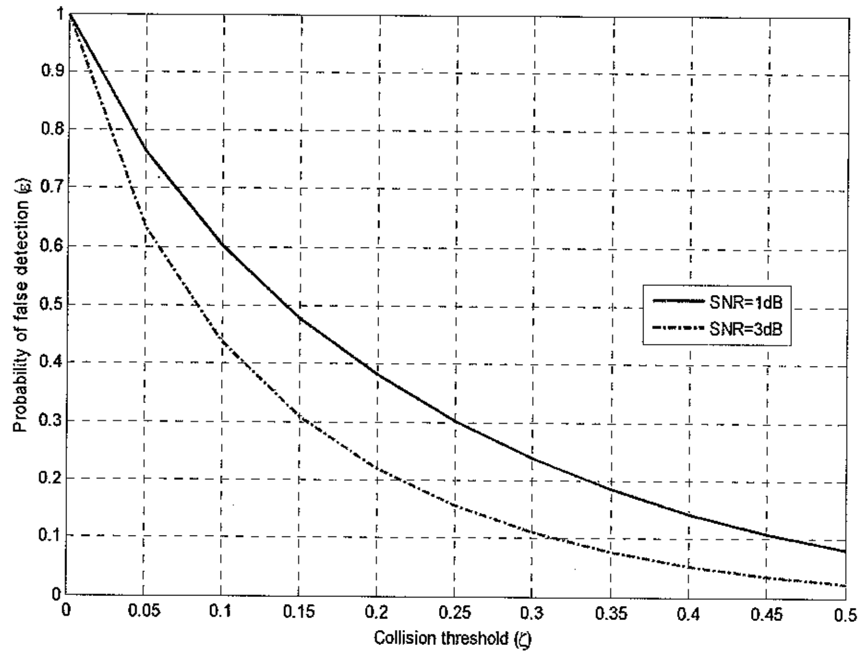

Figure 4.14 Probability of false detection (P_F) as a function of collision threshold (ζ)

Furthermore, simulation changes number of channel, N = 5, while keeping other parameter setting remain unchanged. The obtained results show in Fig. 4.15 with different SNR values.

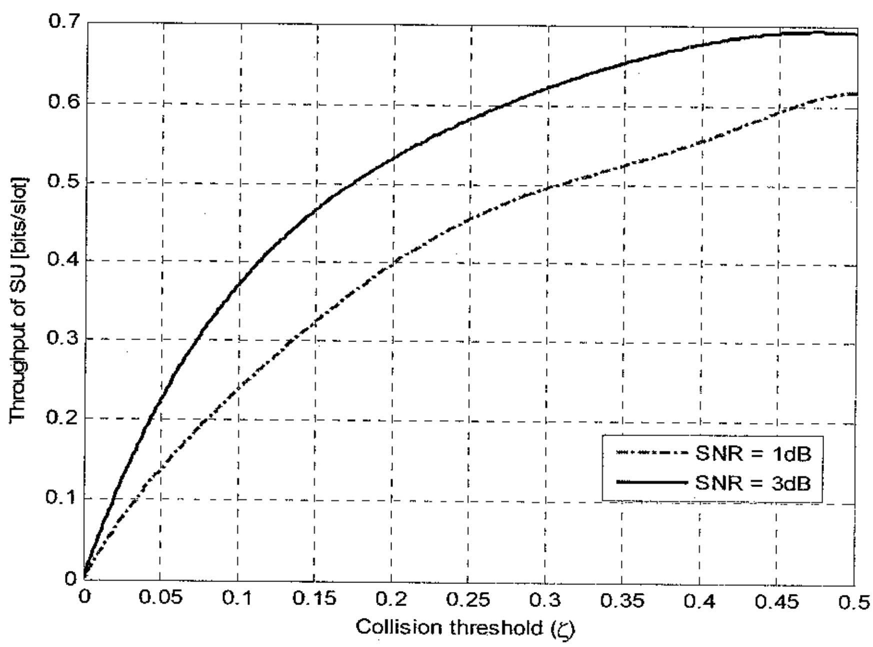

Figure 4.15 Throughput performance over imperfect channel sensing based on greedy approach with $B = 1, N = 5, T = 25, \alpha = 0.1$ and $\beta = 0.9$

As the earlier results, increasing collision threshold is able to improve the throughput performance since high collision threshold decreases probability of false detection and lead to the throughput improvement (refer to the plot of P_F as a function of ζ in Fig 4.14). A little bit improvement is shown when channel setting is changed. To distinguish the performance amongst them, it is clearly shown in Fig. 4.16.

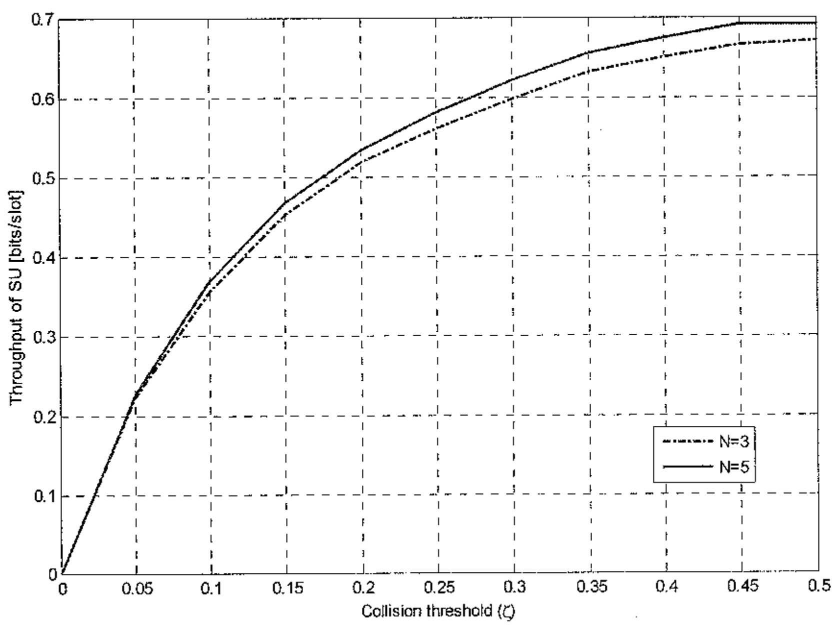

Figure 4.16 The comparison of throughput performance with different number of channel setting (N), SNR = 3dB, B = 1, T = 25, α = 0.1 and β = 0.9

The result shows that increasing number of sensed channel lead to improve the throughput performance, meaning that the probability of SU to utilize the available channel is higher when number of sensed channel increases.

Furthermore, Fig. 4.17 shows the performance comparison between spectrum sensing over perfect and imperfect propagation cases. Simulation sets number of channel N = 3, number of slot T = 25, transition probabilities (α, β) = (0.1, 0.9), channel bandwidth B = 1, and collision threshold for imperfect channel ζ = 0.2. The results plot the throughput performance as a function of slot number (T). According to the obtained results, increasing number of slot lead to improve the throughput performance for perfect and imperfect cases. The throughput of SU without sensing errors has completely higher values than SU with sensing errors (imperfect). Fading and noise degrade the throughput performance. Both cases can gain the rewards from previous slot and improve the throughput performance by exploiting sensing outcomes and past observation.

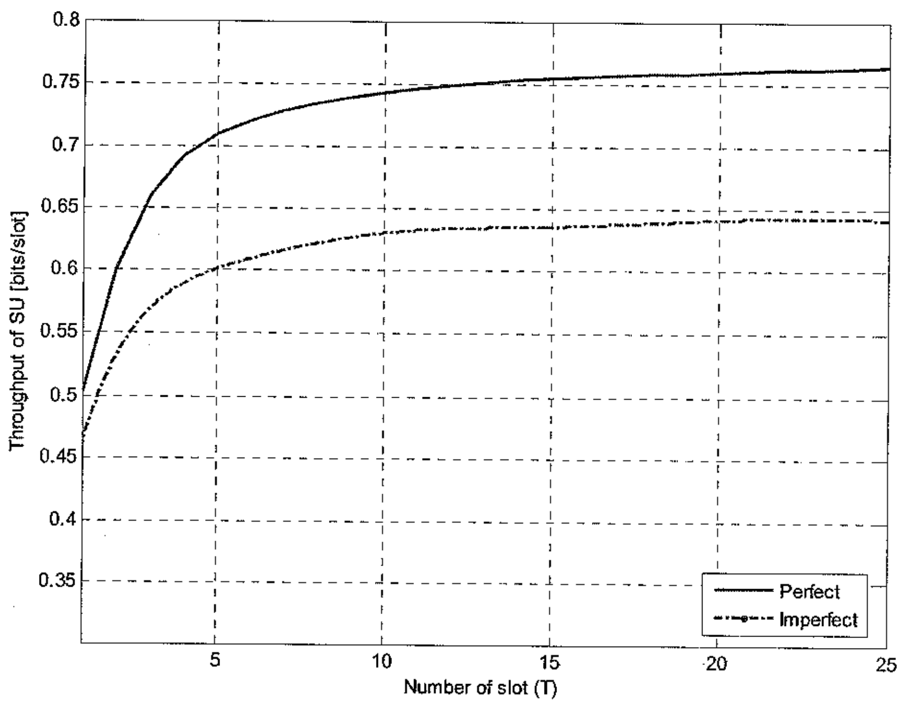

Figure 4.17 Perfect and imperfect comparison with N = 3, SNR = 5 dB, $B = 1$, ζ=0.2, $T = 25$, $\alpha = 0.1$ and $\beta = 0.9$.

Then, simulation setting for probability of collision allowable by PU is changed by increasing collision threshold value into $\zeta = 0.5$. As shown in Fig. 4.18, although setting of ζ is changed (the threshold value of collision allowed by PU network on imperfect channel is increased), the throughput performance of perfect channel sensing case outperform the imperfect one, since sensing errors absolutely cause collision and waste the access opportunities. Spectrum sensing over perfect channel results higher throughput performance than imperfect case, since noise has a significant impact to the performance degradation.

The following simulation investigates the effect of noise to the throughput performance of CR system through varying SNR values. SNR value relates to how good primary signal is detected by SU transceiver. To evaluate the performance, throughput as a function of slot number is used as a metric.

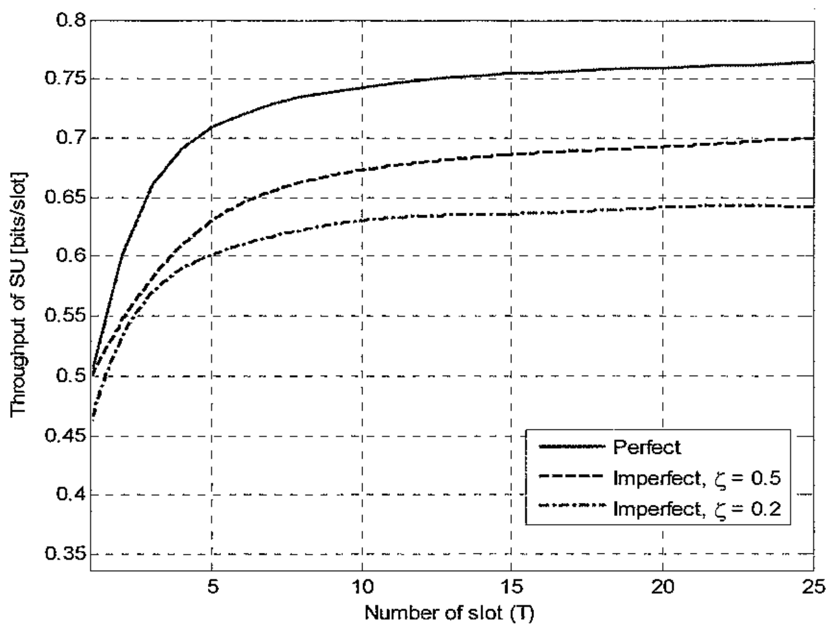

Figure 4.18 Comparison of perfect and imperfect with N = 3, SNR = 5 dB, B = 1, T = 25, $\alpha = 0.1$ and $\beta = 0.9$

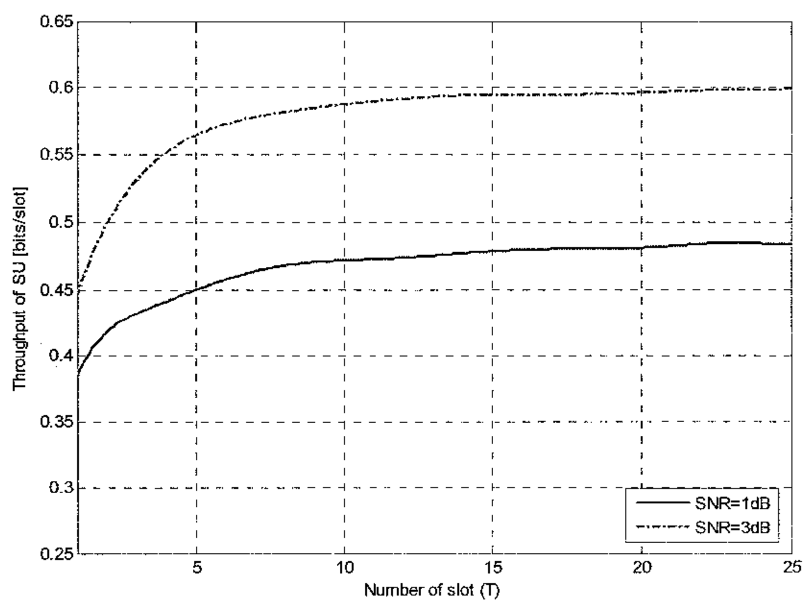

Figure 4.19 The impact of signal to noise ratio (SNR) to the imperfect greedy sensing strategy

As the obtained results in Fig. 4.19, greedy sensing over imperfect sensing case is able to maximize the throughput and gains the information during T slot transmission time. The comparison is taken when SNR is set to 1 dB and 3 dB, and probability of collision allowable by PU, ζ = 0.3. Increasing value of SNR can improve the throughput performance since high SNR value results to high probability of detection and lead to the throughput improvement.

Fig. 4.20 shows the obtained results in investigating the impact of SNR to the throughput performance.

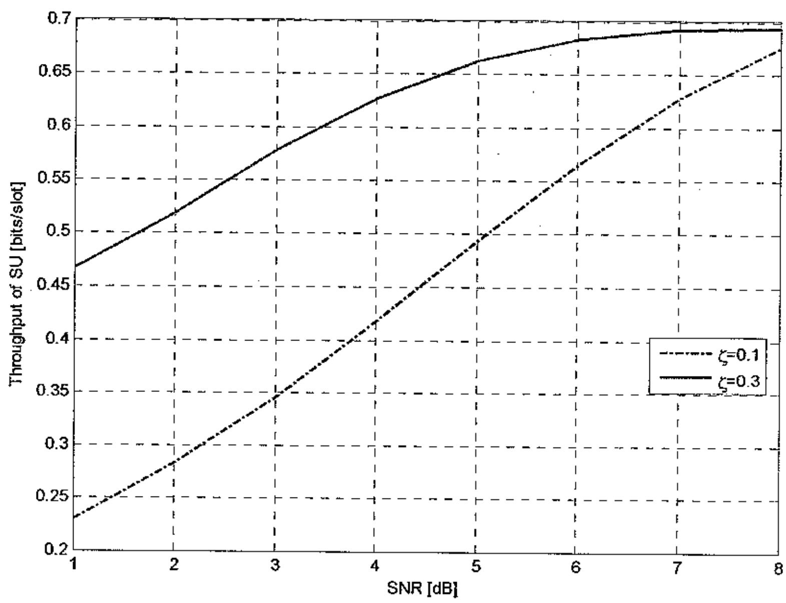

Figure 4.20 The throughput performance as a function of SNR with different collision threshold

The results draw the throughput performance as a function of SNR with different collision threshold ζ = [0.1, 0.3]. Increasing SNR can improve the throughput performance, since spectrum sensing errors is minimized. The throughput performance with collision threshold ζ = 0.3 is higher than ζ = 0.1. However, when SNR increases, the throughput performance with collision threshold ζ = 0.1 improves significantly. It means that increasing SNR can increase detection probability as well, and lead to the improvement of throughput performance.

According to the simulation and the obtained results, two kinds of parameter affect to probability of detection. Those are collision threshold (ζ) and SNR. Increasing these values will improve the throughput performance. Previously shown the relation function curve between false detection (ε) and ζ. Lower false detection increases detection probability and automatically will improve the throughput performance. This simulation keeps other parameter setting remain unchanged, where number of slot T = 25, number of channel N = 3, bandwidth B = 1, transition probabilities $\alpha = 0.1$ and $\beta = 0.9$.

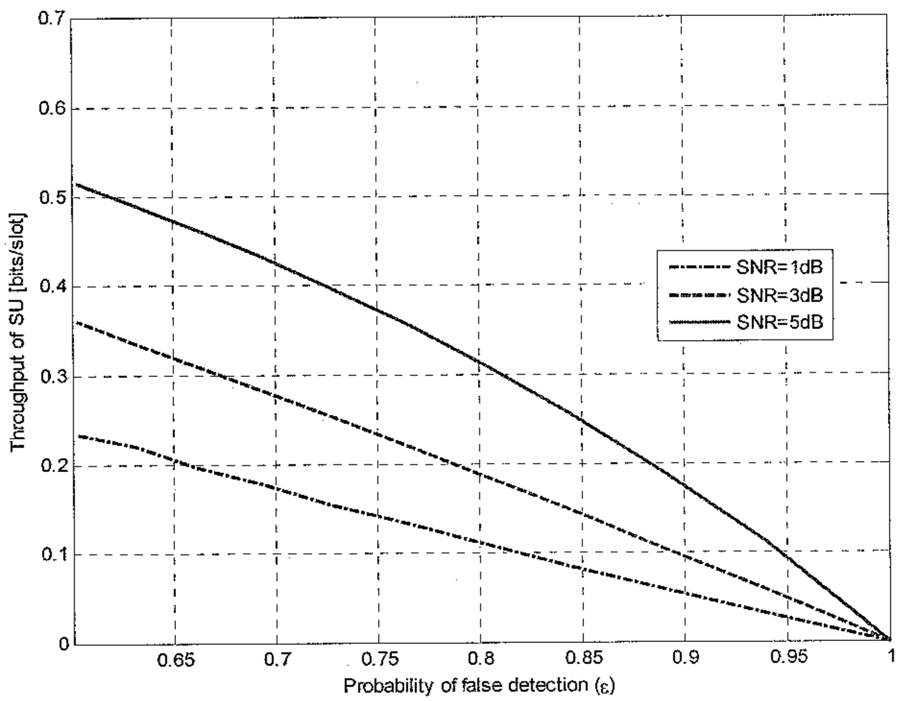

Figure 4.21 The throughput performance of SU as a function of false detection probability with different SNR setting

The obtained results on Fig. 4.21 describe the impact of false detection to the throughput performance with different SNR setting. The comparison of the throughput performance with 3 different SNR values; 1 dB, 3 dB, and 5 dB, is plotted as a function of false detection probability. The throughput performance is inversely proportional to the SNR values. In each of 3 values of SNR setting, increasing false detection (ε) can degrade the throughput performance.

At SNR = 5dB, the throughput performance is higher than other values of SNR setting. It is due to higher value of SNR improves the detection capability of SU as well as decrease the probability of false detection. This simulation set number of slot T = 25, bandwidth B = 1, number of channel N = 3, transition probabilities $\alpha = 0.1$ and $\beta = 0.9$.

4.4.2 Performance of spectrum efficiency

We further study the spectrum efficiency by considering both primary and secondary users. Spectrum efficiency is defined as a number of transmitted bits during one slot transmission over a given bandwidth. The obtained results are presented in Fig. 4.22. It evaluates the spectrum efficiency as a function of collision threshold with different SNR as a metric.

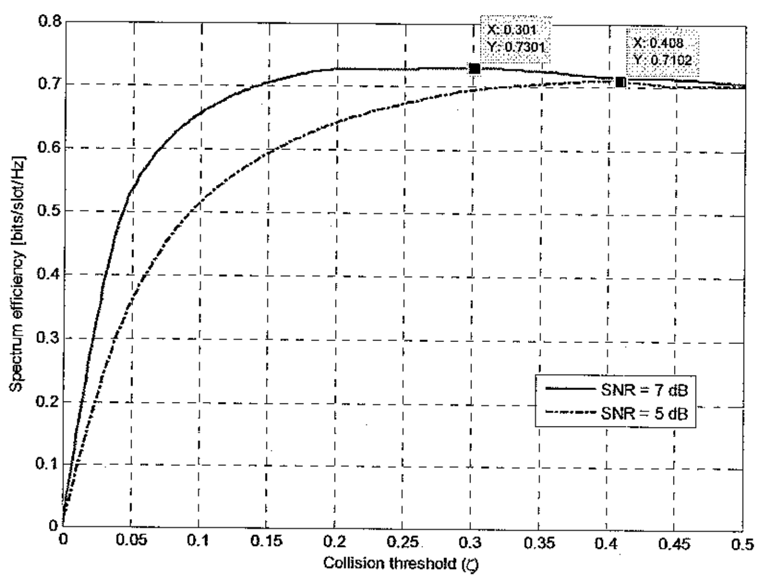

Figure 4.22 Spectrum efficiency as a function of collision threshold

As described in that figure that frequent collision indicated by higher collision probability decreases overall spectrum efficiency for primary and secondary users. At lower values of collision threshold, spectrum efficiency is gradually improved. At certain point of value, spectrum efficiency starts to decrease as probability of collision threshold increases. At this point, spectrum efficiency reaches the maximum value. In that figure, at SNR = 5 dB, the maximum value of spectrum efficiency or the best spectrum efficiency reaches 0.7107 bits/slot/Hz when collision threshold, $\zeta_{5dB} = 0.4$. The different SNR may change the achievable spectrum efficiency as well. At SNR = 7 dB, the best spectrum efficiency that can be achieved are 0.7301 bits/slot/Hz at collision threshold $\zeta_{3dB} = 0.3$. This simulation set N = 3, B = 1, T = 25, $\alpha = 0.1$ and $\beta = 0.9$.

Number of sensed channels has an impact to the spectrum efficiency in CR system. As described in Fig. 4.23, the comparison of 3 and 5 number of sensed channels as function of collision threshold at SNR = 5 dB is taken.

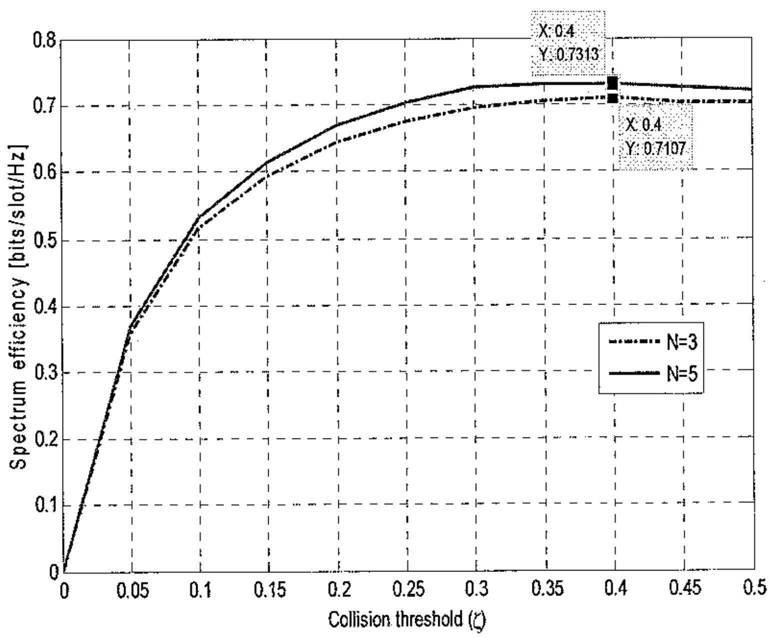

Figure 4.23 Spectrum efficiency as a function of collision threshold with different N

Increasing number of sensed channels can improve the spectrum efficiency. The existing number of sensed channels can increase the probability of accessible channel by SU.

Then, the next simulation studies the impact of SNR to spectrum efficiency performance. Simulation plots spectrum efficiency (bit/slot/Hz) as function of SNR with different number of channel. As shown in Fig. 4.24, increasing SNR and number of channel can affect to the spectrum efficiency improvement. Simulation keep other parameter setting remain unchanged, where $N_1 = 3$ and $N_2 = 5$ channels, B = 1, T = 25, $\alpha = 0.1$, $\beta = 0.9$, and $\zeta = 0.05$.

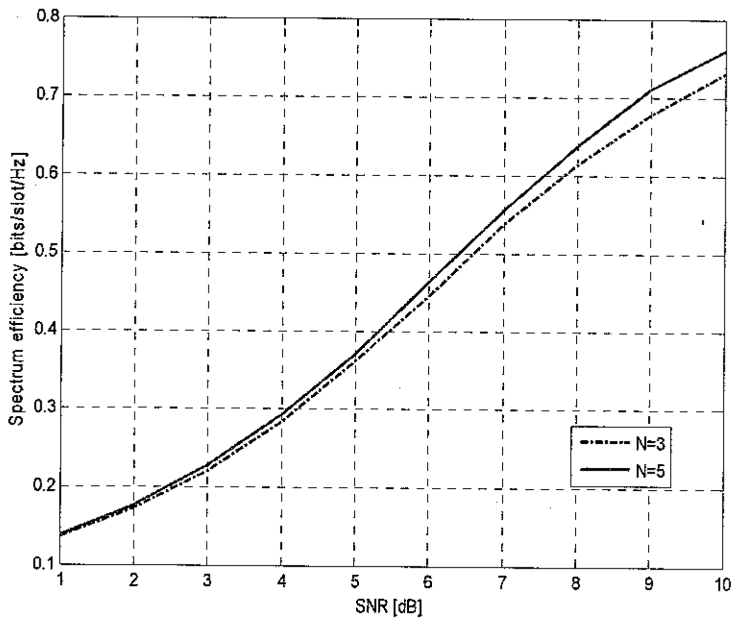

Figure 4.24 Spectrum efficiency as a function of SNR values with different N

4.5 Cross Layer Design Principle in Cognitive Radio System

This simulation studies spectrum sensing on physical layer and spectrum access (in term of throughput) on MAC layer. In other word, the impact of spectrum sensing at physical layer is further investigated by considering spectrum access at MAC layer. The impact of channel measurement (L) and the percentage of sensing time during one slot time to the throughput of SU are studied. The more sample of channel measurement is taken leads to the more spectrum occupancy state data can be achieved. It improves the fidelity of sensing outcome. However, this action will decrease the data transmission time and drops the throughput performance.

To accomplish the requirement, simulation adopt POMDP framework, which has a limited spectrum sensing capability by modelling primary network behaviour as Markov discrete process. The values of 0 indicate channel spectrum is available for SU and allow to access using those channels. While the values of 1 indicate channel is in busy state, meaning that primary user is using the channel for transmission. In this state, SU is not allowed to use the channel; otherwise it collides to PU activity.

According to the structure of slot in cognitive MAC as describe in Fig. 3.6, at the beginning of slot, SU choose L number of channel to sense with the same value of SNR. The collision to PU occurred when SU senses busy state as idle channel (miss-detection). The throughput of SU obtains optimal value when probability of collision threshold equal to miss-detection probability ($\delta_* = \zeta$).

The ROC curve is shown in Fig. 4.25. The curve plots the probability of detection P_D (1-δ) as a function of probability of false detection P_F with different sample of channel measurement (L). We set the sample channel (L) to 2 and 4 and the received signal by SU is 5 dB.

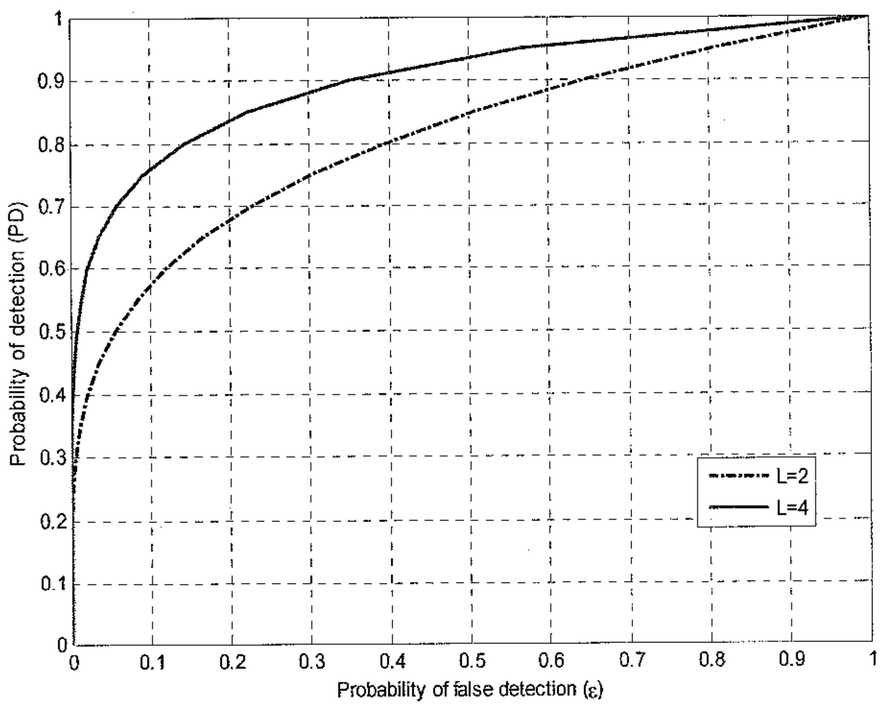

Figure 4. 25 Characteristic of ROC curve with L = [2, 4] and SNR = 5dB

Through this curve, we design spectrum sensor and achieve the tradeoff between probability of false alarm and probability of miss-detection. Higher probability of false detection can degrade the throughput performance of SU. On the other hand, if miss-detection case is more frequently occurred, it can cause collision to PU.

Firstly, we have to determine the optimal sensor operating point with regard to the MAC layer performance in terms of throughput and collision probability. The more sample of channel measurement is taken, higher probability of detection value can be obtained and decrease δ value. Increasing number of sample can increase probability of detection and lead to increase the fidelity of sensing outcome. However, taking more sample of channel measurement requires longer time for sensing and it causes lower throughput achievement. The requirement of this design objective is how to achieve good throughput performance while maintaining the sensing time low.

False detection and miss identification are types of sensing error that cannot be avoided during primary signal detection. High detection probability can increase the accuracy of signal detection and at the same time decreases miss identification. On the other hand, lower detection probability implies to increase false detection and waste the access opportunities. When SU misses the channel access opportunities, it will drop the throughput performance.

Regarding to this issue, it is required to determine which the optimal sensor point must be taken by considering false detection and miss identification while maintaining optimal detection probability. By using ROC curve, we design the tradeoff of sensing capability and the throughput of SU (optimal design can be derived when $\delta_* = \zeta$)

Simulation plots a curve for false detection probability as function of SNR with detection probability, $P_D = 0.9$. The values of SNR indicate primary signal power, where increasing it will increase the capability of primary signal detection by SU. Simulation varies the values of SNR and observes the plot of false detection probability. Sample of channel measurement is set to $L = 5$.

According to Fig. 4.26, increasing the signal power of primary user (SNR) can decrease false detection probability. It implies to the improvement of throughput performance since less false detection means less sensing error for primary signal detection. Previously, simulation plots a curve between throughput performances as a function of primary signal power (SNR) with different collision threshold, where increasing SNR can improve the throughput, otherwise it degrades the performance.

This section will plot and observe the throughput performance in relation to false detection. It mentioned earlier that false detection wastes the access opportunities of SU and lead to the lower throughput performance.

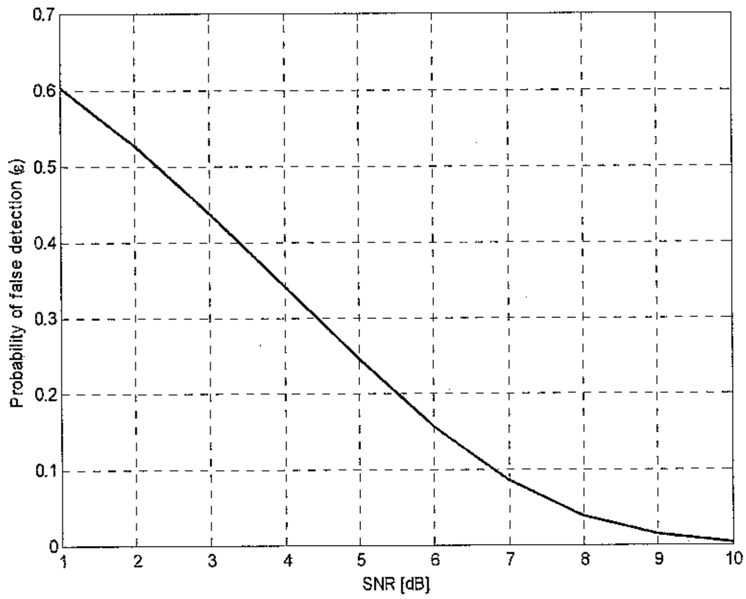

Figure 4.26 Probability of false detection as a function of SNR with L = 5

Fig. 4.21 describes the achievable throughput performance as function of false detection with different signal power. Increasing signal power definitely improves the throughput performance. Less false detection implies to higher primary signal detection capability.

According to that figure, SU achieves a good throughput performance at less value of ε. When false detection increases, it gradually drops the throughput performance. This simulation result confirms that increasing level of signal power, can decrease false detection and lead to the improvement of throughput performance.

Fig. 4.27 shows probability of false detection P_F (ε) as a function of channel measurement sample (L) with collision threshold $\delta = 0.15$ and SNR = 5dB. As mentioned earlier that false detection has an impact to the optimality of spectrum access. Higher values of false detection waste the opportunities, meaning that the probability of SU miss the available channel to be accessed becomes high.

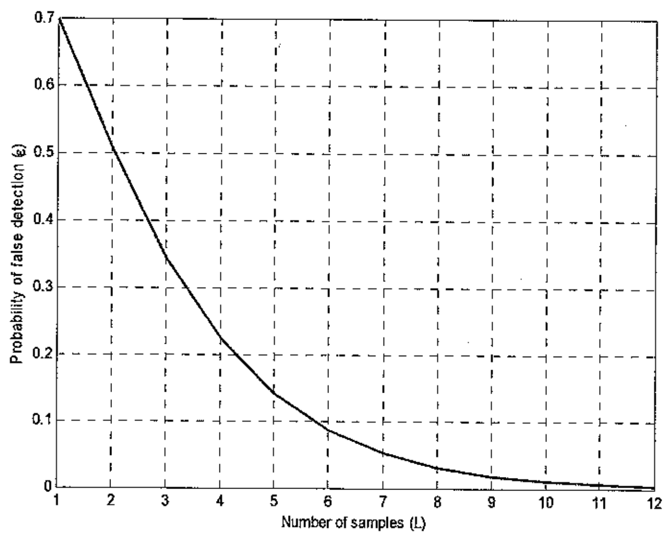

Figure 4.27 Probability of false detection as a function of number of measurement sample

Conversely, low false detection makes the probability of SU misses the available channel spectrum to be accessed becomes low. In this case, increasing channel measurement sample can decrease false detection and lead to high throughput performance. However, when channel measurement sample is low, probability of false detection becomes high, and lead to the low throughput performance.

Moreover, there is a relation between number of sample (L) and time requirement for sensing. More number of measurement sample will need longer time for sensing, on the other hand, less number of measurement sample makes time requirement for sensing becomes shorter. Therefore, there is tradeoff between period of sensing (sensing capability) and data transmission (throughput performance) of SU. The requirement is high throughput performance while maintaining sensing time low.

4.5.1 Throughput performance as a function of measurement sample

The curve between spectrum sensing actions to the throughput performance is shown in Fig. 4.33, where the effect of channel measurement sample (L) to the throughput of SU was further studied. Measurement sample indirectly relates to time requirement for sensing.

At first done, simulation assumes that spectrum sensing action take 3% allocation of one slot time for channel measurement. During this period, SU senses the availability of primary channel. As previously mentioned, reward is number of bit transmitted over one slot and it is proportional to channel bandwidth. When simulation takes a certain portion of slot to sense the existing primary channel, the period of data transmission time slot becomes 1-P*L. Notation of P is defined as the slot portion of channel sensing (%). In this case, the slot of data transmission time becomes 1-0.03L. According to the formulation of reward function, it can be modified becomes

$$r_{j,A_1,A_2}(t) = (1 - 0.03L) \sum_{i \epsilon A_2} S_i(t) B_i \tag{5.9}$$

where $S_i(t)$ is state of the primary channel. Channel bandwidth (B) for each channel is set to 1, transition probability $\alpha = 0.1$, $\beta = 0.9$, number of slots T = 25, and signal to noise ratio SNR = 5dB for each channel.

Fig. 4.28 shows the throughput of SU as a function of channel measurement sample (L) with different collision threshold ζ to PU, 0.05, 0.15, and 0.25 respectively. L number of channel measurement has an impact to the values of false alarm probability (P_F) and miss-detection probability (P_M) as shown in the formulation (4.4) and (4.5).

Probability of false detection ε denotes the percentage of channel detection for idle state as a busy state. When ε is high, the percentage of SU that refraining from data transmission becomes high. It is because SU waste the opportunities of channel access and influences to lower throughput performance. On the other hand, less false detection makes the probability of channel access becomes high that leads to higher performance of throughput.

There is a trade-off between sample of channel measurement *(L)* and the throughput performance. As described in the figure, the throughput of SU has an improvement when sample of channel measurement increases, and it reaches the optimal value at certain point of measurement sample. However, it gradually drops the performance when sample of channel measurement is getting higher. It can be explained that when number of sample channel measurement is low, time requirement for sensing action becomes shorter and lead to improve the throughput performance of SU until a certain point of L. On the other hand, when number of channel measurement increased, the time requirement for sensing action is getting longer and it gradually drops the performance of throughput. The optimal values are reached at 0.4602, 0.5426, and 0.5793 [bits/slot] for collision threshold ζ 0.05, 0.15, and 0.25 respectively. The derived results conclude that a fewer channel measurement sample (L) should be taken when probability of collision allowable by PU (ζ) is high.

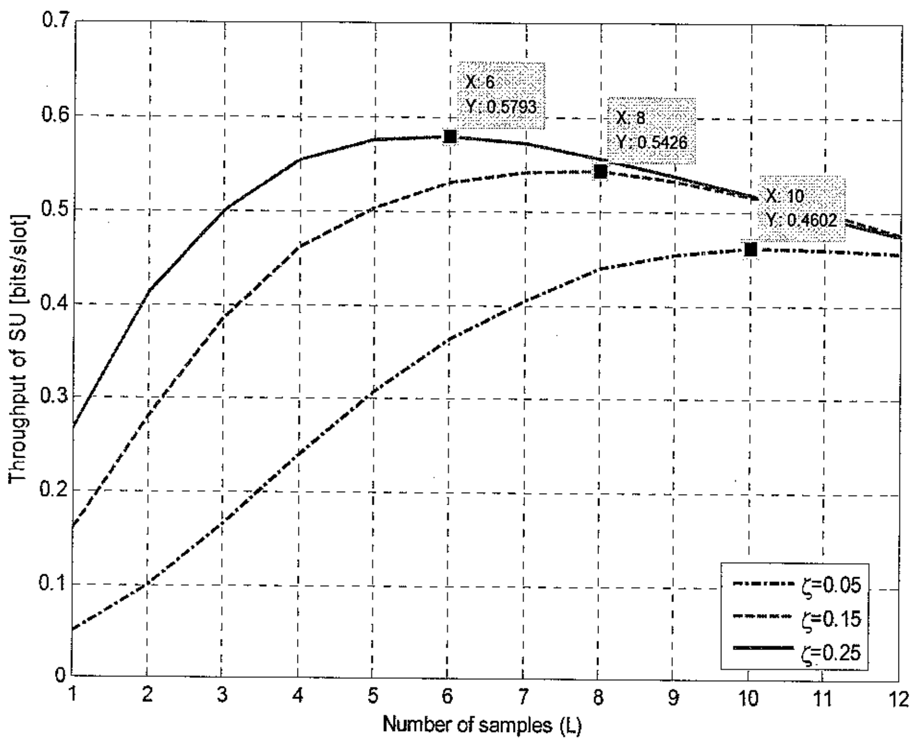

Figure 4.28 Throughput performance as a function of number of L with different ζ, B = 1, N = 3, T = 25, α = 0.1, β = 0.9, and SNR = 5dB

Furthermore, simulation changes setting of transition probabilities. The transition probabilities set to α = 0.3 and β = 0.7 and keep other parameters remain unchanged. The simulation result is shown in Fig. 4.29. The change of parameter setting result the different optimal throughput. The throughput performance reaches the optimal values at 0.3814, 0.4456, 0.4730 [bits/slot] at measurement samples L = 10, L = 7, and L = 5 for collision threshold 0.05, 0.15, and 0.25, respectively.

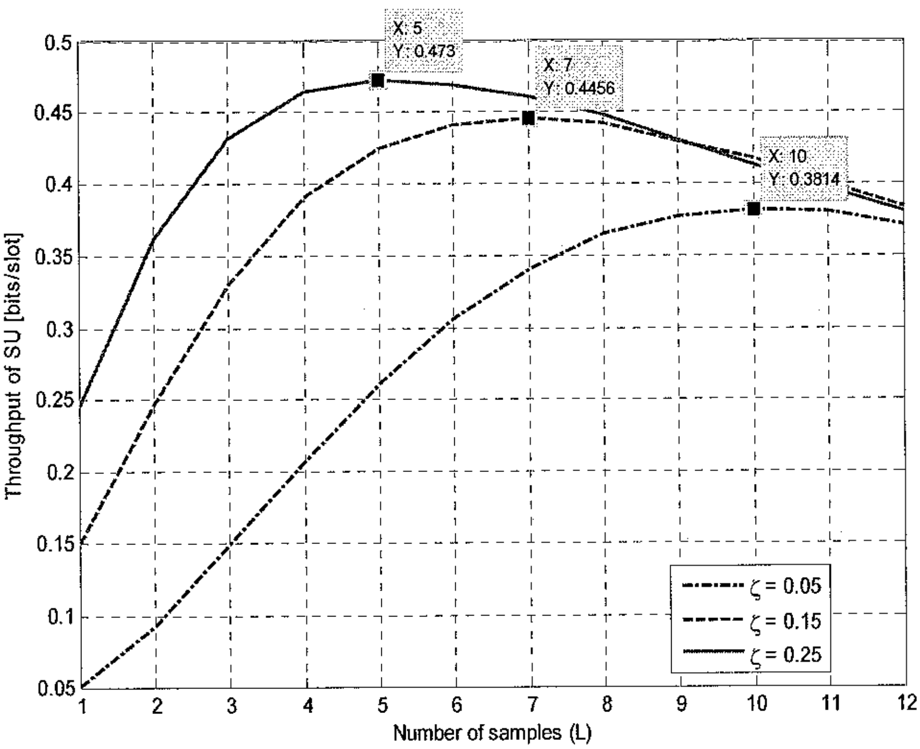

Figure 4.29 Throughput performance as a function of L with different collision threshold (Pc), $B = 1$, N = 3, T = 25, α = 0.3, β = 0.7, and SNR = 5dB

4.5.2 Throughput performance as a function of sensing slot portion

Fig. 4.30 shows the curve of throughput performance as a function of sensing slot [%] with different collision threshold ζ. Collision threshold is defined as how frequently CR user is allowed to collide with PU. Higher value of collision allowable by PU causes number of bit transmitted within one slot becomes higher (throughput improvement). The throughput improvement is influenced by frequency of collision. As described in that figure, When ζ is set to 0.25, the throughput performance outperforms other setting of ζ.

This figure confirms that increasing the portion of sensing slot (time requirement for sensing action becomes longer) will lead to decrease the time slot for data transmission action (time requirement for data transmission becomes shorter) and will have lower throughput performance of SU.

According to the structure of cognitive slot, longer sensing period can achieve more spectrum occupancy state data that will increase the fidelity of sensing outcome. However, this action will reduce the period of data transmission. In order to achieve the optimal throughput performance, it is requires to consider the curve between throughput performances as a function of measurement sample. As the derived results, a fewer sample of measurement L should be taken when ζ increases.

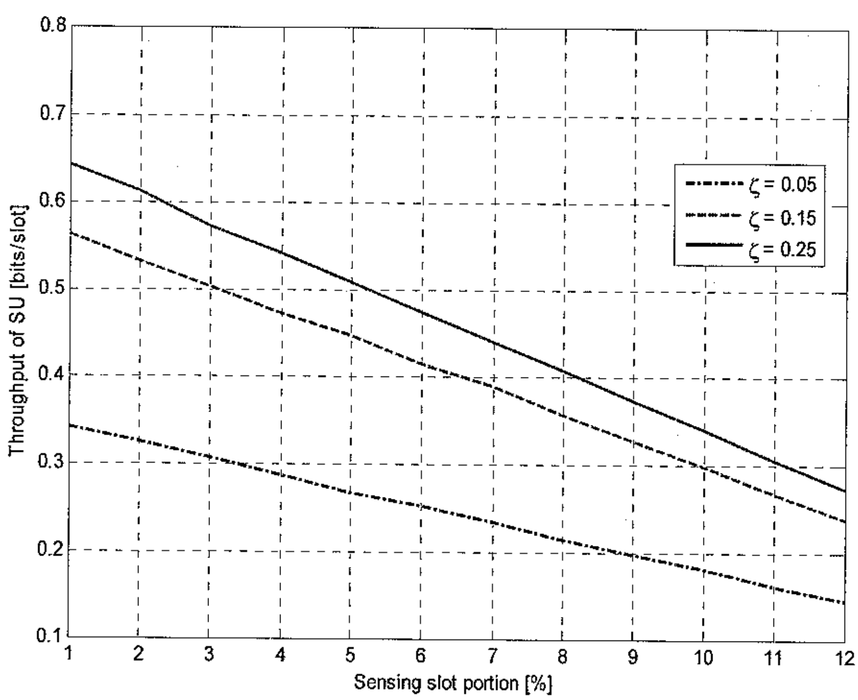

Figure 4.30 Throughput performance as a function of sensing slot portion with different ζ, B = 1, N = 3, T = 25, $\alpha = 0.1$, $\beta = 0.9$, and SNR = 5dB

4.6 Decentralized Multiuser Cooperative Spectrum Sensing Model

This section discusses simulation results for decentralized CSS model under POMDP. To validate our proposed model, it is compared with single user sensing, full band random CSS model and centralized CSS model. A certain number of SUs are considered in this work.

The performance is evaluated based on the greedy sensing policy. Sensing error is considered in this simulation as well, in which SU senses spectrum opportunities over imperfect propagation. At the beginning of a slot, each of SUs sense spectrum opportunities and observing spectrum occupancy states. For SU who have no packets to transmit, it is no need to participate in channel selection for sensing. Secondary user updates belief states according to Markovian model of spectrum occupancy. Secondary users with packets to transmit will select channels according to the greedy sensing policy and update their belief states based on sensing outcomes and observation.

Based on the exchange of local sensing result, SU makes a final decision. If SU select one available channel, it means that one of them will succeed in channel access and packet transmission. Channel access of DMCSS follows eq. (3.41) where error function (probability of miss detection) can be calculated by eq. (3.39) and (3.40).

4.6.1 Decentralized Multiuser Cooperative Spectrum Sensing

This sub-section concentrates on investigation of the performance for DMCSS model. Then, the following sub-section compares the proposed DMCSS model against single user sensing, full band random CSS model, and CMCSS model.

Fig. 4.31 shows the performance of DMCSS model where SU has different transition probabilities, case 1: $\alpha_1 = 0.1$, $\beta_1 = 0.9$; case 2: $\alpha_2 = 0.2$, $\beta_2 = 0.8$; and case 3: $\alpha_3 = 0.3$, $\beta_3 = 0.7$. There are 5 number of SUs sense 10 channels (N) where each channel has bandwidth B = 1, SNR = 5 dB, and probability of user i to sense channel, p = 0.5. Maximum collision allowed by PU (collision threshold) $\zeta = 0.3$. Secondary user transmits data packet during T slots. (T = 25).

According to the obtained results, each case is able to improve the throughput performance by gaining the information from previous slots and past observation. Case 1 outperforms other cases (case 2 and 3) since setting of transition probability remain unchanged (β) is greater than others. As presented in previous chapter that increasing transition probability β can improve the throughput performance. Number of transmitted bits was improved with number of slot increases.

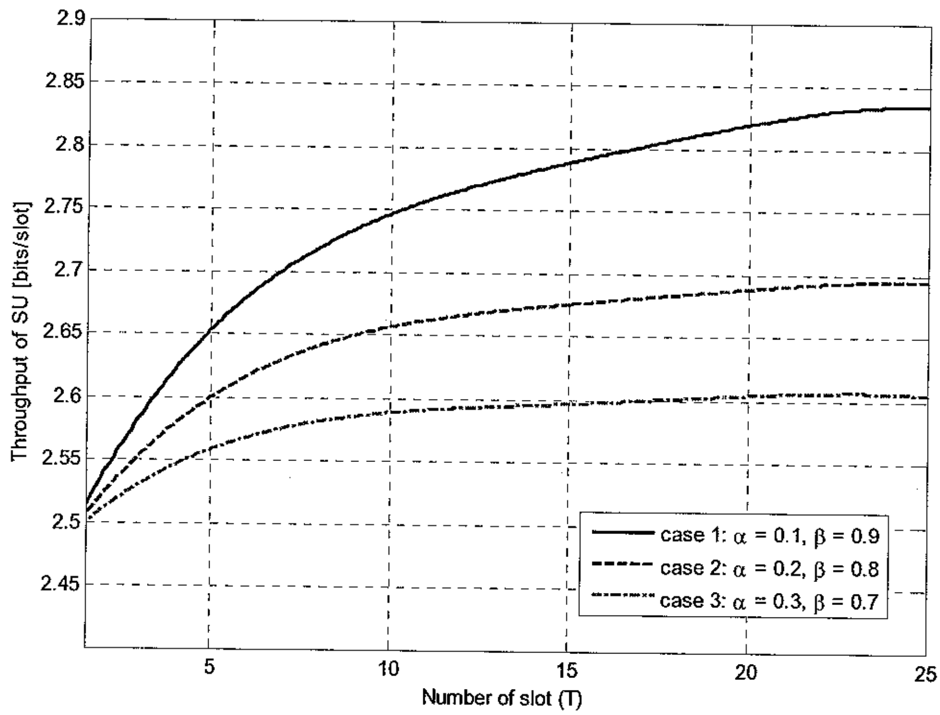

Figure 4.31 The throughput performance with different transition probability for DMCSS model

Fig. 4.32 shows the throughput performance with different probability of miss detection (δ). Simulation result compares 2 cases with different miss detection probability setting, δ_1 = 0.1 and δ_2 = 0.3. Higher probability of miss detection will drop the throughput performance.

Fig. 4.33 clearly shows the result for throughput performance as a function of probability of miss detection. Miss detection causes collision to PU activity and lead to the degradation of throughput performance. Increasing probability of miss detection means more frequent collision to PU is occurred. This condition definitely decrease the number of bit transmitted during T slots. Simulation sets probability of user *i* to sense channel L, $p = 0.5$.

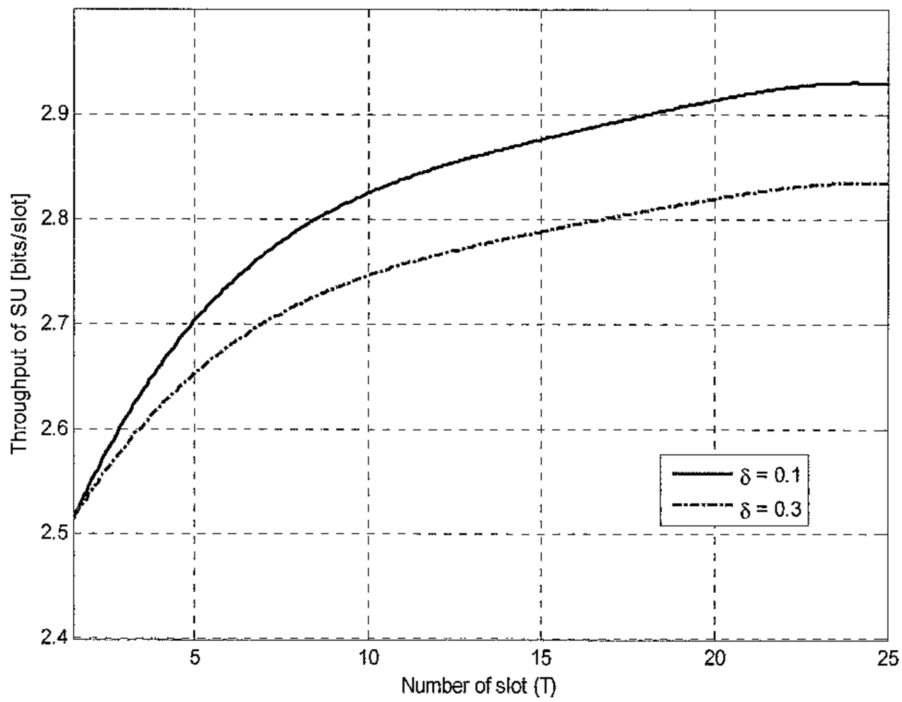

Figure 4.32 Throughput performance with different probability of miss detection for DMCSS model

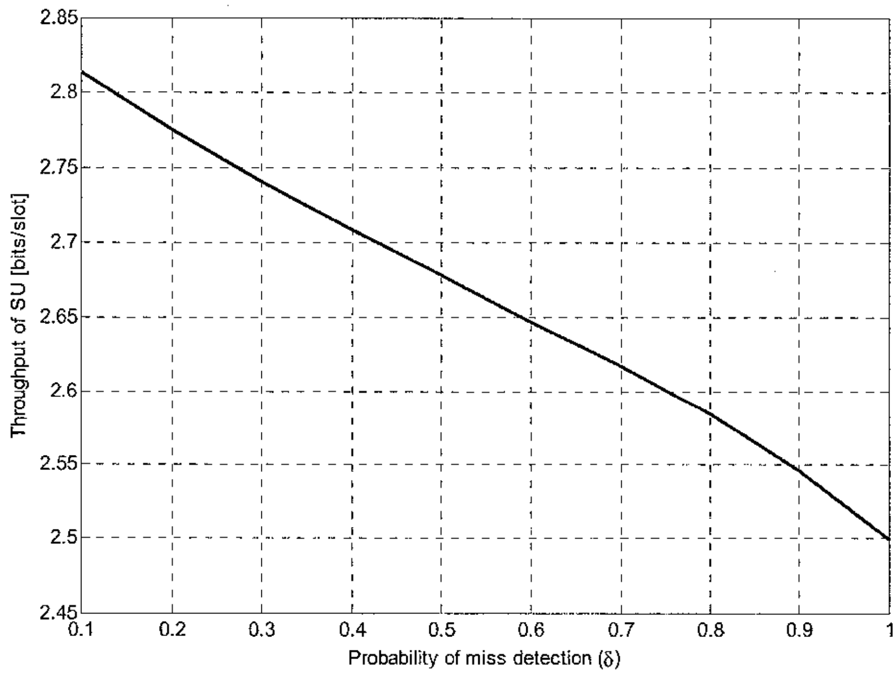

Figure 4.33 Throughput performance as function of miss detection probability for DMCSS model.

Fig. 4.34 shows the comparison of 2 cases for p = 0.5 and p = 0.9. According to the obtained results indicates that when the probability of SU select a certain channel to sense is higher, it implies to the throughput performance. Higher probability value of *p* leads to improve the throughput performance.

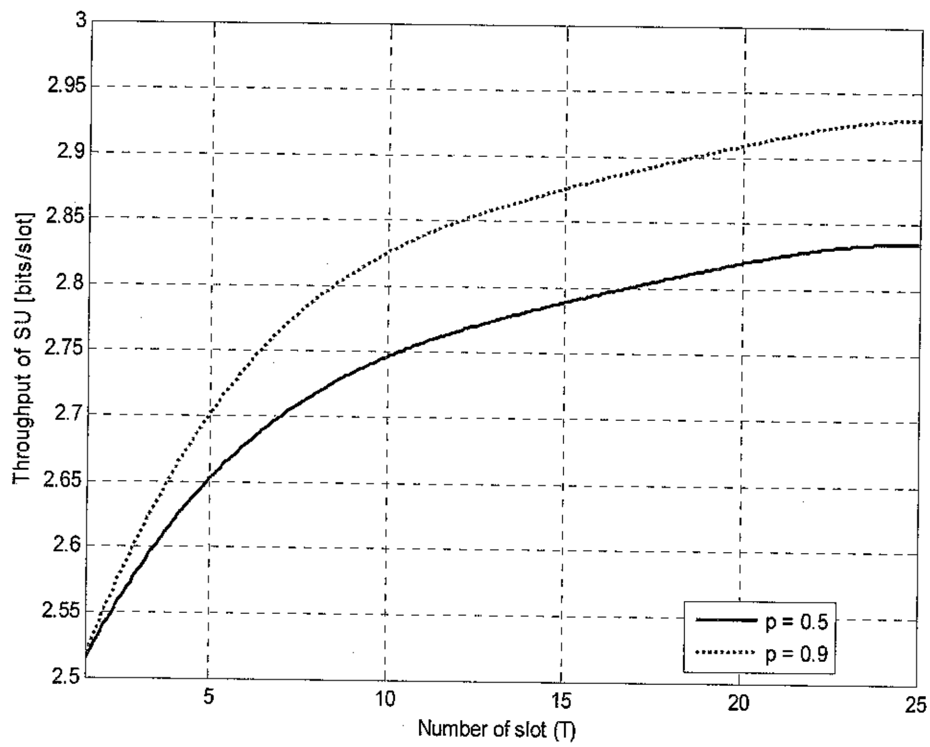

Figure 4.34 Throughput performance as function of slot number with different probability value of *p* for DMCSS model

Furthermore, simulation draws the plot of result for achievable throughput as a function of selected channel probability (p) in Fig. 4.35. The performance of throughput improves as the probability of selected channel (*p*) increases.

The impact of number of SU that collaborated for sensing against throughput performance is described in Fig. 4.36. We draw the plot of throughput performance during T transmission slot with different number of SUs. It is assumed that 5 and 10 SUs that have collaboration to sense channel spectrum by keeping previous parameter setting (i.e. B, α, β, N, and ζ) remain unchanged. The obtained results show that simulation with 10 numbers of SU has better throughput performance than 5 SUs.

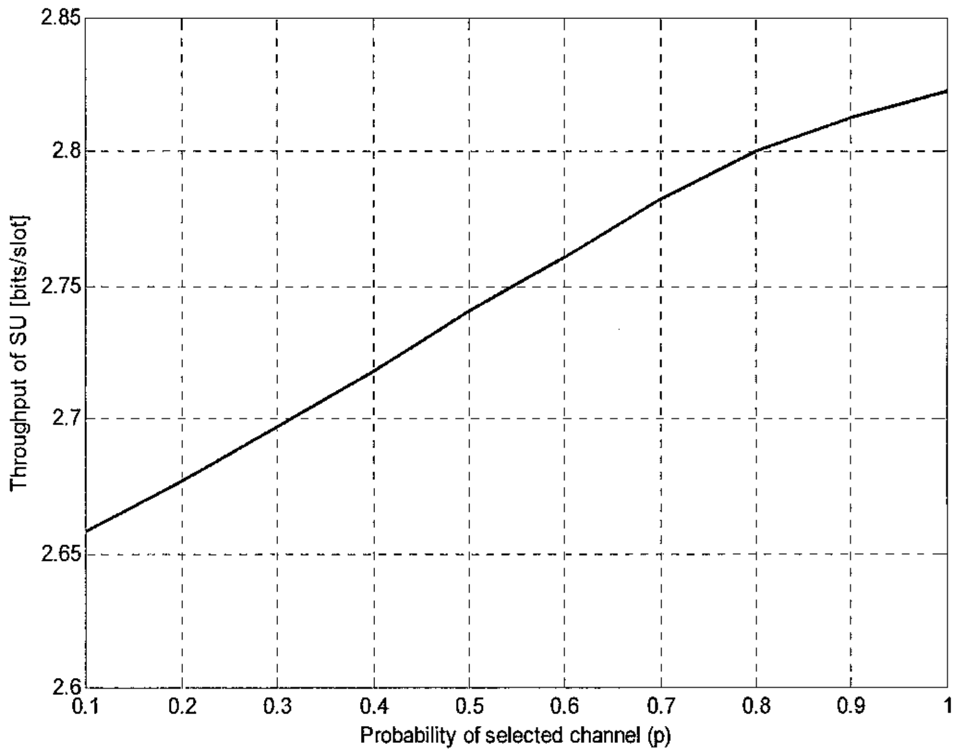

Figure 4.35 Throughput performance as a function of selected channel probability *p*

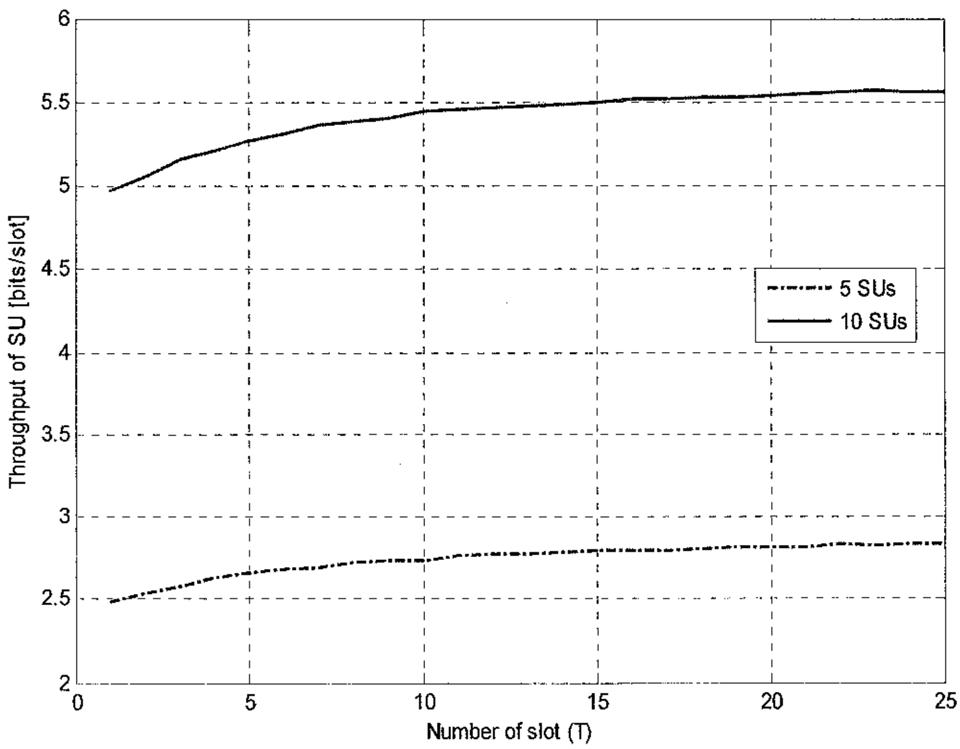

Figure 4.36 Throughput performance with different number of SU

Increasing number of collaborated user for channel sensing is able to increase probability of detection and implies to improve throughput performance. It is more clearly shown in Fig. 4.37, which describes the achievable throughput performance as a function of number of collaborated user. The obtained result concludes that throughput performance is proportional to number of collaborated user.

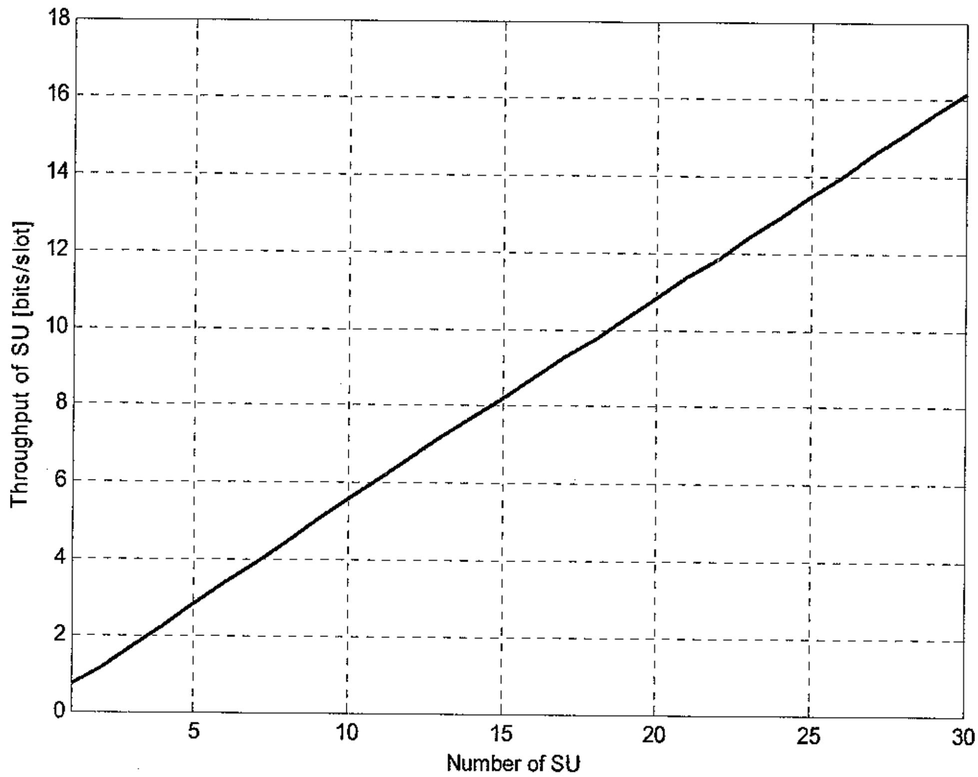

Figure 4 37 Throughput performance as a function of number of SU

Fig. 4.38 describes the throughput performance that is measured during T transmission slot with different channel fading. It is indicated by different received signal to noise ratio (SNR) and assumes each SU has uniformly SNR values. Simulation sets two values of SNR (0 dB and 5 dB).

According to the obtained result shows that different received SNR implies to the throughput performance. The throughput improves with the received signal power (SNR) increases. It is more clearly shown in Fig. 4.39 which plots the performance of throughput as function of SNR (ζ = 0.3). The received signal power has a significant impact to the throughput performance of SU.

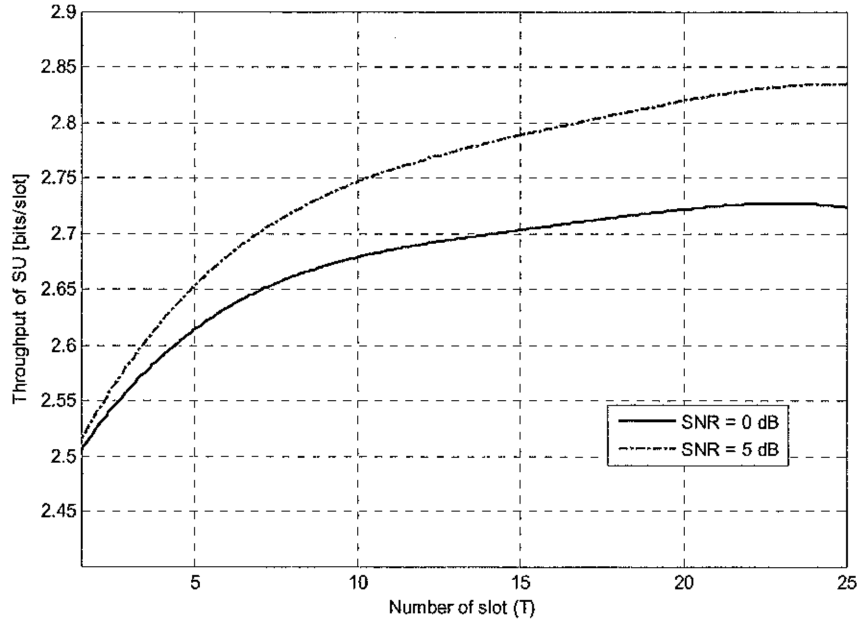

Figure 4.38 The throughput performance with different received signal power

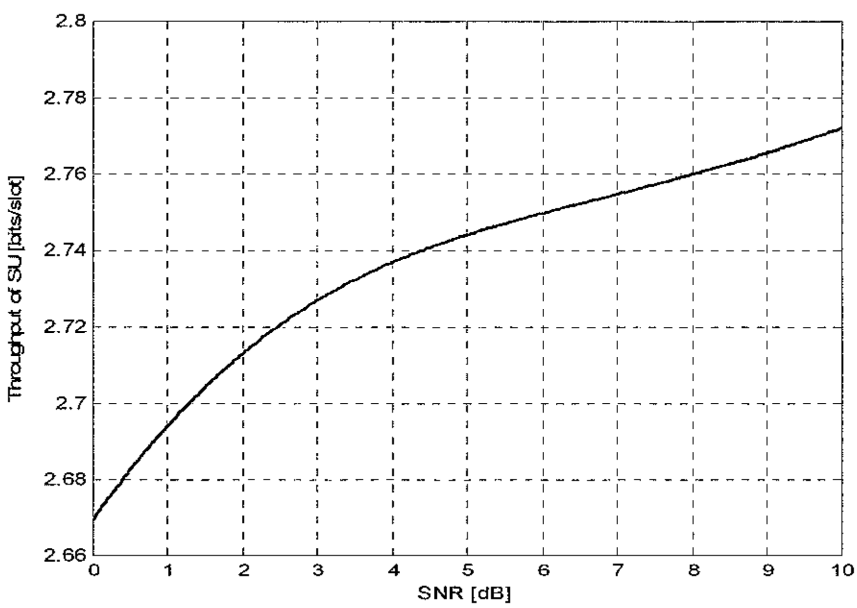

Figure 4.39 The performance of throughput as a function of received signal power (SNR)

According to queuing theory, arrival rate is defined as a number of packet or data arrivals during one time unit. The following simulation draws the plot of throughput as a function of arrival rate. Packet arrival rate forms Poisson process with rate λ. The packet length is distributed with the average of 50 packets. It is assumed that the transmission of one packet to be one slot.

Secondary user transmitter sends the packet continuously and will assign randomly to the receiver. Those SUs who do not have a packet to send, they will not participate to select a channel for sensing and access. They turn to sleep mode on and update their belief vector according to Markovian model of spectrum occupancy state. On the other hand, SU who have a packet to send will select a certain number of channels to sense and access by following greedy sensing policy. After transmission, SU updates belief vector according to sensing outcome and observation.

Fig. 4.40 shows the performance of throughput as a function of packet arrival rate. Simulation sets number of SUs = 5 that participate on channel sensing and access with uniform signal to noise ratio values, SNR = 5 dB over decentralized CSS. The derived results show the throughput improves with arrival rate (λ) increases.

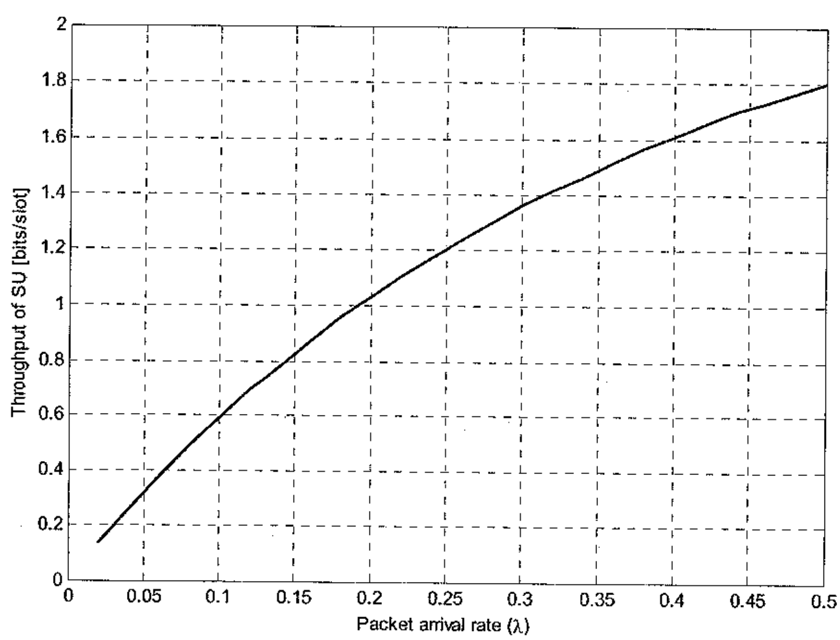

Figure 4.40 Throughput as a function of packet arrival rate (λ)

Furthermore, the achievable throughput performance compared with different number of SUs that participates on channel selection for sensing and access is described in Fig. 4.41. It is shown that the performance with number of 7 collaborated users outperforms 5 SUs setting as λ increases.

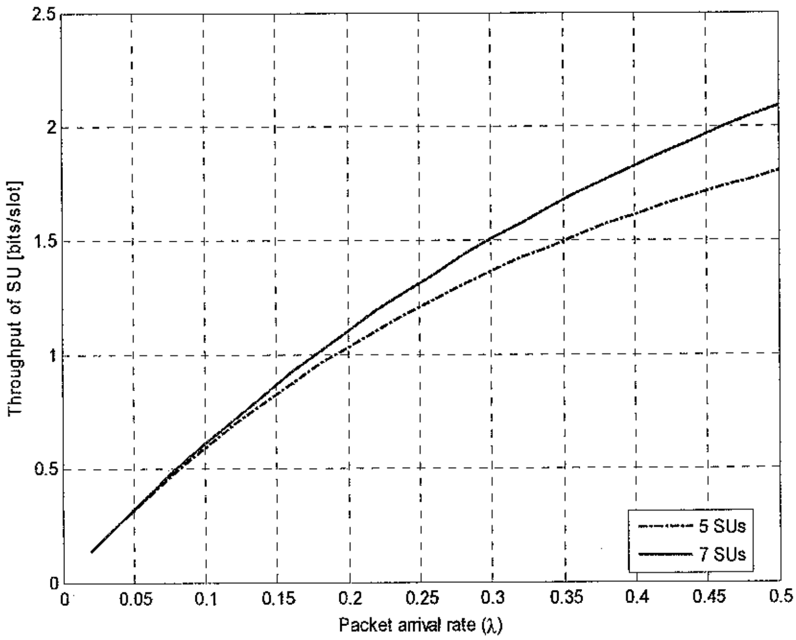

Figure 4.41 Throughput as a function of packet arrival rate (λ) with different user

4.6.2 Comparison and Validity

To validate our works, the proposed DMCSS model is compared with single user sensing, full band random CSS, and CMCSS model. It is used to observe and confirm our proposed model against the existing works.

CMCSS and full band random CSS model is used to compare the performance of DMCSS while single user is used to confirm that how robustness the performance of CSS model.

The fidelity of sensing outcome is affected by spectrum sensor design and probability of detection performance. Fig. 4.42 shows the comparison of detection probability between single user sensing and CSS model as a function of miss-detection probability. The obtained result confirms that CSS model outperforms single user sensing in term of detection probability. It definitely implies to throughput performance.

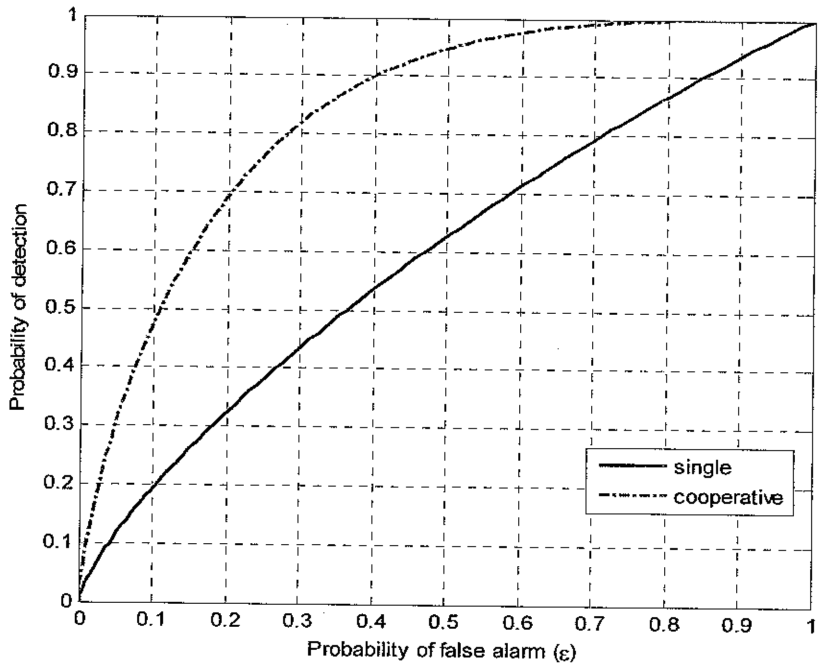

Figure 4.42 Characteristic of ROC for single user sensing and CSS model

4.6.2.1 Throughput performance as a function of number of slot

This sub-section presents throughput performance as a function of number of slot. Firstly, simulation result for DMCSS model is compared with the performance of single user sensing, random CSS, and CMCSS model, where the throughput or reward function (bits/slot) is used as a metric to evaluate the performance of SU. This simulation aims to observe the performance of proposed DMCSS and CMCSS model against single user sensing and random CSS model in CR system

In single user sensing, SU selects a channel without cooperation at each time slot. Simulation of CSS model sets number of SU = 5, number of channel N = 10 with equal bandwidth B = 1, transition probabilities $\alpha = 0.1$ and $\beta = 0.9$, collision threshold or maximum collision allowable by PU $\zeta = 0.3$, signal to noise ratio (SNR) for each SU is set to SNR = 5dB, and number of slot T = 25.

The achievable throughput performance of SU is shown in Fig. 4.43. Single user sensing is the worst case of throughput performance. In three cases (single user sensing, CMCSS and DMCSS model), simulation result confirms that SU improves the throughput performance as number of slot increases.

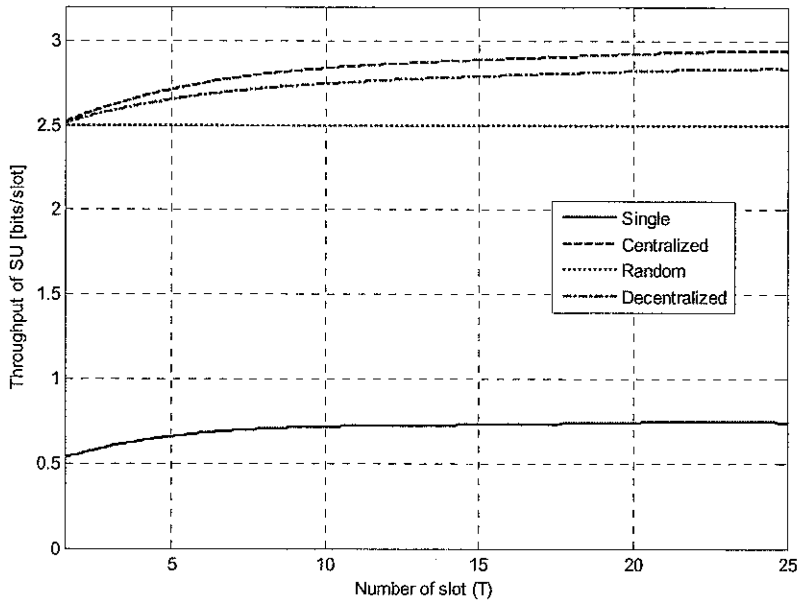

Figure 4.43 Throughput performance for single user sensing, random CSS, CMCSS and DMCSS model

In such cases SU gains information from previous slots and past observation for spectrum access, so that the total reward (total number of bits transmitted during T slot time) improves significantly.

Cognitive radio system under POMDP model provides a strategy that SU accesses channel with the highest idle probability, so that SU increases number of bit transmitted during T transmission slot. Meanwhile, random CSS model assumes SU accesses channel randomly without considering past observation and information from previous slots, so that SU cannot gain the throughput performance. In such case, spectrum access seems to have constant values relatively (throughput as a function of T).

The throughput of CMCSS performance outperforms DMCSS. However, DMCSS is far better than random CSS model and single user sensing. Cooperative spectrum sensing has a capability to reduce sensing error that implies to have a better probability of detection and throughput performance compared with single user sensing.

Simulation result shows that CMCSS model outperforms DMCSS. However, it can be seen later that DMCSS model achieve better performance than CMCSS in certain case. The following work focuses on DMCSS, CMCSS and random CSS model. The throughput performance of each CSS model is further compared as described in Fig. 4.44.

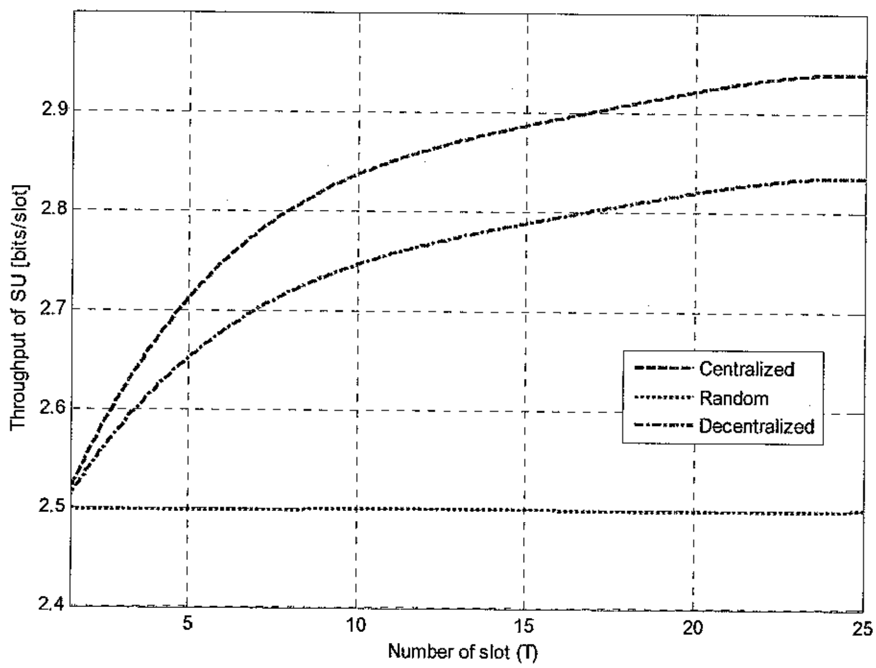

Figure 4.44 Throughput performance for DMCSS and CMCSS model compared with random CSS model

Centralized MCSS and DMCSS model can exploit the information from previous slot and past observation and directly improves the throughput performance. However, unlike CMCSS and DMCSS model, the achievable throughput of full band random CSS model is constant relatively as the transmission slot increases. In such case, SU consider that the selected channels have identical idle and busy probabilities. Secondary user cannot exploit information from previous slot and past observation to improve the throughput performance and gain the reward.

Furthermore, the achievable throughput performance during T transmission slot with different number of collaborated user will be further investigated. Two cases are considered where there are 5 and 10 numbers of collaborated users participating on primary signal detection. To evaluate the performance, the achievable result is compared with random CSS model. The result is presented in Fig. 4.45. In case of 10 numbers of collaborated users, the throughput has a better performance than 5 number of collaborated users. The obtained result confirms that number of collaborated user has a significant impact to the throughput performance.

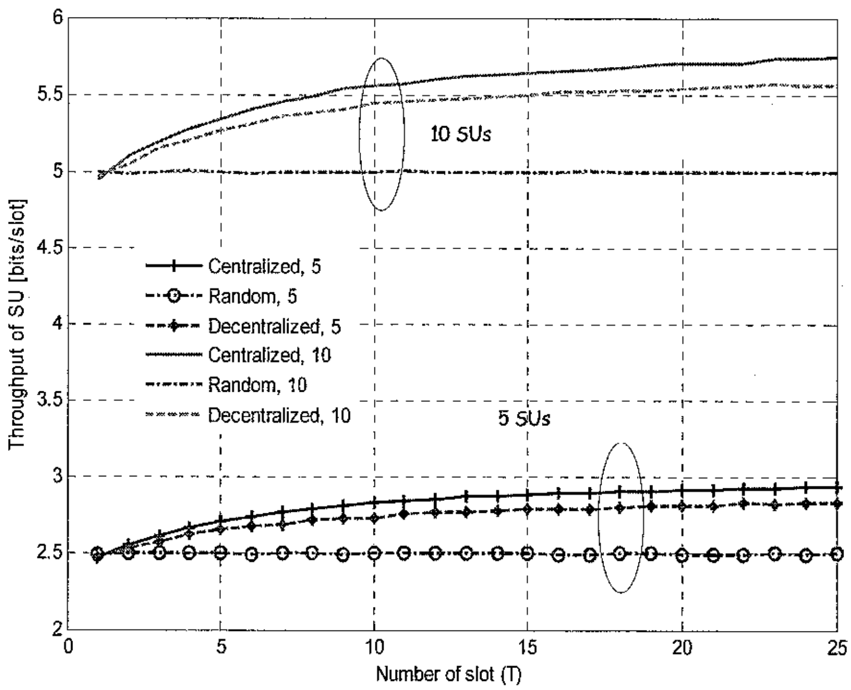

Figure 4.45 Throughput performance for CMCSS and DMCSS model as a function of T transmission

4.6.2.2 Throughput performance as a function of number of SUs

It is more clearly shown in Fig. 4.46 which draws the plot of the achievable throughput as a function of number of SU. The result shows that increasing number of collaborated user indirectly lead to improve the throughput performance. The CMCSS outperforms DMCSS model. However, DMCSS model still outperforms random CSS.

It is simply said that increasing number of SU lead to increase probability of detection. It indirectly implies to the throughput performance.

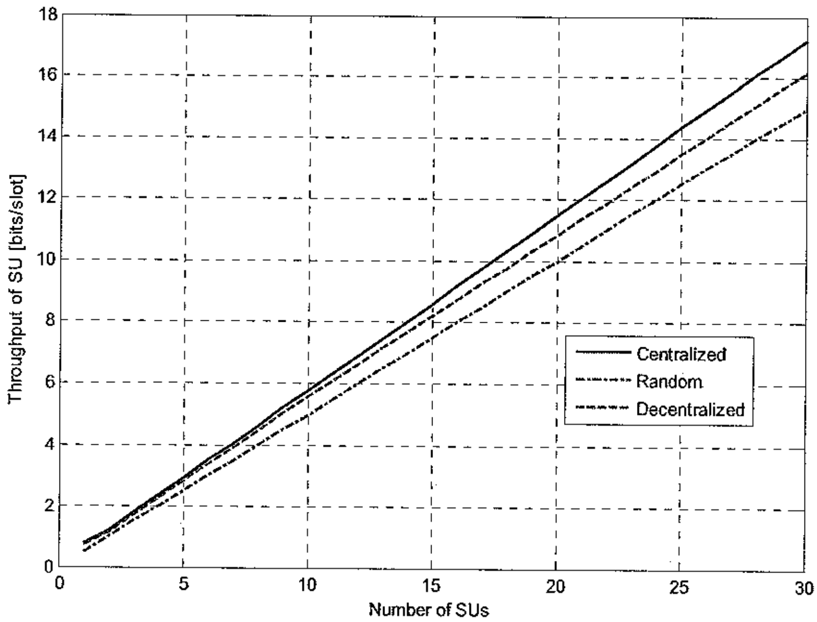

Figure 4.46 The throughput performance as a function of collaborated user number

4.6.2.3 Throughput performance as a function of arrival rate

This sub-section presents the achievable throughput performance as a function of packet arrival rate that is described in Fig. 4.47. The comparison is made for DMCSS, CMCSS, and random CSS model.

According to the derived result, CMCSS still outperform DMCSS model. However, DMCSS outperforms full band random CSS model. Each case can improve the throughput performance as the packet arrival rate increases.

Furthermore, the comparisons are made between DMCSS with partially spectrum sensing against Random CSS with fully spectrum sensing. It takes 7 and 9 SUs which independently senses a certain number of channels. Transition probabilities of each channels α = 0.1 and β = 0.9. The result in Fig. 4.48 shows that SU with partially sensing over license channels outperform from SU with fully spectrum sensing.

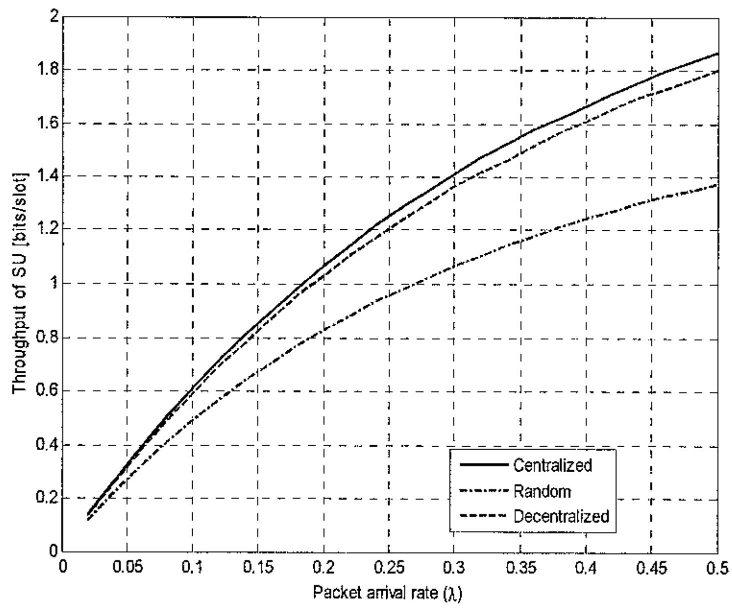

Figure 4.47 The throughput performance as a function of packet arrival rate

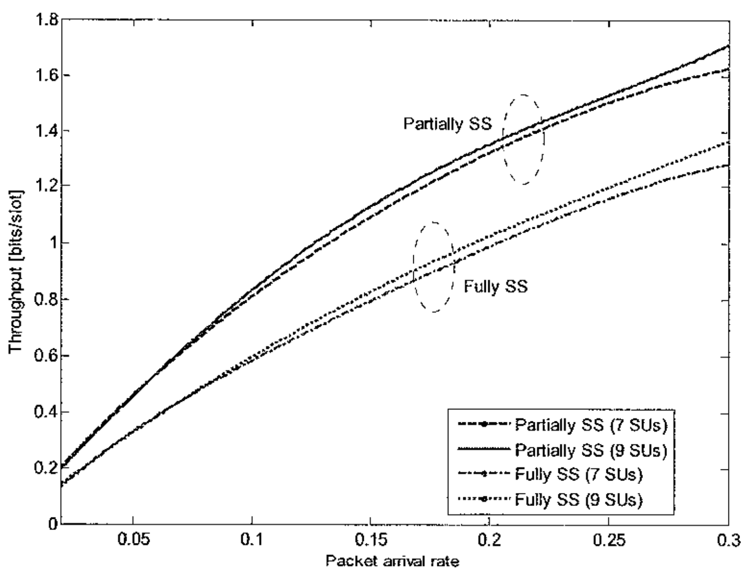

Figure 4.48 DMCSS with Partially SS vs Random CSS with Fully SS

4.6.2.4 Throughput performance as a function of probability of selected channel

Probability of selected channel is defined as probability that SU will select channel after sensing and observation. This sub-section will evaluate throughput as a function of the mentioned probability.

Fig. 4.49 shows the throughput performance for DMCSS and CMCSS model as a function of selected channel probability (p).

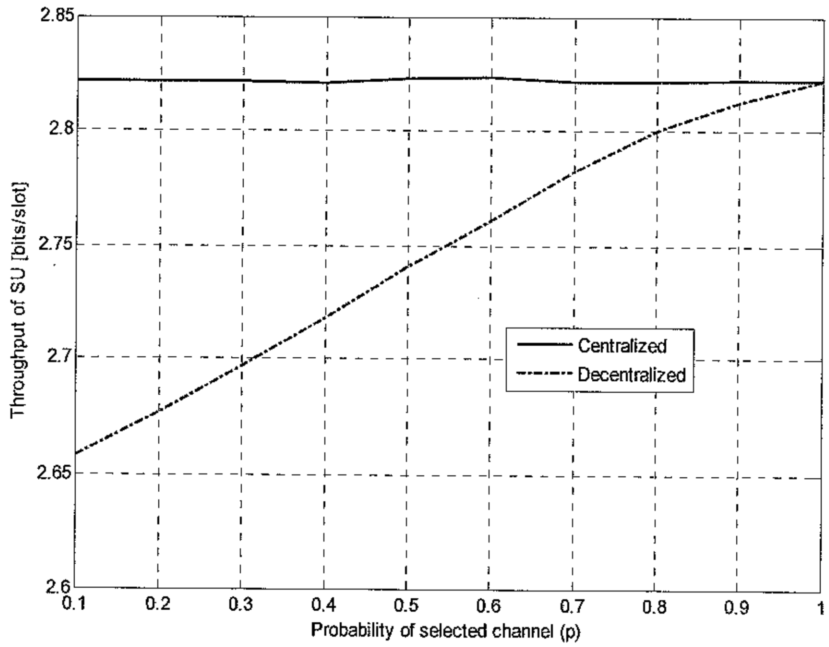

Figure 4.49 The throughput performance as a function of selected channel probability (*p*)

In earlier simulation results show an excellent performance of CMCSS as compared with DMCSS model. However, the achievable result in this figure shows that probability of selected channel by SU for sensing (*p*) has a significant impact to the throughput performance. The proposed DMCSS model reach the same throughput performance as CMCSS when the probability of selected channel by SU for sensing $p = 1$. Although the throughput of CMCSS is far better than DMCSS model at low percentage of selected channel probability (p), DMCSS model gradually improves the performance and reach the optimum throughput at p = 1.

4.6.2.5 Throughput performance as a function of SNR

The throughput performance of CR system is influenced by many factors, such as number of collaborated user, SNR, probability of selected channel, collision threshold, etc. The following work will further observe the impact of collision threshold to the throughput performance for DMCSS and CMCSS model. To complete the evaluation, we draw the plot of throughput as a function of SNR. Fig. 4.50 describes the achievable throughput as a function of signal to noise ratio (SNR) with $\zeta = 0.3$.

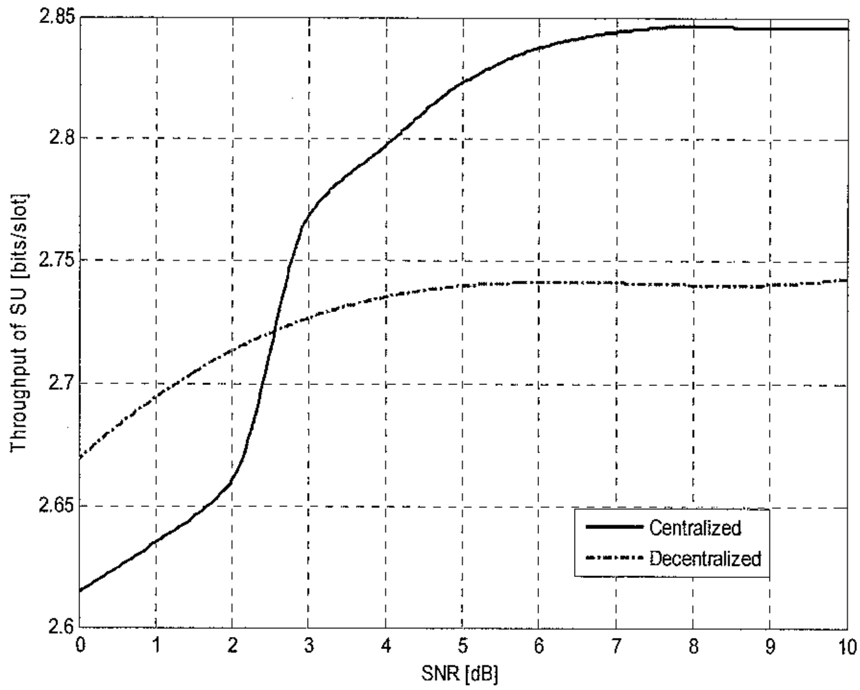

Figure 4.50 The throughput performance as a function of signal to noise ratio (SNR)

It is confirmed that increasing SNR value can improve the throughput performance. The CMCSS outperform DMCSS model when SNR is higher than 2.5 dB. However, less than 2.5 dB, the proposed DMCSS model has a better performance than CMCSS. The proposed DMCSS model outperforms CMCSS when SU experiences heavy fading, which is indicated by low SNR. The DMCSS model has a better performance than CMCSS when SNR $\leq$ 2.5 dB.

Fig. 4.51 confirms the derived results on Fig. 4.50. Simulation draws the plot of throughput performance as a function of slot number (T). The value of SNR is set to 0 dB and keep other parameter setting remain unchanged.

Henceforward, simulation will further investigate the performance of DMCSS model compared with CMCSS that is influenced by collision threshold value. The following result shows the performance of DMCSS model compared with CMCSS.

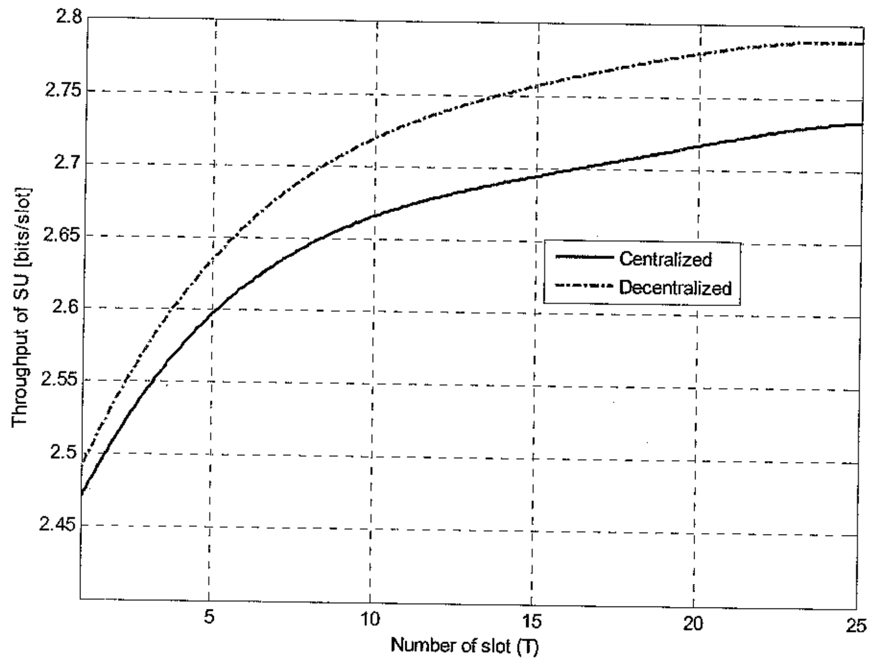

Figure 4.51 Throughput performance for SNR = 2 dB

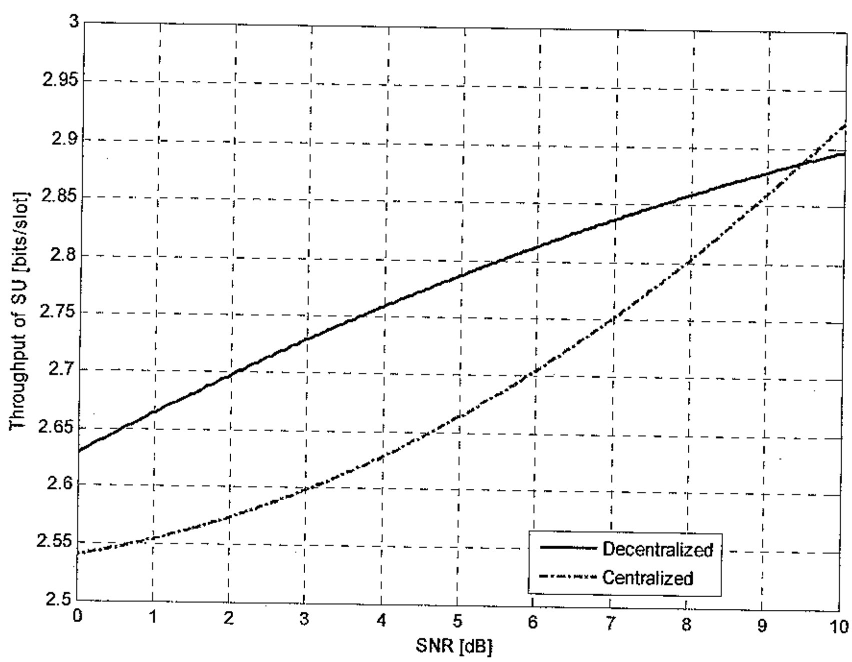

Figure 4.52 Throughput performance for DMCSS and CMCSS with $\zeta = 0.05$

The collision threshold set to ζ = [0.05, 0.2, 0.7] and keep other parameter remains unchanged. Fig. 4.52 shows the throughput performance as a function of

SNR with collision threshold value, $\zeta = 0.05$. The obtained result shows that DMCSS model outperforms CMCSS when SNR $\leq$ 9dB.

The alteration of collision threshold setting has a significant impact to the performance of DMCSS. Fig. 4.53 and Fig. 4.54 show the results for $\zeta = 0.2$ and $\zeta = 0.7$. It is shown that the robustness of DMCSS model is achieved at $SNR_{0.2} \leq 4.5$dB and $SNR_{0.7} \leq -4$dB, respectively.

The comparison of throughput performance for each collision threshold setting for DMCSS is shown in Fig. 4.55. It generally concludes that reducing collision threshold value relatively lead to the derivation of optimum throughput. In this case, when the value of $\zeta = 0.05$, it has higher throughput performance than the others at SNR $> 4dB$.

According to overall results show that the performance of proposed DMCSS model is strongly influenced by collision threshold value. Its performance outperforms CMCSS model at a certain value of SNR with regard to collision threshold. Subsequently, the proposed DMCSS model reaches the same throughput performance as CMCSS when the probability of selected channel (p) is 1 or channel trustingly must be selected by SU for sensing and access.

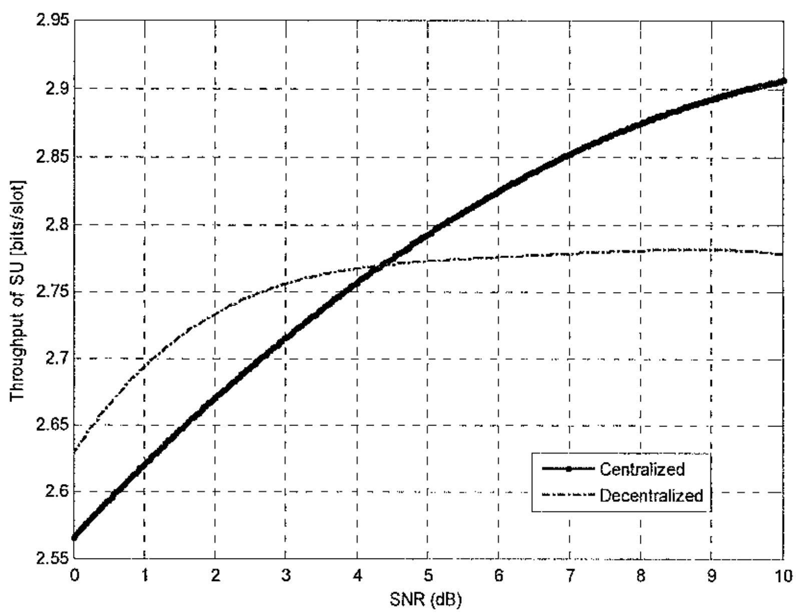

Figure 4.53 Throughput performance for collision threshold $\zeta = 0.2$

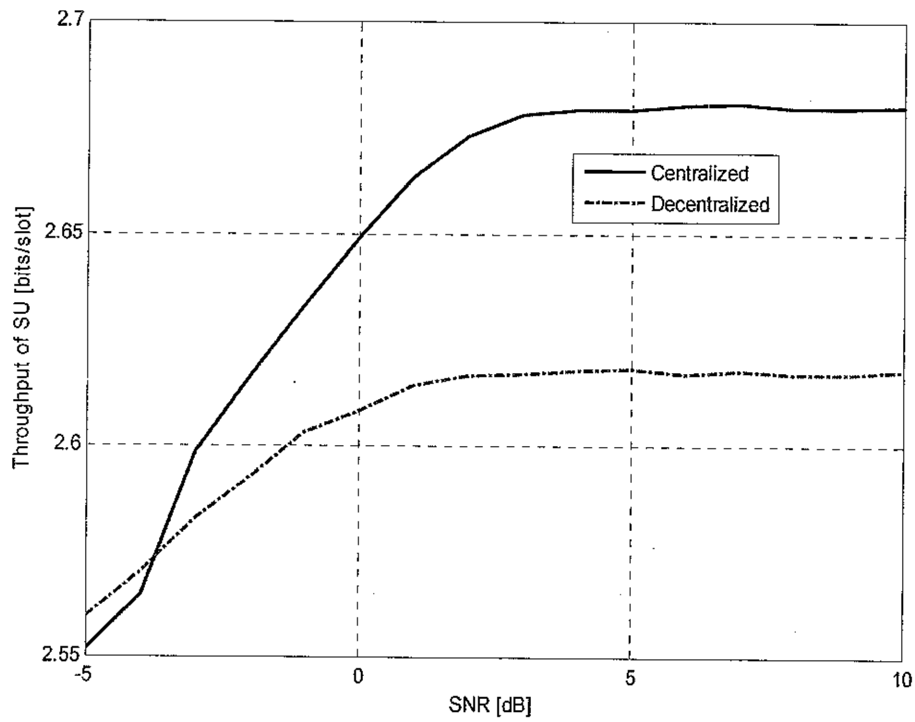

Figure 4.54 Throughput performance for collision threshold $\zeta = 0.7$

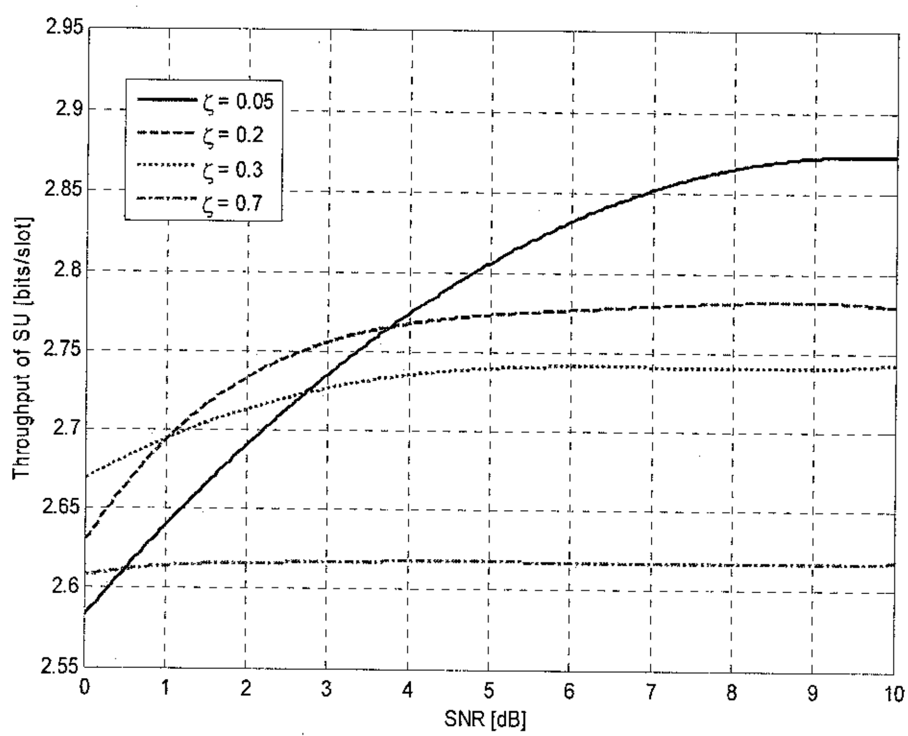

Figure 4.55 Throughput performance for DMCSS model with different ζ

4.7 Summary

This chapter presented simulation results along with discussion for CR system under POMDP framework. Firstly, optimal sensing and sub optimal greedy sensing strategy was evaluated. Sub optimal greedy sensing was used to reduce the complexity and energy constraints appear in optimal sensing.

According to the obtained results shortly conclude that the performance of sub optimal greedy are nearly close and match to the optimal sensing policy under single bandwidth setting with a certain value. However, when greedy sensing is set to multiple bandwidths with different values of (α, β), it generates the performance loss. The parameter of α and β is the probability of channel transition, where primary channel state change from busy to idle state (α) and keep on idle state (β). In the case of probability values of α and β are set to 0.5, it can be considered as random selection and the reward cannot be gained from the previous slot. The throughput performance of this setting seems to be constant relatively.

The two cases of perfect and imperfect channel condition are considered in this simulation work. Sensing errors can decrease the performance of CR system. It is indicated by the throughput performance that degraded as a function of number of slot, SNR, collision threshold, etc. Sensing errors is generated by some obstacles such as building, trees, etc, as well as hidden and exposed terminal.

Collision threshold is defined as how frequently collision allowable by PU. Increasing probability of collision threshold can improve the throughput performance. However, at certain value, the throughput performance can decrease gradually as threshold value increases. Moreover, probability of collision threshold has an impact to spectrum efficiency. At certain threshold point, spectrum efficiency reaches the maximum and obtained the best spectrum efficiency.

Shortly, there are some parameters that able to influence the performance of CR system in case of throughput and spectrum efficiency. The channel bandwidth improves the number of transmitted bits significantly. Number of sensed channel (N) and signal to noise ratio (SNR) are the other two parameters that can improve the performance.

Secondly, simulation studied the impact of spectrum sensing strategy and throughput performance for OSA in CR networks under the constraint of collision to primary network based on POMDP frameworks. Selection of sensor operating point based on the characteristic of ROC in physical layer is able to influences access strategy in MAC layer. Through the ROC design, simulation determines the optimal throughput that is able to be achieved. Furthermore, probability of transmission plays an important role for optimal design of CR system. It implies to how frequently the collision as well as case of waste the opportunity of channel access can be occurred. Both sensors operating point and transmission probability has a strong impact to the tradeoff design of OSA under collision constraint.

False detection and miss identification as types of sensing error in primary signal detection has an impact to channel access strategy. False detection cause waste the opportunities of channel access, hence SU must transmit number of bits even the sensed channel is on busy state with the certain probability (aggressive strategy). In the other hand, miss identification can cause collision to PU, hence CR user must refrain from data transmission even the sensed channel is on idle state (conservative).

The channel measurement sample has an impact to the time requirement for sensing action. In other words, the percentage of sensing slot must be higher. This strategy can increase the fidelity of sensing outcome. However it will drop the throughput performance. When simulation sets the percentage of sensing slot becomes low, it improves the throughput performance. However, it implies to the fidelity of sensing outcome (lower accuracy). This chapter presented the curve of false detection as a function of measurement sample (L). Number of measurement sample is assumed as time requirement for sensing action. According to derived results, when number of sample is low, false detection is high. In other words, when time requirement for sensing action is low, the fidelity of sensing outcome becomes low. On the other hand, it achieves low false detection when number of sample increases. In this case, the fidelity of sensing outcome becomes high when sensing action is set to longer time.

Furthermore, the impacts of channel measurement sample and portion of sensing time period to the throughput performance of SU with different collision threshold were presented. The throughput performance increases when less sample of channel measurement is taken. It gradually drops the performance after reach an optimal value at certain number of sample. In this case, the tradeoff between sample of channel measurement and the throughput performance of SU was derived. The optimum throughput that can be achieved depends on the parameter setting, such as transition probabilities, number of channel, channel bandwidth, collision threshold, etc.

The impact of sensing period to the throughput performance of SU was studied as well. Increasing period of sensing can decrease the period of data transmission and lead to lower throughput performance. On the other hand, when shorter time is taken for sensing causes the throughput performance becomes higher.

Finally, we proposed DMCSS model with limited sensing capability under POMDP. The CMCSS model implements central coordinator to arrange which spectrum channel can be sensed and accessed by SU. The central coordinator as a fusion centre has a responsibility to collect sensing results, which is forwarded by SU and take a final decision for sensing and access. While in DMCSS model, SU independently sense and access license channel without forwarding sensing result to central coordinator.

According to the derived results show that CMCSS model outperforms DMCSS. These two models are able to improve the rewards by exploiting information from previous slots and past observation during T transmission slot time. However, DMCSS still outperforms full band random CSS model and single user sensing. The CSS model can reduce sensing errors in primary signal detection. It has a capability to detect primary signal over fading and uncertainty noises. Such model (CSS) increases fidelity of sensing outcome and has an impact to the throughput performance. Increasing number of collaborated user lead to significant improvement for throughput performance.

The investigation and observation of the proposed DMCSS model under POMDP framework results an excellent performance. The robustness of DMCSS is reached at certain SNR values with certain collision threshold setting. Less collision threshold setting results a good throughput performance. On the other hand, the robustness of decentralized performance at lower SNR can be reached when the frequency of collision to PU larger. In other word, collision threshold is set to high.

Subsequently, increasing the probability of selected channel on each SU can improve the throughput of DMCSS model. The gap of the values among them become closer and reach the same throughput performance at probability of selected channel, p = 1.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

This thesis has investigated CR system with limited spectrum sensing under POMDP framework. It provides mathematical modeling of license spectrum behavior as idle and busy states to ease accessing by secondary user. Spectrum access is conducted under the constraint that collision allowed should be below the threshold to avoid disturbances to PU.

This research works focus on how the performances of CR in term of throughput with limited sensing capability under POMDP framework. Firstly, we studied the categories of MAC protocol for CR system and select one hybrid protocol to investigate CR system performance. POMDP framework as a hybrid protocol integrate spectrum sensing at physical layer, spectrum access at MAC layer and the traffic statistic determined by application layer together.

We investigated optimal and sub optimal greedy sensing strategy under POMDP framework. Greedy sensing policy is used to reduce the complexity of calculation when number of channel increases. We explore more setting of transition probability to evaluate the throughput performance and compares among others. According to the obtained results as presented in chapter IV, that the performance of sub optimal greedy sensing policy are nearly close and match to optimal sensing when initial parameter is set to single bandwidth with a certain value. However, when bandwidth is set to multiple values with different transition probabilities of (α, β), it generates the performance loss for greedy sensing policy.

Furthermore, sensing error was considered for observation. We take probability of false detection and probability of miss detection into account. Problems of hidden and exposed terminal generate sensing error that also causes varying spectrum opportunities to pair of secondary transmitter and receiver. The obtained results show that sensing error drops the throughput performance. The requirement is how to make those errors as small as possible in order to avoid collision to PU. Primary user limits collision, hence collision threshold determines maximum collision allowable by PU. The frequent of collision allowable improves the throughput performance since SU transmitter can send more bits to SU receiver during transmission time. Through the simulation conducted in chapter IV, it simply concludes that some parameter influence the throughput performance of CR system as follows:

- *Number of channel (N).* Throughput can improve significantly when N increases. Increasing channel implies to the possibility of channel access. When SU has more channels to be accessed, SU has a possibility to transmit more bit data during a certain transmission time.
- *Channel bandwidth (B).* A great number of bits can be transferred within a greater channel bandwidth. Bandwidth has a significant impact to the throughput improvement
- *Transition probability,* especially setting of parameter β, that means keeping remain unchanged of idle state. According to the obtained results, high probability of β has highest throughput performance. In this state, SU has longer time to use license channel and transmit a great number of bits during T slot transmission.
- *Maximum collision allowable by PU (collision threshold, ζ).* Increasing this threshold value can improve the throughput performance. However it will reach a certain point of threshold and gradually drops the throughput performance. In the same case, this parameter affects spectrum efficiency (bits/slot/Hz) where it will drop gradually at a certain threshold value.

Furthermore, spectrum sensor design for sensing and access was investigated. Decision of selecting sensor operating point based on the characteristic of ROC in physical layer has an impact into access strategy in MAC layer. Through ROC design, optimal point for throughput performance was defined.

Chapter V presented the detail throughput optimization through ROC design. Optimal throughput can be derived when probability of miss detection equal to collision threshold ($\delta_* = \zeta$). ROC is divided into two regions, aggressive and conservative region. In aggressive region ($\delta_* > \zeta$), SU should transmit data even sensing outcome is on busy state while conservative region ($\delta_* < \zeta$), SU should refrain from transmission even sensing outcome is on idle state.

This chapter investigated and further studied tradeoff design between sensing and access strategy, where SU must sense spectrum as quickly as possible while maintaining the throughput performance becomes optimum. Secondary user requires longer sensing time to increase the fidelity of sensing outcome. However, it automatically drops the throughput performance. More measurement sample should be taken to increase the fidelity of sensing outcome. However it requires longer sensing time. The relation between sensing time, number of measurement sample (L), and throughput performance was presented by detail in this chapter.

According to the obtained results, it is simply stated some conclusions as follows:

- Throughput optimization can be derived through ROC design in physical layer. It is required to accurately design sensor operating point, what SU should do for channel access. Secondary user reaches optimality when it trusts the sensing outcome. It means that probability of miss detection equal to collision threshold ($\delta_* = \zeta$). However, sometime sensor operating point is not laid on optimum line of that curve. Hence, SU follows the rule for aggressive and conservative action where ($\delta_* > \zeta$) and ($\delta_* < \zeta$) as aforementioned above to optimized the throughput performance.
- ROC design is affected by P_D, δ, and ε. However, these parameters are directly influenced by number of measurement sample (L) and SNR. According to the obtained results, increasing L lead to increase the fidelity of sensing outcome since P_D increases and ε decreases. It implies to the throughput improvement.
- The received signal power is determined by SNR. Increasing value of SNR lead to increase P_D, therefore it automatically improves the throughput performance.

- The relation function of spectrum sensing and access is successfully simulated. Increasing sensing time (the portion of sensing slot) is able to drop the throughput performance. Hence, careful design is required.
- The plot of throughput as a function of number of sample (L) shows that SU reaches optimum values at certain L value. By varying number of ζ, it results different optimum values at L.
- Through the tradeoff design between spectrum sensing in physical layer and spectrum access in MAC layer, it simply said that fewer sample of channel measurement (L) should be taken when maximum collision allowable by PU (ζ) increases.

Finally, we proposed and investigated DMCSS model with limited sensing capability. As presented in chapter VI, we compare the proposed model with single user sensing, CMCSS and full band random CSS model. We introduced binomial distribution theory in order to derive probability of miss-detection for local and CSS.

Through the comprehensive and heuristic simulation, CSS is robust. By varying overall parameter setting, the performance of CSS outperforms single user sensing strategy. Implementing collaboration among SU for spectrum sensing can reduce multipath fading effect, hidden and exposed terminal. It automatically leads to increase the probability of detection that indirectly implies to the throughput improvement.

The DMCSS and CMCSS model outperform full band random CSS. The figure plot of these two models improves the throughput performance by exploiting information from the previous slot and past observation. Although random CSS model cannot improve throughput during T slot transmission, but the throughput performance improves as packet arrival increases.

To focus our investigation, we compare two different collaboration user methods, CMCSS and DMCSS model. For these two models, increasing number of collaborated user lead to improve the throughput performance. At certain parameter setting, CMCSS outperform DMCSS model. However, at some other setting, DMCSS has an excellent performance compared with CMCSS model. We briefly conclude those mentioned parameter as follows:

- Probability of selected channel (p). It is defined as what the percentage of SU to sense and access license channel. CMCSS model outperform DMCSS when $p < 1$ or probability of SU to select channel for sensing and access below 100%. However, according to the obtained result, the proposed DMCSS model has the same throughput performance as CMCSS when $p = 1$ or probability of SU to select channel for sensing and access equal to 100%.
- Maximum collision allowable by PU (ζ). This parameter has significant impact to CMCSS and DMCSS model performance in term of throughput. Higher value of ζ implies to the throughput improvement. According to the obtained results presented in chapter VI, DMCSS has a possibility to achieve higher throughput performance than CMCSS model at certain received signal power (SNR) depends on ζ value setting. At high ζ value, DMCSS model outperforms CMCSS when SU receives weak signal power (low SNR). In this case, when $\zeta = 0.7$, DMCSS has greater performance than CMCSS model at SNR ≤ -4dB. On the other hand, at low ζ value, DMCSS outperforms CMCSS model when SU receives strong signal power (high SNR). Through the simulation, when $\zeta = 0.05$, DMCSS has greater performance than CMCSS model at SNR ≤ 9dB. It can refer to the comparison for each values of ζ that the throughput results have different performance improvement. Low value of ζ ($\zeta = 0.05$) has a significant improvement compared with others. In this case, throughput of $\zeta = 0.05$ has a greater performance than others.

5.2 Research Contribution

Finally, we conclude main contributions of research work that is summarized into the following points:

1. Decentralized Multiuser Cooperative Spectrum Sensing

We proposed decentralized CSS model under POMDP framework. Unlike full band random CSS, in our proposed model, SU has limited sensing capability where licensed band is partially sensed and exchange their sensing result cooperatively amongst SU in order to improve the system performance. To validate the proposed model, comparison is made against single user sensing, full band random CSS, and CMCSS model. Centralized multiuser CSS model is infrastructure-based CR system that requires central coordinator to arrange spectrum access while decentralized CSS model does not need infrastructure to access the spectrum opportunities. SU independently sensing and access without forwarding the sensing result to central coordinator. Random sensing is full band sensing capability where SU detect channel spectrum opportunity randomly even it has been sensed by other SU. Its principle is the more the number of SU, the more likely the number of sensed channel is large. When the number of SU is large enough, SU can sense all of the licensed channels.

2. Binomial distribution theory for probability of miss detection.

We introduced binomial distribution theory to derive probability of miss detection for DMCSS model. Binomial distribution statistical theory is defined as discrete probability distribution for sequence number of independence experiment with probability of successful selection. Unlike the existing works that probability of miss detection is derived by OR and AND rule to fuse the detection result from SU, binomial distribution theory enable SU to have successful channel selection and transmission with probability p.

5.3 Future work

In order to improve the performance, the direction of future work is summarized as follows:

1. Spectrum sensing methodology that is used in our work is energy detector. It is categorized as semi precision signal detector. However, this method is the most common used due to its low computational and implementation

complexity and also more generic compared to others since it is no need of any knowledge on PU signal. For further research, it is recommended to apply other signal detector such as cyclostationary or matched filter as optimal signal detector.

2. The spectrum occupancy states of PU may vary with time of the day and location. It is required for SU to learn longer characteristic of PU activity and accordingly alters its spectrum selection and data transmission strategy. Hence, the problem of mapping detailed channel occupancy is required for further research.

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APPENDIX A: FORMULATION FOR DMCSS

Value function for optimal sensing

$$V_t(\pi) = \max_{a=1,\dots,N}\left\{\sum_{i=1}^{M}\pi_i\sum_{j=1}^{M}p_{i,j}\sum_{\theta=0}^{1}Pr\left[\Theta_{j,a}=\theta\right](\theta B_a + V_{t+1}(\tau(\pi|a,\theta)))\right\}$$

The greedy action $a*(t)$ in slot t that maximize the expected immediate reward is given by

$$a_*(t) = \underset{a=1,\dots,N}{\text{argmax}}(\omega_a(t)\beta_a + (1-\omega_a(t))\alpha_a)B_a$$

Then, the recursive equation to maximize the expected reward based on the greedy policy is formulated as follows:

$$W_t(\Omega) = (\omega_{a*}\beta_{a*} + (1-\omega_{a*})\alpha_{a*})B_{a*} + \sum_{\theta=0}^{1}Pr[\Theta_{a*}=\theta|\Omega,a_*]W_{t+1}(\tau(\Omega|a_*,\theta$$

The channel a_* selected by greedy approach when considering sensing error is thus given by

$$a_*(t) = arg\max_{a=1,\dots,N}\left(\omega_a(t)\beta_a + \left(1-\omega_a(t)\right)\alpha_a\right)(1-\varepsilon)B_a$$

In decentralized multiuser cooperative spectrum sensing, we adopt Binomial distribution theory to derive probability of miss-detection (δ). The OR rule technique cannot be used for decentralized cognitive radio system. If each SU makes a final decision using the same fusion technique, the cooperative spectrum sensing results will have an identical value. The detail derivation of probability of miss detection for DMCSS model is as follow:

$$\binom{n}{i} p^i(1-p)^{n-i} \qquad i = 1, 2, \ldots, n$$

where *n, i, and p* denote number of SU, number of user that select channel L, and probability of user i to sense channel L, respectively. The average of miss detection probability, C_M, for DCU can be calculated as the following formula

$$C_M = \frac{P_M\ x\ Prob.\ number\ of\ users\ select\ channel\ i\ to\ sense}{\sum_{i=1}^{n} Prob.of\ user\ j\ select\ channel\ i\ to\ sense}$$

$$= \frac{\sum_{i=1}^{n} {P_M}^i \binom{n}{i} p^i(1-p)^{n-i}}{1-(1-p)^n}$$

The optimal strategy can be derived when the probability of miss detection is equal to maximum collision probability allowed by PUs ($C_M = \zeta$). Thus, the probability of miss detection for the local sensing result, P_M, can be calculated as bellows:

$$\zeta = \frac{(P_M\ x\ p + 1 - p)^n - (1-p)^n}{1-(1-p)^n}$$

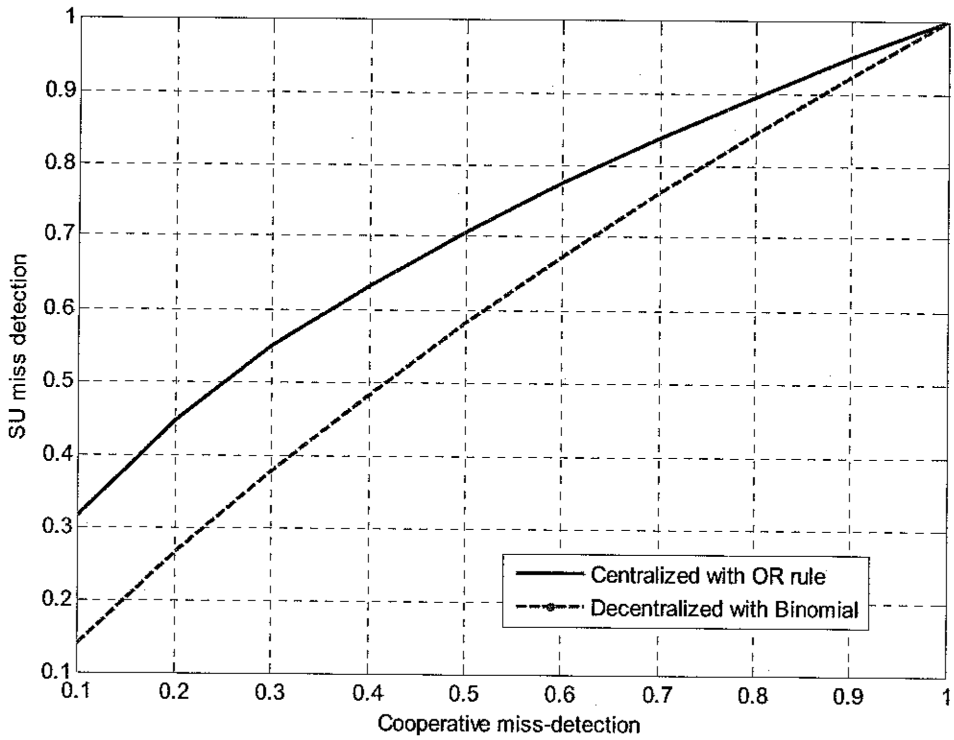
$$P_M = \frac{(\zeta(1-(1-p)^n) + (1-p)^n)^{\frac{1}{n}} + (p-1)}{p}$$

where ζ denotes a collision threshold or a maximum collision probability allowed by PUs. Thus, the chosen action in slot t to maximize the expected immediate reward can be given by

$$a_*(t) = arg \max_{a=1,\ldots,N} \left(\omega_a(t)\beta_a + \left(1-\omega_a(t)\right)\alpha_a\right)(1 - f(\delta_{DMCSS}))\, B_a$$

The notation of δ_{DMCSS} is defined as probability of miss-detection for decentralized cooperative system.

Probability of miss-detection indirectly influences the throughput performance. The performance comparison for miss-detection between Centralized (CMCSS) with OR rule against Decentralized (DMCSS) with Binomial distribution statistic theory is shown as figure bellows:



SU miss detection for DMCSS model has a fewer values than CMCSS with the same value of cooperative miss-detection. It indirectly leads to the throughput improvement. However, the throughput performance for DMCSS is influenced by probability of selected channel (p), collision threshold (ζ), and SNR.

APPENDIX B: DATA FOR OPTIMAL AND GREEDY SENSING POLICY

Performance of optimal and sub-optimal Greedy sensing policy

Perfect channel sensing

Parameter	**Value**
N	3
B	1
T	25
α	Varied
β	Varied

T	$\alpha = 0.1$; $\beta = 0.9$	$\alpha = 0.2$; $\beta = 0.8$	$\alpha = 0.3$; $\beta = 0.7$	$\alpha = 0.4$; $\beta = 0.6$	$\alpha = 0.5$; $\beta = 0.5$
1	0.4951	0.4996	0.493	0.5058	0.5065
2	0.5959	0.5754	0.5488	0.5266	0.50375
3	0.656667	0.613467	0.570667	0.5362	0.5039
4	0.686825	0.635725	0.584275	0.54265	0.50285
5	0.70584	0.64932	0.59298	0.54352	0.5018
6	0.718117	0.657717	0.598567	0.545217	0.501933
7	0.727271	0.662743	0.602443	0.546443	0.502571
8	0.7344	0.666988	0.60445	0.547225	0.502538
9	0.740378	0.670344	0.606211	0.547767	0.502211
10	0.74491	0.67348	0.60795	0.5487	0.50159
11	0.748655	0.676136	0.608845	0.549245	0.501236
12	0.751467	0.678117	0.609825	0.549317	0.501067
13	0.753631	0.679977	0.610777	0.549554	0.500992
14	0.7556	0.681186	0.611393	0.549971	0.500871
15	0.75758	0.682233	0.612453	0.550087	0.50096
16	0.759369	0.683175	0.6134	0.550219	0.501513
17	0.760718	0.683906	0.613829	0.550618	0.501547
18	0.761822	0.684422	0.614011	0.550961	0.501072

19	0.762879	0.684968	0.614253	0.551074	0.501074
20	0.763615	0.68542	0.61458	0.55147	0.501155
21	0.764324	0.68591	0.614995	0.551705	0.501395
22	0.764968	0.685855	0.615355	0.552114	0.501
23	0.765883	0.685974	0.615317	0.552513	0.501122
24	0.766596	0.686229	0.615579	0.552575	0.500563
25	0.76724	0.686584	0.61614	0.552584	0.50072

T	$\alpha = 0.6$; $\beta = 0.4$	$\alpha = 0.7$; $\beta = 0.3$	$\alpha = 0.8$; $\beta = 0.2$	$\alpha = 0.9$; $\beta = 0.1$
1	0.4986	0.5018	0.496	0.4984
2	0.5301	0.546	0.5718	0.59865
3	0.535767	0.567333	0.6	0.6331
4	0.541125	0.576125	0.619625	0.663
5	0.54158	0.58398	0.62906	0.68186
6	0.54335	0.586817	0.637133	0.69395
7	0.542257	0.589143	0.642829	0.703243
8	0.54255	0.591588	0.646013	0.710313
9	0.543056	0.592611	0.648989	0.716056
10	0.54386	0.59434	0.65152	0.72038
11	0.5439	0.595345	0.653773	0.723973
12	0.544258	0.5964	0.654758	0.727133
13	0.545338	0.596915	0.655992	0.7294
14	0.545721	0.597457	0.657086	0.731729
15	0.546987	0.597613	0.65842	0.733513
16	0.547025	0.598381	0.65875	0.735069
17	0.547576	0.598488	0.659859	0.736024
18	0.547906	0.598372	0.660572	0.737228
19	0.548121	0.599042	0.661326	0.738384
20	0.548355	0.599495	0.661995	0.73956
21	0.548281	0.599886	0.662552	0.740414
22	0.548123	0.599945	0.6633	0.741595
23	0.548422	0.59983	0.663752	0.742348
24	0.548763	0.600396	0.663829	0.743058
25	0.548692	0.600248	0.664464	0.743572

Performance of perfect and imperfect channel sensing

Parameter	Value
N	3
B	1
T	25
α	0.1
β	0.9
ζ	0.2

T	Throughput [bits/slot]	
	Imperfect	Perfect
1	0.4618	0.5036
2	0.533	0.6001
3	0.567333	0.6598
4	0.58755	0.69065
5	0.60392	0.70858
6	0.61055	0.719917
7	0.615714	0.728057
8	0.619313	0.734238
9	0.629644	0.738833
10	0.62873	0.74305
11	0.632891	0.746364
12	0.633483	0.748833
13	0.636154	0.751262
14	0.637093	0.753321
15	0.635607	0.754947
16	0.632944	0.75605
17	0.637218	0.757218
18	0.641317	0.758161
19	0.642037	0.758979
20	0.641585	0.75987
21	0.639062	0.760629
22	0.64365	0.761527
23	0.644309	0.762439
24	0.64165	0.763171
25	0.641824	0.763988

Performance of imperfect channel sensing (Throughput performance as a function of SNR)

Parameter	Value
N	3
B	1
T	25
α	0.1
β	0.9
ζ	0.1
SNR	Varied

T	Throughput [bits/slot] vs SNR [dB]				
	1 dB	2 dB	3 dB	4 dB	5 dB
1	0.1962	0.2348	0.2862	0.3283	0.3717
2	0.2109	0.2565	0.30775	0.36515	0.4235
3	0.2201	0.269567	0.324633	0.390467	0.4547
4	0.21905	0.270625	0.33125	0.395575	0.475125
5	0.22772	0.27654	0.33414	0.41112	0.48058
6	0.225567	0.27785	0.338467	0.415	0.4853
7	0.2305	0.280414	0.342171	0.417214	0.492657
8	0.230125	0.283138	0.35175	0.425088	0.49775
9	0.231411	0.285556	0.346289	0.420511	0.499344
10	0.23089	0.27976	0.34993	0.426	0.50243
11	0.233045	0.287309	0.3512	0.425155	0.503355
12	0.232575	0.285325	0.354392	0.426375	0.5092
13	0.231923	0.286392	0.349254	0.423269	0.508831
14	0.231021	0.289114	0.352343	0.422993	0.507229
15	0.233467	0.291367	0.352867	0.429153	0.50892
16	0.233613	0.288981	0.353531	0.431319	0.509338
17	0.234376	0.290153	0.354424	0.431653	0.508653
18	0.231967	0.28895	0.35145	0.429656	0.509206
19	0.235279	0.288489	0.355432	0.430216	0.509774
20	0.23347	0.29025	0.357505	0.430615	0.51229
21	0.234957	0.292357	0.356795	0.43279	0.516767
22	0.233632	0.290868	0.354941	0.434823	0.513864

23	0.234635	0.290522	0.356039	0.431278	0.514404
24	0.236104	0.292192	0.356463	0.434467	0.515542
25	0.237644	0.288524	0.357416	0.43304	0.51352

T	Throughput [bits/slot] vs SNR [dB]				
	6 dB	**7 dB**	**8 dB**	**9 dB**	**10 dB**
1	0.4201	0.4542	0.4769	0.4931	0.4951
2	0.48515	0.53335	0.5606	0.57735	0.59525
3	0.5227	0.581	0.6167	0.633467	0.642733
4	0.537325	0.59515	0.642275	0.67	0.67475
5	0.54786	0.61218	0.65928	0.68598	0.69082
6	0.560217	0.620433	0.66525	0.691867	0.7067
7	0.563357	0.6241	0.676571	0.700857	0.713814
8	0.571425	0.624963	0.690863	0.705275	0.719575
9	0.571622	0.635178	0.684022	0.711644	0.727511
10	0.57208	0.64238	0.68901	0.7189	0.72552
11	0.575373	0.637991	0.691036	0.718982	0.735736
12	0.57925	0.643517	0.69475	0.720183	0.735933
13	0.576877	0.648638	0.697277	0.724585	0.738977
14	0.587643	0.646571	0.700029	0.729321	0.745243
15	0.582727	0.648307	0.699193	0.732653	0.741807
16	0.583994	0.649525	0.69685	0.732744	0.741206
17	0.584829	0.648082	0.702982	0.735788	0.744071
18	0.584522	0.652867	0.702178	0.734122	0.7496
19	0.588926	0.651516	0.705389	0.734716	0.745953
20	0.587475	0.652465	0.70258	0.733735	0.745835
21	0.587514	0.655043	0.703419	0.737733	0.747605
22	0.588595	0.654259	0.706382	0.736695	0.749714
23	0.587178	0.656383	0.704361	0.738339	0.746548
24	0.592446	0.653717	0.707721	0.738621	0.749925
25	0.58634	0.657748	0.706056	0.736156	0.754392

APPENDIX C: DATA FOR CROSS LAYER DESIGN PRINCIPLE

Tradeoff design: spectrum sensing and throughput performance

Throughput performance as a function of number of sample (M) with varied collision threshold (ζ)

Parameter	**Value**
N	3
B	1
T	25
SNR	5 dB
α	0.1
β	0.9

ζ		0.05	0.1	0.15	0.2	0.25	0.3	0.35
Throughput [bit/slot]	M=1	0.050847	0.104892	0.159189	0.212566	0.265838	0.366555	0.316538
	M=2	0.099091	0.19614	0.27977	0.348187	0.412201	0.502148	0.462924
	M=3	0.164776	0	0.384351	0.453093	0.499222	0.570745	0.53223
	M=4	0.238762	0.374542	0.460948	0.510523	0.553886	0.598308	0.578744
	M=5	0.305881	0.437104	0.5032	0.545846	0.57492	0.601154	0.594524
	M=6	0.362283	0.478467	0.530432	0.56087	0.579258	0.586293	0.587291
	M=7	0.404629	0.498383	0.541188	0.565011	0.572469	0.573647	0.571799
	M=8	0.439186	0.511152	0.542579	0.55363	0.556077	0.551857	0.558922
	M=9	0.453143	0.509417	0.532132	0.536991	0.537969	0.5296	0.532868
	M=10	0.460239	0.504622	0.516149	0.519756	0.516961	0.510065	0.512778
	M=11	0.458912	0.492747	0.498365	0.497001	0.494334	0.487275	0.490823
	M=12	0.455058	0.476956	0.475796	0.475694	0.473119	0.464612	0.470405

ζ		0.4	0.45	0.5	0.55	0.6	0.65	0.7
Throughput [bit/slot]	M=1	0.406946	0.447283	0.476685	0.502297	0.555554	0.577394	0.589267
	M=2	0.52578	0.567331	0.590854	0.60756	0.615873	0.613643	0.608075
	M=3	0.58988	0.608528	0.613737	0.615215	0.608601	0.601834	0.595599
	M=4	0.606887	0.608823	0.611959	0.602518	0.596098	0.590026	0.576499
	M=5	0.600494	0.597326	0.596571	0.588176	0.579955	0.569653	0.554176
	M=6	0.584854	0.5824	0.575519	0.566492	0.558423	0.549666	0.532551
	M=7	0.566787	0.56102	0.554567	0.549221	0.537649	0.5296	0.515409
	M=8	0.548586	0.539302	0.535198	0.527619	0.516922	0.508118	0.496654
	M=9	0.526266	0.518478	0.512521	0.50403	0.498032	0.487357	0.478927
	M=10	0.506162	0.499688	0.491557	0.486657	0.477372	0.468062	0.455888
	M=11	0.483716	0.477702	0.471937	0.467381	0.454732	0.447464	0.437821
	M=12	0.460288	0.455508	0.449157	0.442327	0.43637	0.430236	0.418079

Parameter	Value
N	3
B	1
T	25
SNR	5 dB
α	0.3
β	0.7

ζ		0.05	0.1	0.15	0.2	0.25	0.3	0.35
Throughput [bit/slot]	M=1	0.05018	0.100539	0.150482	0.199416	0.246073	0.28951	0.333308
	M=2	0.093045	0.175081	0.24675	0.308482	0.361851	0.40549	0.435735
	M=3	0.148334	0	0.329489	0.388661	0.431609	0.459739	0.480007
	M=4	0.207412	0.319574	0.390474	0.435135	0.46427	0.479692	0.489058
	M=5	0.260392	0.367955	0.425082	0.454638	0.473018	0.481505	0.483106
	M=6	0.306605	0.400212	0.441111	0.462306	0.469197	0.470506	0.473343
	M=7	0.340338	0.416128	0.445614	0.456374	0.460472	0.460336	0.457467
	M=8	0.364891	0.420313	0.442001	0.445606	0.44771	0.444956	0.443229

	M=9	0.37713	0.418062	0.429754	0.432072	0.429923	0.428098	0.422582
	M=10	0.38141	0.410726	0.417609	0.416133	0.413146	0.411704	0.408094
	M=11	0.380236	0.397122	0.399872	0.398433	0.396514	0.392296	0.389377
	M=12	0.370698	0.382956	0.383985	0.380252	0.380175	0.376223	0.373466

ζ		0.4	0.45	0.5	0.55	0.6	0.65	0.7
Throughput [bit/slot]	M=1	0.371161	0.406698	0.438549	0.462318	0.480883	0.49316	0.504652
	M=2	0.462051	0.483239	0.493116	0.501806	0.505837	0.505652	0.504927
	M=3	0.490596	0.501013	0.50303	0.503372	0.500147	0.494385	0.491171
	M=4	0.493254	0.493789	0.493525	0.492314	0.484605	0.482715	0.47897
	M=5	0.483531	0.482113	0.479747	0.476119	0.471393	0.466956	0.458626
	M=6	0.470372	0.467138	0.461909	0.459974	0.453854	0.452499	0.445309
	M=7	0.454699	0.449943	0.447254	0.445247	0.439433	0.43444	0.426436
	M=8	0.437128	0.435772	0.42974	0.426558	0.422773	0.415823	0.411257
	M=9	0.421628	0.416497	0.41337	0.408374	0.404613	0.399949	0.394512
	M=10	0.40334	0.400932	0.396721	0.394108	0.388046	0.384233	0.379128
	M=11	0.386102	0.385346	0.379566	0.37624	0.372665	0.367337	0.362226
	M=12	0.367299	0.366298	0.362043	0.358533	0.355251	0.349729	0.346476

Throughput performance as a function of slot portion (%) for sensing

ζ		0.05	0.1	0.15	0.2	0.25	0.3	0.35
Throughput vs Sensing slot portion [%]	1	0.340233	0.491625	0.563179	0.613282	0.643382	0.659266	0.669841
	2	0.324382	0.461624	0.53267	0.578495	0.61191	0.624287	0.636509
	3	0.306119	0.438386	0.502843	0.547655	0.572546	0.594952	0.602725
	4	0.285808	0.412368	0.47167	0.515248	0.541459	0.556557	0.564973
	5	0.26658	0.385632	0.445563	0.481404	0.508932	0.522462	0.530508
	6	0.252137	0.361136	0.413532	0.452777	0.473875	0.489423	0.496474
	7	0.234086	0.33345	0.38778	0.417219	0.439366	0.453856	0.460093
	8	0.214188	0.310478	0.356102	0.386645	0.40662	0.41641	0.423893
	9	0.197448	0.28239	0.327083	0.354858	0.372115	0.383539	0.388786

	10	0.181094	0.259562	0.296498	0.321664	0.338254	0.34792	0.35307
	11	0.160927	0.230485	0.265786	0.289843	0.304576	0.313587	0.318807
	12	0.143909	0.206546	0.237688	0.256859	0.271419	0.279058	0.281366

ζ		0.4	0.45	0.5	0.55	0.6	0.65	0.7
Throughput vs Sensing slot portion [%]	1	0.671126	0.670149	0.663062	0.659353	0.6463	0.632157	0.621213
	2	0.637049	0.635285	0.62865	0.619499	0.611154	0.602248	0.587999
	3	0.602177	0.598448	0.594017	0.585888	0.580863	0.56644	0.556862
	4	0.566947	0.564163	0.561072	0.550202	0.542966	0.53416	0.521174
	5	0.531126	0.531873	0.524376	0.519123	0.510792	0.501507	0.493305
	6	0.495368	0.490277	0.488412	0.483896	0.475294	0.46844	0.45932
	7	0.460551	0.457358	0.454444	0.451381	0.44401	0.436093	0.425896
	8	0.423749	0.421493	0.418378	0.412853	0.407714	0.399766	0.393062
	9	0.389424	0.385598	0.38403	0.377839	0.374944	0.368526	0.359678
	10	0.354508	0.35206	0.34926	0.34564	0.338192	0.334622	0.328276
	11	0.318409	0.317052	0.314019	0.311706	0.305197	0.300366	0.294019
	12	0.284186	0.281528	0.278885	0.275802	0.27207	0.266006	0.261493

APPENDIX D: DATA FOR DECENTRALIZED, RANDOM, AND

CENTRALIZED MULTIUSER COOPERATIVE SPECTRUM SENSING

Performance of centralized (CMCSS) and decentralized (DMCSS) for different transition probability (α, β)

Parameter	Value
N	10
B	1
T	25
α	Varied
β	Varied
Number of collaborated users	5
Probability of selected channel (p) for DCU	0.2
SNR	5 dB
ζ	0.3

Case I: $\alpha = 0.1$; $\beta = 0.9$

T	Single	CMCSS	Random	DMCSS
1	0.49924	2.47712	2.49838	2.48448
2	0.5648	2.5541	2.50145	2.53925
3	0.61322	2.62329	2.50072	2.58158
4	0.64425	2.67449	2.4993	2.62733
5	0.66536	2.71452	2.49884	2.65588
6	0.68287	2.74472	2.49657	2.6845
7	0.69533	2.7767	2.49899	2.69412
8	0.70315	2.79808	2.50126	2.71791
9	0.71255	2.82068	2.49794	2.73374
10	0.71759	2.83541	2.50254	2.73572
11	0.722	2.84439	2.50021	2.75863
12	0.72594	2.86	2.4993	2.76994

13	0.73104	2.87341	2.49983	2.77596
14	0.73467	2.87658	2.50172	2.7828
15	0.73662	2.89265	2.50059	2.7916
16	0.73879	2.89672	2.49806	2.79516
17	0.74082	2.90036	2.49745	2.7968
18	0.74349	2.90822	2.50067	2.80843
19	0.74379	2.91422	2.50121	2.81601
20	0.74541	2.92269	2.49753	2.81998
21	0.74747	2.92452	2.49748	2.81889
22	0.74811	2.93387	2.49814	2.83446
23	0.74912	2.92815	2.50143	2.82839
24	0.75035	2.93932	2.49846	2.83234
25	0.75117	2.94253	2.49987	2.83684

Case I: $\alpha = 0.2$; $\beta = 0.8$

T	Single	CMCSS	Random	DMCSS
1	0.5012	2.48061	2.50425	2.48694
2	0.55193	2.53493	2.49417	2.52055
3	0.58169	2.57368	2.49847	2.5579
4	0.5984	2.6167	2.49568	2.579
5	0.6102	2.64886	2.50143	2.59822
6	0.62077	2.6626	2.50172	2.62103
7	0.62372	2.68535	2.49805	2.62495
8	0.63045	2.69047	2.49826	2.64455
9	0.63298	2.70522	2.50406	2.64991
10	0.63566	2.70782	2.49857	2.65205
11	0.63827	2.71925	2.49919	2.65989
12	0.64102	2.72553	2.50068	2.66802
13	0.64294	2.7327	2.49949	2.66811
14	0.64484	2.73876	2.49876	2.67284
15	0.64631	2.74072	2.49904	2.67418
16	0.64582	2.74598	2.49851	2.67923
17	0.64792	2.75053	2.50204	2.68095
18	0.64772	2.75117	2.50175	2.68412
19	0.64966	2.75476	2.50118	2.68577
20	0.65013	2.75717	2.4999	2.68659

21	0.64937	2.75938	2.49879	2.69169
22	0.65174	2.76107	2.49977	2.69171
23	0.65194	2.76476	2.50079	2.69045
24	0.65188	2.76661	2.50213	2.69426
25	0.65236	2.76938	2.50016	2.69515

Case I: $\alpha = 0.3$; $\beta = 0.7$

T	Single	CMCSS	Random	DMCSS
1	0.49935	2.47331	2.4941	2.48378
2	0.53188	2.51203	2.50276	2.51303
3	0.55096	2.54556	2.50573	2.53539
4	0.55982	2.56811	2.50184	2.54747
5	0.56556	2.58424	2.49891	2.56069
6	0.56909	2.59443	2.49858	2.56381
7	0.5711	2.60523	2.49971	2.57852
8	0.57457	2.61965	2.49784	2.57784
9	0.57612	2.61722	2.50082	2.583
10	0.57887	2.6211	2.50198	2.58575
11	0.57796	2.62455	2.49835	2.59328
12	0.5806	2.63215	2.49768	2.5936
13	0.58052	2.6322	2.49909	2.59247
14	0.58057	2.63285	2.50105	2.59575
15	0.58219	2.63432	2.49923	2.59974
16	0.5833	2.64018	2.49919	2.60032
17	0.58298	2.64209	2.50193	2.59912
18	0.58242	2.6407	2.50139	2.60309
19	0.58304	2.64437	2.49843	2.60173
20	0.58408	2.64597	2.50122	2.60041
21	0.58349	2.64856	2.49973	2.6076
22	0.58454	2.64627	2.4995	2.60322
23	0.58472	2.64756	2.50004	2.60552
24	0.58423	2.65111	2.50219	2.60745
25	0.58524	2.65128	2.49889	2.60504

Performance for different collision threshold (ζ)

Parameter	Value
N	10
B	1
T	25
α	0.1
β	0.9
Number of collaborated users	5
Probability of selected channel (p) for DMCSS	0.2
SNR	5 dB
ζ	Varied

$\boldsymbol{\delta = \zeta = 0.1}$

T	Single	CMCSS	Random	DMCSS
1	0.50013	2.47569	2.49092	2.47181
2	0.56369	2.50606	2.50089	2.55155
3	0.60385	2.54781	2.50278	2.60648
4	0.62971	2.58928	2.50455	2.66657
5	0.64579	2.62283	2.50423	2.7072
6	0.65943	2.65268	2.50067	2.7363
7	0.66882	2.67396	2.49961	2.76125
8	0.67666	2.69045	2.50174	2.78767
9	0.68321	2.69751	2.5006	2.80569
10	0.68765	2.71577	2.50059	2.82796
11	0.69171	2.7239	2.50177	2.83546
12	0.69445	2.7295	2.49558	2.85291
13	0.69757	2.74562	2.4959	2.85336
14	0.69959	2.75095	2.50227	2.86858
15	0.70262	2.76228	2.49891	2.87628
16	0.70282	2.76845	2.49841	2.88327
17	0.7054	2.7712	2.50064	2.89189
18	0.70607	2.78066	2.50022	2.90086
19	0.70858	2.7906	2.4993	2.91006
20	0.70844	2.79468	2.49835	2.91278
21	0.71067	2.8025	2.49958	2.91985

22	0.71078	2.80611	2.49979	2.92333
23	0.71176	2.81229	2.49823	2.9227
24	0.71193	2.81227	2.49853	2.92974
25	0.71298	2.82383	2.50326	2.93197

$\delta = \zeta = 0.2$

T	Single	CMCSS	Random	DMCSS
1	0.49865	2.47567	2.5018	2.48299
2	0.57137	2.55502	2.49305	2.54025
3	0.61664	2.62373	2.49768	2.59259
4	0.64756	2.67943	2.50057	2.63928
5	0.66766	2.72764	2.49931	2.68078
6	0.6815	2.75284	2.49934	2.70565
7	0.69352	2.78162	2.50052	2.73172
8	0.69993	2.79813	2.49977	2.75326
9	0.70753	2.82095	2.50221	2.76475
10	0.71341	2.83804	2.49877	2.77896
11	0.7174	2.84834	2.4987	2.79798
12	0.71964	2.86429	2.50171	2.80312
13	0.72461	2.8709	2.49787	2.81578
14	0.72635	2.88471	2.5027	2.82758
15	0.72794	2.88737	2.50153	2.83002
16	0.72937	2.9031	2.50105	2.83252
17	0.73203	2.90965	2.50141	2.84671
18	0.73254	2.91628	2.50119	2.85214
19	0.73499	2.9239	2.4999	2.85703
20	0.73549	2.92198	2.49971	2.86149
21	0.73653	2.93312	2.50143	2.87223
22	0.73811	2.93984	2.50007	2.87045
23	0.73882	2.94864	2.49793	2.87589
24	0.73992	2.95294	2.50026	2.87826
25	0.74052	2.95686	2.50194	2.88622

$\delta = \zeta = 0.3$

T	Single	CMCSS	Random	DMCSS
1	0.49924	2.47712	2.49838	2.48448
2	0.5648	2.5541	2.50145	2.53925
3	0.61322	2.62329	2.50072	2.58158
4	0.64425	2.67449	2.4993	2.62733
5	0.66536	2.71452	2.49884	2.65588
6	0.68287	2.74472	2.49657	2.6845
7	0.69533	2.7767	2.49899	2.69412
8	0.70315	2.79808	2.50126	2.71791
9	0.71255	2.82068	2.49794	2.73374
10	0.71759	2.83541	2.50254	2.73572
11	0.722	2.84439	2.50021	2.75863
12	0.72594	2.86	2.4993	2.76994
13	0.73104	2.87341	2.49983	2.77596
14	0.73467	2.87658	2.50172	2.7828
15	0.73662	2.89265	2.50059	2.7916
16	0.73879	2.89672	2.49806	2.79516
17	0.74082	2.90036	2.49745	2.7968
18	0.74349	2.90822	2.50067	2.80843
19	0.74379	2.91422	2.50121	2.81601
20	0.74541	2.92269	2.49753	2.81998
21	0.74747	2.92452	2.49748	2.81889
22	0.74811	2.93387	2.49814	2.83446
23	0.74912	2.92815	2.50143	2.82839
24	0.75035	2.93932	2.49846	2.83234
25	0.75117	2.94253	2.49987	2.83684

$\delta = \zeta = 0.4$

T	Single	CMCSS	Random	DMCSS
1	0.49822	2.48096	2.4973	2.4875
2	0.55909	2.54845	2.49676	2.53611
3	0.59967	2.60799	2.5027	2.56665
4	0.63011	2.65798	2.49857	2.59832
5	0.65269	2.69049	2.50065	2.62889

6	0.66915	2.72788	2.50238	2.65199
7	0.68132	2.74561	2.49763	2.66534
8	0.69315	2.76481	2.49986	2.68491
9	0.69899	2.79253	2.49929	2.70443
10	0.7078	2.80936	2.49935	2.71115
11	0.71239	2.81304	2.49847	2.71188
12	0.71733	2.8278	2.49879	2.73332
13	0.72019	2.84347	2.49945	2.73564
14	0.72255	2.84963	2.50169	2.74175
15	0.72668	2.86054	2.50164	2.75175
16	0.72765	2.86762	2.50023	2.75607
17	0.73036	2.86654	2.50169	2.76767
18	0.73337	2.87835	2.50229	2.77256
19	0.73446	2.88192	2.49788	2.77305
20	0.73694	2.88309	2.5021	2.77963
21	0.7383	2.89104	2.49956	2.78006
22	0.73862	2.90133	2.49941	2.78739
23	0.73946	2.90179	2.50139	2.79107
24	0.74069	2.90568	2.49817	2.78935
25	0.74202	2.9093	2.50044	2.79428

$\delta = \zeta = 0.5$

T	Single	CMCSS	Random	DMCSS
1	0.50017	2.47905	2.49309	2.494
2	0.5491	2.54036	2.49954	2.52293
3	0.58634	2.59342	2.4974	2.5596
4	0.61361	2.63676	2.50137	2.58078
5	0.63438	2.66811	2.50069	2.60162
6	0.64751	2.696	2.50102	2.62745
7	0.66291	2.71473	2.4985	2.63181
8	0.67256	2.73273	2.50018	2.65236
9	0.68028	2.75262	2.49833	2.67598
10	0.68763	2.76761	2.50006	2.67723
11	0.69155	2.78676	2.49752	2.68775
12	0.6964	2.78828	2.50059	2.6965
13	0.70015	2.79978	2.49768	2.70486

14	0.70353	2.80661	2.49605	2.71294
15	0.70603	2.81232	2.49725	2.71588
16	0.70886	2.82463	2.49897	2.72388
17	0.71093	2.82516	2.49939	2.7296
18	0.71372	2.83133	2.50003	2.73418
19	0.71604	2.83803	2.50065	2.73809
20	0.71629	2.84282	2.49872	2.74032
21	0.71806	2.84496	2.5006	2.74593
22	0.72017	2.85281	2.50023	2.74479
23	0.72074	2.84817	2.50149	2.75449
24	0.72267	2.85875	2.49903	2.74941
25	0.72376	2.86228	2.49879	2.7551

$\delta = \zeta = 0.6$

T	Single	CMCSS	Random	DMCSS
1	0.50136	2.47759	2.5008	2.49088
2	0.53976	2.53898	2.4993	2.51619
3	0.56917	2.57557	2.49694	2.53641
4	0.59309	2.60637	2.49885	2.56862
5	0.61217	2.63747	2.49385	2.57737
6	0.62295	2.65889	2.49778	2.59322
7	0.638	2.67836	2.49716	2.61287
8	0.64797	2.7049	2.4991	2.62732
9	0.65511	2.70462	2.50271	2.63608
10	0.66213	2.72683	2.50024	2.64392
11	0.66662	2.7354	2.49846	2.65748
12	0.67065	2.74939	2.49993	2.65932
13	0.67509	2.74758	2.50114	2.67014
14	0.67794	2.76366	2.49948	2.67577
15	0.68112	2.77048	2.49959	2.68027
16	0.68402	2.77686	2.49957	2.68712
17	0.68497	2.78354	2.50245	2.68549
18	0.68758	2.78466	2.50368	2.69309
19	0.68955	2.7935	2.49691	2.70488
20	0.68965	2.7953	2.49977	2.70458
21	0.69247	2.80359	2.49946	2.70393

22	0.69317	2.80208	2.4992	2.7092
23	0.69495	2.80169	2.5002	2.71182
24	0.69529	2.81229	2.49926	2.71721
25	0.6973	2.8114	2.50062	2.7121

$\delta = \zeta = 0.7$

T	Single	CMCSS	Random	DMCSS
1	0.50113	2.4897	2.49709	2.49602
2	0.52928	2.53675	2.50086	2.50833
3	0.55413	2.55844	2.49692	2.53919
4	0.57263	2.58295	2.49996	2.54794
5	0.58795	2.60851	2.49739	2.56665
6	0.59896	2.62252	2.49524	2.57448
7	0.60896	2.64396	2.50056	2.58949
8	0.6166	2.65861	2.49855	2.59556
9	0.62438	2.66949	2.49894	2.61003
10	0.62845	2.68147	2.49787	2.61308
11	0.63415	2.68676	2.50117	2.62047
12	0.6395	2.69413	2.49879	2.6299
13	0.64181	2.70651	2.50248	2.63469
14	0.64814	2.71542	2.4979	2.63973
15	0.64886	2.72053	2.50164	2.64718
16	0.65109	2.72197	2.49901	2.64899
17	0.65235	2.73013	2.49887	2.64731
18	0.65401	2.74179	2.50018	2.66098
19	0.6559	2.74125	2.49882	2.65726
20	0.65888	2.74387	2.49946	2.66395
21	0.65869	2.74759	2.50006	2.66839
22	0.66104	2.75019	2.49772	2.67008
23	0.66259	2.75303	2.49582	2.67249
24	0.66324	2.75762	2.49825	2.67307
25	0.66356	2.75842	2.50303	2.67746

$\delta = \zeta = 0.8$

T	Single	CMCSS	Random	DMCSS
1	0.50126	2.49507	2.49864	2.49973
2	0.51822	2.51379	2.50463	2.5138
3	0.53824	2.53573	2.50122	2.52121
4	0.5512	2.55792	2.50014	2.53411
5	0.55898	2.57332	2.4975	2.54416
6	0.56938	2.58652	2.4944	2.55624
7	0.57707	2.59359	2.49802	2.56089
8	0.58539	2.61452	2.49892	2.56312
9	0.58927	2.62275	2.50035	2.57818
10	0.59247	2.63452	2.49786	2.57779
11	0.59929	2.64075	2.50206	2.58187
12	0.60237	2.648	2.50079	2.58975
13	0.60472	2.65466	2.50073	2.60179
14	0.60689	2.65884	2.49996	2.60447
15	0.60792	2.66214	2.50101	2.59918
16	0.61047	2.66988	2.50089	2.60989
17	0.61369	2.68378	2.50158	2.60962
18	0.61409	2.67419	2.50258	2.61407
19	0.61713	2.6881	2.50143	2.60977
20	0.61797	2.68745	2.49904	2.61602
21	0.61777	2.68644	2.49683	2.62145
22	0.62036	2.69347	2.50198	2.62156
23	0.62081	2.69491	2.49847	2.62337
24	0.62153	2.6957	2.50071	2.62189
25	0.62192	2.69602	2.49996	2.62739

$\delta = \zeta = 0.9$

T	Single	CMCSS	Random	DMCSS
1	0.49952	2.49988	2.49341	2.49664
2	0.51198	2.5066	2.50418	2.49978
3	0.51736	2.52312	2.49849	2.50348
4	0.52773	2.52946	2.49964	2.5157
5	0.53071	2.53527	2.49957	2.51361

6	0.53831	2.55221	2.49992	2.52773
7	0.54019	2.56004	2.49949	2.5287
8	0.54366	2.56156	2.50146	2.53599
9	0.54905	2.56973	2.50057	2.54508
10	0.55048	2.5815	2.50006	2.53696
11	0.55405	2.57626	2.50206	2.55131
12	0.55561	2.5864	2.50439	2.55039
13	0.55727	2.58433	2.50074	2.54947
14	0.55893	2.59768	2.49738	2.55586
15	0.56033	2.59713	2.49716	2.56002
16	0.55968	2.60045	2.50204	2.56234
17	0.5638	2.60192	2.49855	2.55919
18	0.56668	2.59782	2.49756	2.55952
19	0.56236	2.60752	2.49919	2.5674
20	0.56669	2.6111	2.50151	2.5668
21	0.56659	2.61322	2.50001	2.5651
22	0.56724	2.61727	2.4996	2.57156
23	0.5677	2.61608	2.50223	2.57161
24	0.56891	2.62343	2.50151	2.57453
25	0.56954	2.6256	2.49951	2.57292

$\boldsymbol{\delta = \zeta = 1.0}$

T	Single	CMCSS	Random	DMCSS
1	0.50038	2.50025	2.4993	2.50333
2	0.49801	2.5029	2.50274	2.50265
3	0.50159	2.49038	2.50169	2.50122
4	0.49778	2.50677	2.49967	2.49414
5	0.50089	2.50039	2.50312	2.49821
6	0.49835	2.50203	2.50284	2.49423
7	0.50072	2.4952	2.49663	2.48621
8	0.49845	2.49906	2.50242	2.49836
9	0.49959	2.49578	2.49877	2.49919
10	0.49904	2.49069	2.50103	2.49861
11	0.50036	2.50176	2.50095	2.50375
12	0.50003	2.49344	2.50174	2.49425
13	0.50079	2.50039	2.50111	2.50096

14	0.49696	2.50297	2.49838	2.49541
15	0.5001	2.50323	2.50299	2.50495
16	0.50079	2.50209	2.5004	2.50279
17	0.5006	2.50552	2.49971	2.50437
18	0.49985	2.50237	2.49944	2.49958
19	0.49794	2.50377	2.49795	2.50513
20	0.50063	2.49984	2.49788	2.49289
21	0.5	2.50099	2.49876	2.4969
22	0.50063	2.50217	2.50027	2.50128
23	0.49992	2.49893	2.49737	2.50168
24	0.49956	2.49975	2.49911	2.49372
25	0.4989	2.49891	2.49946	2.49788

Performance of decentralized multiuser cooperative spectrum sensing (DMCSS) for different collision threshold (ζ)

Parameter	**Value**
N	10
B	1
T	25
α	0.1
β	0.9
Number of collaborated users	5
ζ	0.3
SNR	5 dB
Probability of selected channel (p) for DMCSS	Varied

T	**Single**	**CMCSS**	**Random**	**DMCSS**		
				$p = 0.1$	$p = 0.2$	$p = 0.3$
1	0.49869	2.47869	2.49164	2.49499	2.48557	2.48937
2	0.56804	2.54304	2.49846	2.51729	2.52681	2.5324
3	0.61235	2.61888	2.50018	2.54683	2.5518	2.55913
4	0.64457	2.67003	2.50227	2.57064	2.58499	2.59271

5	0.66609	2.71301	2.5005	2.58857	2.60469	2.61404
6	0.68291	2.74225	2.49977	2.60581	2.62136	2.63952
7	0.69423	2.76967	2.49762	2.62499	2.63618	2.65232
8	0.70402	2.79014	2.50217	2.63348	2.65237	2.6754
9	0.71065	2.80928	2.49863	2.65146	2.67004	2.68817
10	0.71716	2.83298	2.50113	2.66064	2.67496	2.70249
11	0.72265	2.8473	2.49916	2.66587	2.68699	2.70765
12	0.72707	2.86076	2.49744	2.67322	2.69599	2.7149
13	0.73016	2.86924	2.50124	2.68261	2.69926	2.72798
14	0.73398	2.87994	2.49696	2.68626	2.70869	2.73413
15	0.73623	2.89203	2.49981	2.69447	2.71249	2.74776
16	0.7377	2.89591	2.49935	2.6964	2.72457	2.74929
17	0.73958	2.90445	2.49836	2.70981	2.72294	2.75407
18	0.74284	2.90698	2.49721	2.7127	2.73306	2.76016
19	0.74317	2.91224	2.49972	2.71485	2.73649	2.75712
20	0.74609	2.92405	2.50081	2.71039	2.74375	2.7614
21	0.74677	2.92504	2.49902	2.71495	2.74175	2.76788
22	0.74813	2.93012	2.50101	2.72014	2.74762	2.77017
23	0.74851	2.93532	2.49864	2.72511	2.75224	2.77402
24	0.7503	2.9413	2.49984	2.72931	2.75154	2.77547
25	0.75186	2.94337	2.50067	2.72979	2.75921	2.78147

DMCSS						
T	$p = 0.5$	$p = 0.6$	$p = 0.7$	$p = 0.8$	$p = 0.8$	$p = 1.0$
1	2.48448	2.47969	2.48587	2.4817	2.47857	2.48
2	2.53925	2.53917	2.54606	2.55538	2.54744	2.54926
3	2.58158	2.58921	2.59807	2.60344	2.61104	2.61769
4	2.62733	2.63651	2.63887	2.65275	2.66693	2.67281
5	2.65588	2.66819	2.68277	2.69412	2.70329	2.711
6	2.6845	2.68943	2.71302	2.72394	2.74081	2.74692
7	2.69412	2.71063	2.73101	2.74776	2.76429	2.76924
8	2.71791	2.74082	2.75518	2.77096	2.78249	2.79614
9	2.73374	2.7497	2.77602	2.79562	2.80809	2.81296
10	2.73572	2.76607	2.79357	2.80935	2.82509	2.83749
11	2.75863	2.78142	2.80189	2.82123	2.83994	2.84572

12	2.76994	2.78814	2.81495	2.83815	2.85117	2.85638
13	2.77596	2.79681	2.82656	2.84709	2.8584	2.87059
14	2.7828	2.8107	2.83356	2.85598	2.87337	2.88063
15	2.7916	2.81363	2.83839	2.86207	2.86945	2.89284
16	2.79516	2.8243	2.85098	2.87145	2.88157	2.89098
17	2.7968	2.82781	2.85678	2.87776	2.89169	2.90131
18	2.80843	2.83639	2.85666	2.88083	2.8963	2.91001
19	2.81601	2.84122	2.86653	2.88522	2.90207	2.91804
20	2.81998	2.84217	2.87252	2.89451	2.91045	2.9201
21	2.81889	2.84855	2.8761	2.89971	2.91376	2.92694
22	2.83446	2.85184	2.87825	2.90334	2.9209	2.93139
23	2.82839	2.85598	2.88365	2.90621	2.92242	2.93853
24	2.83234	2.85899	2.88955	2.91246	2.92663	2.93625
25	2.83684	2.86384	2.89085	2.91238	2.93221	2.94431

Throughput performance vs Signal to Noise Ratio (SNR) with different ζ

Parameter	Value
N	10
B	1
T	25
α	0.1
β	0.9
Number of collaborated users	5
ζ	0.05
Probability of selected channel (p) for DCU	0.2
SNR	Varied

SNR = -3 dB

T	Single	CMCSS	Random	DMCSS
1	0.50116	2.49788	2.503	2.50041
2	0.50649	2.49845	2.49763	2.50193
3	0.51288	2.50517	2.50121	2.50229
4	0.51649	2.50244	2.50004	2.52074

5	0.51928	2.51046	2.49942	2.53122
6	0.52166	2.50751	2.49771	2.53577
7	0.52499	2.51277	2.49801	2.54301
8	0.52706	2.51765	2.49914	2.54459
9	0.52659	2.51536	2.5019	2.54319
10	0.52738	2.51878	2.50073	2.54766
11	0.52861	2.52046	2.50405	2.55538
12	0.52999	2.52458	2.49906	2.55261
13	0.5308	2.5237	2.4989	2.55012
14	0.53054	2.52816	2.49959	2.55768
15	0.53156	2.52787	2.50057	2.56348
16	0.53288	2.53129	2.50056	2.5576
17	0.53122	2.52789	2.50078	2.56878
18	0.53274	2.53367	2.49768	2.5685
19	0.53125	2.53066	2.49754	2.57141
20	0.532	2.53087	2.49925	2.5717
21	0.53369	2.53102	2.50041	2.57006
22	0.5326	2.53593	2.49805	2.5716
23	0.53193	2.53384	2.5004	2.57659
24	0.53329	2.53374	2.49993	2.5746
25	0.53364	2.53054	2.50095	2.57693

SNR = -2 dB

T	Single	CMCSS	Random	DMCSS
1	0.49966	2.48553	2.50094	2.49751
2	0.50785	2.50591	2.49815	2.50291
3	0.51354	2.50237	2.49739	2.51272
4	0.52013	2.51079	2.498	2.52282
5	0.52424	2.50989	2.50046	2.53137
6	0.52813	2.51424	2.50181	2.54833
7	0.53077	2.51923	2.49929	2.54893
8	0.53462	2.51831	2.50129	2.55629
9	0.53454	2.52218	2.49923	2.55538
10	0.53313	2.52613	2.50315	2.56057
11	0.53562	2.5339	2.50381	2.56321

12	0.53819	2.52922	2.49994	2.56922
13	0.5385	2.53318	2.50151	2.56548
14	0.53976	2.53125	2.50046	2.57363
15	0.53846	2.53446	2.49917	2.57648
16	0.53995	2.53673	2.49908	2.57602
17	0.53954	2.53288	2.49905	2.58037
18	0.53995	2.5362	2.50127	2.5828
19	0.53975	2.53991	2.50011	2.5892
20	0.54101	2.5396	2.50194	2.58551
21	0.54114	2.54127	2.50043	2.58939
22	0.54065	2.53922	2.496	2.58826
23	0.54203	2.53962	2.49879	2.5916
24	0.54181	2.54073	2.50134	2.59846
25	0.54318	2.5427	2.49797	2.59403

SNR = -1 dB

T	Single	CMCSS	Random	DMCSS
1	0.4994	2.49814	2.50131	2.48622
2	0.51403	2.50374	2.49904	2.50395
3	0.51866	2.51026	2.49805	2.5107
4	0.5248	2.50664	2.49584	2.52059
5	0.53247	2.50863	2.49873	2.53756
6	0.53604	2.51484	2.49862	2.55044
7	0.53836	2.52318	2.50176	2.55936
8	0.54109	2.52399	2.5021	2.56413
9	0.54374	2.52387	2.50372	2.57327
10	0.54644	2.53395	2.5036	2.57148
11	0.54516	2.5386	2.50136	2.57711
12	0.54724	2.54548	2.50004	2.57983
13	0.54844	2.54215	2.50107	2.58886
14	0.54984	2.53898	2.4983	2.59007
15	0.55035	2.54638	2.50289	2.58925
16	0.55053	2.54897	2.50007	2.59482
17	0.55099	2.54652	2.49966	2.59448
18	0.55165	2.55179	2.50054	2.59892
19	0.55148	2.55406	2.50247	2.60555

20	0.55263	2.55393	2.49959	2.60593
21	0.55365	2.55966	2.50017	2.60748
22	0.55248	2.55864	2.49934	2.6093
23	0.55312	2.56019	2.49899	2.61125
24	0.55447	2.55813	2.49848	2.61503
25	0.55417	2.56085	2.50024	2.61855

SNR = 0 dB

T	Single	CMCSS	Random	DMCSS
1	0.50005	2.49449	2.49948	2.49189
2	0.51205	2.50301	2.49526	2.50599
3	0.5264	2.50057	2.49923	2.53166
4	0.53353	2.51283	2.49634	2.55161
5	0.54051	2.51712	2.50567	2.57215
6	0.54672	2.52152	2.49357	2.588
7	0.54941	2.52756	2.49857	2.59882
8	0.55295	2.53184	2.49803	2.6019
9	0.55331	2.53556	2.49913	2.61172
10	0.55693	2.54141	2.50083	2.61902
11	0.55795	2.54742	2.4979	2.62419
12	0.5599	2.54933	2.50209	2.62875
13	0.5607	2.55397	2.49847	2.63088
14	0.56185	2.55487	2.50171	2.63476
15	0.56247	2.55896	2.50268	2.64623
16	0.56447	2.55567	2.50327	2.6444
17	0.56416	2.55784	2.50001	2.64856
18	0.56443	2.56286	2.49752	2.64825
19	0.5651	2.56565	2.49933	2.65228
20	0.56475	2.56727	2.4984	2.65957
21	0.56591	2.56489	2.49942	2.66165
22	0.56645	2.57008	2.49779	2.66458
23	0.56681	2.56976	2.49893	2.6674
24	0.5677	2.57006	2.50014	2.672
25	0.56822	2.57074	2.50209	2.67047

SNR = 1 dB

T	Single	CMCSS	Random	DMCSS
1	0.50059	2.494	2.49301	2.48649
2	0.51985	2.50087	2.5106	2.49904
3	0.5326	2.50942	2.50639	2.53305
4	0.54412	2.51741	2.4982	2.55754
5	0.55237	2.52269	2.5005	2.58351
6	0.55875	2.53011	2.50283	2.59725
7	0.56089	2.53763	2.50013	2.60912
8	0.56614	2.54839	2.49591	2.62061
9	0.57078	2.54845	2.50167	2.62808
10	0.5727	2.55374	2.49761	2.63615
11	0.57582	2.56304	2.50129	2.63441
12	0.5759	2.56681	2.49912	2.64617
13	0.57635	2.57349	2.50177	2.6526
14	0.57824	2.57449	2.49818	2.65193
15	0.57918	2.57198	2.4994	2.66006
16	0.57993	2.57823	2.50068	2.66112
17	0.58187	2.58271	2.49657	2.673
18	0.58135	2.5804	2.49978	2.6713
19	0.58196	2.58505	2.49905	2.67885
20	0.58327	2.58661	2.50033	2.68302
21	0.58394	2.58921	2.50297	2.68682
22	0.5845	2.58878	2.50233	2.68346
23	0.58366	2.58959	2.4993	2.69077
24	0.58398	2.59705	2.50016	2.69207
25	0.58457	2.59665	2.50033	2.69579

SNR = 2 dB

T	Single	CMCSS	Random	DMCSS
1	0.50144	2.49798	2.50438	2.47858
2	0.52541	2.49965	2.50361	2.50449
3	0.54263	2.5109	2.50169	2.54083
4	0.55596	2.52313	2.49728	2.57248
5	0.56445	2.53075	2.50512	2.58998
6	0.5736	2.53945	2.50232	2.61263

7	0.57959	2.5536	2.49867	2.63577
8	0.58336	2.5614	2.50037	2.64149
9	0.58725	2.56941	2.49947	2.6507
10	0.58955	2.5774	2.50102	2.65819
11	0.59328	2.58384	2.50161	2.67529
12	0.59483	2.58968	2.49984	2.67105
13	0.59726	2.59739	2.49617	2.67811
14	0.59794	2.59996	2.50029	2.68841
15	0.59863	2.60588	2.50239	2.69382
16	0.59821	2.60508	2.50036	2.68799
17	0.6	2.61093	2.49975	2.69706
18	0.60194	2.61388	2.49835	2.70061
19	0.60152	2.6183	2.49807	2.70392
20	0.60298	2.616	2.49781	2.71226
21	0.60251	2.62241	2.49967	2.71271
22	0.60371	2.62585	2.50026	2.71801
23	0.60359	2.62638	2.50117	2.72069
24	0.60424	2.62675	2.49834	2.7252
25	0.60455	2.62491	2.5003	2.72841

SNR = 3 dB

T	Single	CMCSS	Random	DMCSS
1	0.49963	2.49386	2.49618	2.47636
2	0.53027	2.50564	2.50299	2.50781
3	0.55504	2.51264	2.50388	2.5457
4	0.57048	2.52765	2.49431	2.58021
5	0.58337	2.53719	2.50226	2.61773
6	0.59015	2.55006	2.49698	2.6349
7	0.5959	2.56554	2.49764	2.65484
8	0.60261	2.56979	2.50082	2.66665
9	0.60549	2.58299	2.50073	2.67556
10	0.60906	2.58925	2.49956	2.68844
11	0.61323	2.59989	2.50061	2.69899
12	0.61542	2.60315	2.49855	2.70953
13	0.61684	2.60817	2.50168	2.71167
14	0.61825	2.61838	2.49757	2.72425

15	0.6187	2.6229	2.49955	2.72942
16	0.6215	2.62846	2.50361	2.7285
17	0.62192	2.62954	2.50116	2.73156
18	0.62361	2.6312	2.49948	2.73893
19	0.62486	2.63608	2.49909	2.74718
20	0.62346	2.63739	2.50081	2.74627
21	0.62441	2.64278	2.49977	2.75438
22	0.62459	2.64357	2.49849	2.75943
23	0.62615	2.64633	2.49882	2.7655
24	0.62604	2.65127	2.49688	2.76523
25	0.62703	2.65156	2.49907	2.77169

SNR = 4 dB

T	Single	CMCSS	Random	DMCSS
1	0.50046	2.4893	2.49699	2.47592
2	0.54198	2.50456	2.50514	2.54275
3	0.57005	2.51303	2.4983	2.61304
4	0.58896	2.53595	2.50426	2.65922
5	0.60259	2.56088	2.50185	2.70872
6	0.61221	2.58103	2.49857	2.73627
7	0.62033	2.59193	2.49799	2.7572
8	0.62518	2.60452	2.499	2.77524
9	0.62943	2.61442	2.49866	2.79618
10	0.63226	2.62884	2.50094	2.80585
11	0.63743	2.63509	2.50159	2.82057
12	0.6382	2.64649	2.50181	2.83799
13	0.64192	2.65735	2.49932	2.8437
14	0.64195	2.66021	2.50144	2.85255
15	0.64497	2.6645	2.502	2.86078
16	0.64558	2.671	2.49869	2.8603
17	0.64703	2.67375	2.50113	2.8762
18	0.64746	2.67913	2.49919	2.87853
19	0.64844	2.68973	2.49844	2.8845
20	0.6497	2.69451	2.50078	2.89299
21	0.65037	2.6932	2.49941	2.89412
22	0.65166	2.70243	2.50107	2.89676

23	0.65124	2.70305	2.4964	2.90183
24	0.65372	2.70701	2.50285	2.90489
25	0.65297	2.71261	2.4993	2.91539

SNR = 5 dB

T	Single	CMCSS	Random	DMCSS
1	0.50101	2.48179	2.49561	2.48195
2	0.5507	2.50245	2.49843	2.54651
3	0.58469	2.5296	2.50115	2.62769
4	0.60536	2.54656	2.50043	2.682
5	0.62024	2.57273	2.49898	2.71805
6	0.63057	2.59327	2.49681	2.74756
7	0.63829	2.60836	2.49962	2.78172
8	0.64682	2.6192	2.49855	2.80136
9	0.65074	2.63168	2.50083	2.81777
10	0.65591	2.64412	2.50022	2.83799
11	0.65919	2.65292	2.499	2.85356
12	0.66156	2.6568	2.49888	2.86401
13	0.6646	2.66798	2.5003	2.87663
14	0.66642	2.67402	2.49851	2.88669
15	0.66725	2.68889	2.49999	2.89345
16	0.67002	2.69026	2.5002	2.89582
17	0.67072	2.69842	2.49599	2.90918
18	0.67274	2.7044	2.49908	2.91647
19	0.67194	2.70819	2.49742	2.91904
20	0.67285	2.71712	2.49779	2.93262
21	0.67512	2.72274	2.50141	2.93819
22	0.67594	2.72746	2.50207	2.93759
23	0.67552	2.72971	2.50053	2.94495
24	0.67607	2.73933	2.49946	2.94424
25	0.67639	2.74146	2.50073	2.95651

SNR = 6 dB

T	Single	CMCSS	Random	DMCSS
1	0.50017	2.4744	2.49312	2.48207

2	0.56048	2.50692	2.49835	2.55494
3	0.60005	2.54064	2.4969	2.62461
4	0.6248	2.5947	2.5023	2.68343
5	0.64279	2.61848	2.5008	2.7245
6	0.65481	2.64802	2.50167	2.7646
7	0.66443	2.66895	2.49975	2.79389
8	0.67162	2.68087	2.49905	2.82114
9	0.67694	2.69795	2.50143	2.83971
10	0.68181	2.71339	2.50219	2.85735
11	0.68496	2.71919	2.50054	2.87746
12	0.68803	2.7357	2.49955	2.88753
13	0.68978	2.74909	2.49818	2.89807
14	0.69194	2.75566	2.49665	2.9136
15	0.69423	2.76511	2.50188	2.92117
16	0.6958	2.77577	2.49746	2.93544
17	0.69724	2.7824	2.49913	2.93464
18	0.69954	2.79121	2.50274	2.93944
19	0.69946	2.79757	2.50192	2.94912
20	0.70084	2.80771	2.49837	2.95832
21	0.70151	2.81374	2.50103	2.96423
22	0.70293	2.82436	2.50255	2.96792
23	0.70281	2.82863	2.50137	2.98024
24	0.70421	2.83026	2.50099	2.97837
25	0.70419	2.8376	2.50204	2.98123

SNR = 7 dB

T	Single	CMCSS	Random	DMCSS
1	0.49855	2.46829	2.50557	2.47516
2	0.57215	2.50888	2.5005	2.55329
3	0.61565	2.55908	2.50196	2.621
4	0.64091	2.60864	2.49436	2.68161
5	0.6617	2.63401	2.50476	2.73039
6	0.67566	2.671	2.49829	2.76829
7	0.68332	2.69108	2.49955	2.79993
8	0.69225	2.70753	2.49943	2.82804
9	0.69997	2.72431	2.5003	2.85285

10	0.70347	2.73958	2.50531	2.87316
11	0.70732	2.74631	2.50186	2.88727
12	0.71062	2.76474	2.50044	2.90121
13	0.71314	2.77743	2.50316	2.9082
14	0.71684	2.78343	2.49977	2.92193
15	0.71742	2.79294	2.50079	2.93764
16	0.71925	2.79777	2.50295	2.94402
17	0.72063	2.81122	2.49968	2.95001
18	0.72204	2.82056	2.49939	2.95729
19	0.72367	2.82686	2.5008	2.9691
20	0.72513	2.8306	2.50275	2.97155
21	0.72562	2.84167	2.50083	2.97861
22	0.72619	2.85197	2.50075	2.98688
23	0.72789	2.85752	2.49947	2.98568
24	0.72812	2.86686	2.50081	2.99418
25	0.72904	2.87002	2.50022	3.00107

SNR = 8 dB

T	Single	CMCSS	Random	DMCSS
1	0.50026	2.47142	2.49756	2.48111
2	0.58097	2.51178	2.49451	2.55393
3	0.62759	2.55683	2.49471	2.63163
4	0.65504	2.6077	2.49686	2.68528
5	0.6768	2.65223	2.49429	2.73247
6	0.68803	2.67786	2.49753	2.77139
7	0.69845	2.70549	2.4988	2.80649
8	0.70695	2.72547	2.50021	2.82678
9	0.71251	2.74254	2.49812	2.84632
10	0.71731	2.76556	2.50059	2.87718
11	0.72164	2.78246	2.50017	2.88741
12	0.72439	2.79412	2.49991	2.90765
13	0.72879	2.80554	2.50252	2.91476
14	0.73136	2.8164	2.49904	2.92702
15	0.7325	2.82857	2.49982	2.93974
16	0.73376	2.83813	2.49936	2.94717
17	0.73587	2.84644	2.50143	2.95478

18	0.73764	2.85803	2.50092	2.96701
19	0.73798	2.86209	2.50127	2.97364
20	0.73837	2.86968	2.49965	2.97997
21	0.73986	2.87881	2.5001	2.98469
22	0.74126	2.8853	2.50153	2.98899
23	0.74321	2.89466	2.49838	2.99743
24	0.74263	2.90223	2.50021	3.00258
25	0.74432	2.90874	2.49848	3.00778

SNR = 9 dB

T	Single	CMCSS	Random	DMCSS
1	0.50119	2.46534	2.50409	2.47196
2	0.58689	2.56238	2.50035	2.55579
3	0.63943	2.63435	2.50121	2.63364
4	0.67347	2.70691	2.49786	2.68575
5	0.6967	2.7533	2.50105	2.73595
6	0.7093	2.79124	2.50001	2.7737
7	0.72127	2.82591	2.5002	2.80208
8	0.73026	2.85172	2.50059	2.83297
9	0.73816	2.87509	2.49793	2.85279
10	0.74273	2.89308	2.5009	2.87182
11	0.74635	2.90972	2.49744	2.89132
12	0.74968	2.92944	2.50274	2.90646
13	0.75259	2.94413	2.4986	2.92515
14	0.75625	2.95887	2.50121	2.92774
15	0.75861	2.97339	2.50045	2.94032
16	0.75968	2.98516	2.50046	2.94888
17	0.76184	2.99155	2.50134	2.95704
18	0.76337	3.00633	2.49852	2.96273
19	0.76463	3.01305	2.49718	2.97095
20	0.76585	3.02376	2.50219	2.984
21	0.76813	3.03425	2.49715	2.98636
22	0.76809	3.04258	2.50092	2.99266
23	0.76953	3.05044	2.50078	2.99836
24	0.77027	3.05625	2.50277	3.00806
25	0.77091	3.06846	2.50093	3.00848

SNR = 10 dB

T	Single	CMCSS	Random	DMCSS
1	0.50078	2.46637	2.50207	2.47644
2	0.58859	2.56217	2.50267	2.56212
3	0.64738	2.645	2.4957	2.63247
4	0.68492	2.7164	2.50007	2.68813
5	0.70852	2.76734	2.50011	2.73407
6	0.726	2.81229	2.49848	2.76959
7	0.73716	2.84533	2.49457	2.8087
8	0.74629	2.87083	2.50139	2.83426
9	0.75384	2.89738	2.5	2.85368
10	0.75897	2.91637	2.50141	2.86994
11	0.76321	2.93829	2.49769	2.88973
12	0.7679	2.95988	2.49894	2.8999
13	0.7716	2.97178	2.49632	2.91245
14	0.77453	2.98555	2.50116	2.9326
15	0.77708	3.00532	2.50423	2.93916
16	0.77916	3.01813	2.49906	2.9495
17	0.78072	3.02784	2.49895	2.95717
18	0.78412	3.04082	2.49914	2.96563
19	0.78367	3.04698	2.50073	2.9759
20	0.78611	3.05948	2.50082	2.97945
21	0.78681	3.07216	2.49795	2.98553
22	0.78774	3.0798	2.50204	2.99141
23	0.78933	3.08742	2.49889	2.99921
24	0.78989	3.09343	2.49576	3.00492
25	0.79149	3.0998	2.50091	3.01185

Parameter	Value
N	10
B	1
T	25
α	0.1
β	0.9
Number of collaborated users	5

ζ	0.2
Probability of selected channel (p) for DMCSS	0.2
SNR	Varied

SNR = 0 dB

T	Single	CMCSS	Random	DMCSS
1	0.49639	2.48695	2.50897	2.48192
2	0.53609	2.50656	2.50433	2.51392
3	0.55496	2.51646	2.49821	2.53471
4	0.5668	2.53307	2.49896	2.55562
5	0.57819	2.5436	2.49756	2.57595
6	0.58312	2.5619	2.50006	2.59831
7	0.58948	2.57013	2.5014	2.60031
8	0.59412	2.57945	2.5	2.61228
9	0.59952	2.58381	2.50208	2.6256
10	0.60187	2.58437	2.49773	2.62819
11	0.60429	2.59251	2.49496	2.63611
12	0.60602	2.59496	2.50009	2.64454
13	0.60798	2.59134	2.50128	2.65185
14	0.61024	2.59747	2.49727	2.64775
15	0.61065	2.608	2.50138	2.65747
16	0.61259	2.61157	2.49656	2.65502
17	0.61299	2.60889	2.49805	2.65946
18	0.61423	2.62042	2.50113	2.6563
19	0.61656	2.621	2.50146	2.67033
20	0.61525	2.61999	2.499	2.66183
21	0.61599	2.62484	2.50061	2.66661
22	0.61665	2.62721	2.50114	2.67337
23	0.61722	2.6309	2.49854	2.67378
24	0.61853	2.63695	2.49792	2.67515
25	0.61833	2.63246	2.49944	2.67913

SNR = 1 dB

T	Single	CMCSS	Random	DMCSS
1	0.49779	2.48677	2.4962	2.48631

2	0.54205	2.50814	2.50906	2.53067
3	0.56582	2.52996	2.49928	2.57788
4	0.58421	2.56066	2.50047	2.61097
5	0.59655	2.57688	2.501	2.63943
6	0.60547	2.59759	2.49816	2.65828
7	0.61418	2.61286	2.4999	2.67508
8	0.61843	2.62158	2.50007	2.68634
9	0.62383	2.62733	2.50349	2.70012
10	0.62701	2.63956	2.49503	2.71648
11	0.63115	2.64536	2.49996	2.72095
12	0.63451	2.64903	2.50129	2.72779
13	0.63396	2.65757	2.50158	2.72784
14	0.63743	2.65768	2.50321	2.74122
15	0.63801	2.65863	2.50239	2.74152
16	0.63954	2.66636	2.50013	2.7489
17	0.6412	2.67809	2.49983	2.75962
18	0.64181	2.67231	2.49965	2.75184
19	0.6429	2.67849	2.50277	2.75948
20	0.64298	2.68179	2.5011	2.76217
21	0.6459	2.68588	2.499	2.76345
22	0.64416	2.69403	2.50041	2.76851
23	0.6455	2.69292	2.49906	2.76777
24	0.64644	2.70122	2.49779	2.77134
25	0.6471	2.6997	2.50036	2.78003

SNR = 2 dB

T	Single	CMCSS	Random	DMCSS
1	0.50105	2.49137	2.49014	2.48367
2	0.55171	2.49926	2.50279	2.53831
3	0.57968	2.53977	2.49954	2.59072
4	0.5989	2.56845	2.50279	2.62581
5	0.61311	2.5912	2.49928	2.65216
6	0.62291	2.61084	2.5021	2.67818
7	0.63141	2.62929	2.50399	2.69393
8	0.63751	2.63575	2.49712	2.70799
9	0.642	2.6441	2.49849	2.73257

10	0.64663	2.65352	2.49795	2.73539
11	0.65107	2.66391	2.49755	2.75148
12	0.65319	2.66805	2.4978	2.75099
13	0.65653	2.67843	2.49832	2.76317
14	0.65817	2.68216	2.50072	2.7658
15	0.65994	2.68215	2.5028	2.7794
16	0.66207	2.69025	2.49904	2.77907
17	0.66412	2.69287	2.49964	2.7867
18	0.665	2.69691	2.49992	2.78648
19	0.66662	2.70539	2.49854	2.79062
20	0.66626	2.70954	2.49524	2.79794
21	0.66774	2.71572	2.49999	2.80193
22	0.66785	2.71616	2.50373	2.80526
23	0.66922	2.72409	2.50117	2.80553
24	0.67037	2.7211	2.49943	2.80799
25	0.66976	2.73153	2.49885	2.80838

SNR = 3 dB

T	Single	CMCSS	Random	DMCSS
1	0.49865	2.47401	2.50133	2.48702
2	0.55701	2.50831	2.49266	2.53936
3	0.59042	2.54532	2.49765	2.58529
4	0.61326	2.58289	2.50077	2.63635
5	0.62513	2.61409	2.49967	2.66559
6	0.63789	2.63073	2.49978	2.6927
7	0.64749	2.64403	2.49984	2.71302
8	0.65514	2.65922	2.50039	2.72956
9	0.66073	2.67229	2.50159	2.74191
10	0.66547	2.67981	2.49883	2.75907
11	0.66781	2.68725	2.49925	2.7699
12	0.6719	2.70035	2.50175	2.77834
13	0.67529	2.70144	2.49801	2.79177
14	0.67647	2.70548	2.50351	2.80036
15	0.67869	2.71485	2.50306	2.79931
16	0.6803	2.71395	2.50028	2.80972
17	0.68228	2.72522	2.50107	2.81325

18	0.68295	2.73	2.50065	2.82314
19	0.68477	2.73775	2.49958	2.82629
20	0.6862	2.73718	2.49915	2.8298
21	0.68562	2.74379	2.49839	2.83654
22	0.68705	2.74463	2.50075	2.83818
23	0.68881	2.75166	2.49656	2.84032
24	0.6887	2.75714	2.50026	2.84159
25	0.69106	2.76348	2.50068	2.84677

SNR = 4 dB

T	Single	CMCSS	Random	DMCSS
1	0.49831	2.47335	2.49718	2.4881
2	0.56798	2.51145	2.499	2.54184
3	0.59899	2.55052	2.49842	2.59657
4	0.62434	2.59092	2.5015	2.64422
5	0.63812	2.6228	2.49867	2.67759
6	0.6491	2.64654	2.50024	2.70302
7	0.66056	2.66871	2.49955	2.72139
8	0.66897	2.68657	2.4999	2.7382
9	0.67271	2.70073	2.49734	2.76397
10	0.67836	2.7099	2.50141	2.77168
11	0.68181	2.72232	2.49796	2.78828
12	0.68487	2.73237	2.49713	2.80134
13	0.68804	2.7372	2.49876	2.80718
14	0.69008	2.74277	2.49774	2.81561
15	0.69187	2.7528	2.50148	2.82163
16	0.69356	2.76175	2.49778	2.83297
17	0.69571	2.76592	2.49972	2.8343
18	0.69711	2.76729	2.50069	2.84206
19	0.69851	2.7838	2.5012	2.84652
20	0.69927	2.78202	2.49899	2.84912
21	0.70113	2.79066	2.49773	2.85706
22	0.70231	2.78455	2.49976	2.85385
23	0.70255	2.79903	2.49852	2.86251
24	0.70289	2.79964	2.5011	2.86814
25	0.70343	2.80701	2.50127	2.87195

SNR = 5 dB

T	Single	CMCSS	Random	DMCSS
1	0.50148	2.48377	2.49543	2.48058
2	0.57026	2.54896	2.50077	2.53563
3	0.61845	2.62506	2.5011	2.60111
4	0.64698	2.6755	2.4963	2.64419
5	0.66643	2.71985	2.49369	2.67309
6	0.68083	2.75109	2.50406	2.70988
7	0.69183	2.78365	2.50047	2.7253
8	0.69915	2.79735	2.49645	2.74686
9	0.70788	2.81731	2.50113	2.76675
10	0.71417	2.83386	2.50132	2.77908
11	0.71596	2.85084	2.49927	2.79891
12	0.72016	2.86058	2.49635	2.81315
13	0.72338	2.87306	2.49774	2.81709
14	0.72635	2.88232	2.50051	2.8278
15	0.72823	2.88825	2.50192	2.83102
16	0.73065	2.90359	2.50147	2.83695
17	0.7317	2.90984	2.5006	2.84742
18	0.73311	2.91788	2.49661	2.85436
19	0.73445	2.92468	2.49851	2.85974
20	0.73547	2.92828	2.50008	2.86422
21	0.73696	2.93639	2.49633	2.86411
22	0.73799	2.94472	2.50022	2.87521
23	0.7376	2.94547	2.50193	2.87176
24	0.73947	2.95373	2.50156	2.87866
25	0.74018	2.95637	2.5007	2.88447

SNR = 6 dB

T	Single	CMCSS	Random	DMCSS
1	0.49987	2.4781	2.49798	2.48666
2	0.57526	2.55357	2.49981	2.541
3	0.62613	2.63315	2.4975	2.60324
4	0.65735	2.6874	2.50943	2.64123
5	0.68036	2.73536	2.50313	2.67772

6	0.69758	2.76664	2.49802	2.70471
7	0.70891	2.80064	2.49835	2.729
8	0.71881	2.82517	2.49756	2.75167
9	0.72444	2.84588	2.49748	2.76967
10	0.73185	2.86451	2.49873	2.78285
11	0.73606	2.88716	2.50358	2.79642
12	0.74016	2.89331	2.49871	2.80479
13	0.74276	2.90294	2.49934	2.82252
14	0.74645	2.91719	2.50248	2.83297
15	0.74739	2.92798	2.50089	2.84006
16	0.75051	2.93591	2.49996	2.84493
17	0.75327	2.94012	2.49608	2.85259
18	0.75468	2.95394	2.49661	2.86123
19	0.75645	2.95718	2.49995	2.85841
20	0.75786	2.96864	2.50112	2.87036
21	0.75787	2.9719	2.49879	2.86808
22	0.75904	2.97558	2.50143	2.87917
23	0.76127	2.9853	2.50186	2.87755
24	0.7617	2.99205	2.50137	2.88339
25	0.76343	2.99236	2.49981	2.88821

SNR = 7 dB

T	Single	CMCSS	Random	DMCSS
1	0.50032	2.47927	2.49832	2.47799
2	0.57853	2.55726	2.49783	2.54752
3	0.6291	2.63553	2.50159	2.59288
4	0.66373	2.70334	2.4975	2.64206
5	0.68888	2.74178	2.50095	2.67854
6	0.7042	2.78262	2.49864	2.70384
7	0.71823	2.80939	2.50192	2.73183
8	0.7264	2.83733	2.50056	2.74689
9	0.73604	2.86217	2.49836	2.7688
10	0.74175	2.88055	2.49861	2.7833
11	0.74831	2.90505	2.49666	2.80316
12	0.75262	2.91771	2.49595	2.80899
13	0.75495	2.9299	2.50136	2.82306

14	0.7589	2.94223	2.49592	2.83166
15	0.761	2.95306	2.50189	2.84015
16	0.7623	2.9592	2.49532	2.84637
17	0.76483	2.96746	2.5036	2.84987
18	0.76739	2.98209	2.50119	2.86207
19	0.76951	2.98471	2.49806	2.86445
20	0.77018	2.99206	2.50098	2.86917
21	0.77157	2.99893	2.49845	2.87023
22	0.77315	3.00636	2.50183	2.87637
23	0.77296	3.015	2.49855	2.87876
24	0.77436	3.01719	2.50044	2.88903
25	0.77534	3.02191	2.50107	2.89502

SNR = 8 dB

T	Single	CMCSS	Random	DMCSS
1	0.49996	2.47222	2.49432	2.47876
2	0.57969	2.56027	2.5018	2.53936
3	0.6331	2.64089	2.50025	2.59878
4	0.66614	2.70417	2.50214	2.64849
5	0.69237	2.75252	2.5012	2.67539
6	0.70832	2.78673	2.49815	2.70507
7	0.72079	2.81563	2.50057	2.72783
8	0.73246	2.85107	2.49723	2.7608
9	0.73958	2.86999	2.496	2.76633
10	0.74772	2.88744	2.4996	2.79172
11	0.7507	2.90616	2.50169	2.80077
12	0.75617	2.92276	2.4957	2.80841
13	0.76008	2.94152	2.50015	2.823
14	0.76453	2.94961	2.49989	2.82981
15	0.765	2.96088	2.49969	2.83695
16	0.76968	2.97291	2.49753	2.84782
17	0.77015	2.98192	2.50023	2.85533
18	0.77194	2.98872	2.49986	2.86084
19	0.77374	3.00458	2.49903	2.86363
20	0.77569	3.00265	2.50032	2.866
21	0.77734	3.01057	2.49979	2.8734

22	0.77836	3.01705	2.50015	2.87565
23	0.78059	3.0296	2.50044	2.88274
24	0.77974	3.0316	2.50111	2.88634
25	0.78225	3.03948	2.49833	2.88718

SNR = 9 dB

T	Single	CMCSS	Random	DMCSS
1	0.49895	2.47047	2.50009	2.48744
2	0.57962	2.55354	2.4997	2.5395
3	0.63478	2.63154	2.49876	2.59494
4	0.66793	2.69851	2.50164	2.64735
5	0.69171	2.7426	2.49907	2.68262
6	0.70944	2.78261	2.49918	2.70279
7	0.72288	2.82036	2.50336	2.72986
8	0.73373	2.8471	2.50259	2.75164
9	0.74322	2.87568	2.50027	2.77502
10	0.74811	2.8963	2.49699	2.7905
11	0.75459	2.90497	2.50271	2.80185
12	0.75791	2.92009	2.50275	2.81374
13	0.76279	2.94284	2.50037	2.81752
14	0.76442	2.95094	2.49611	2.8302
15	0.76737	2.96481	2.49697	2.84571
16	0.77066	2.9762	2.5014	2.85148
17	0.77327	2.98735	2.49805	2.85596
18	0.77472	2.99184	2.49796	2.86127
19	0.7758	3.00058	2.49864	2.86811
20	0.778	3.01053	2.49933	2.87766
21	0.77832	3.01939	2.49916	2.87225
22	0.77973	3.0257	2.49958	2.88143
23	0.78084	3.03174	2.50083	2.88116
24	0.78169	3.03621	2.49856	2.8886
25	0.78271	3.03946	2.50203	2.89218

SNR = 10 dB

T	Single	CMCSS	Random	DMCSS
1	0.49905	2.47745	2.49351	2.47866

2	0.57786	2.56142	2.49963	2.5431
3	0.63284	2.63118	2.49619	2.58805
4	0.66874	2.7016	2.49977	2.64594
5	0.69108	2.74813	2.50478	2.67886
6	0.70982	2.79233	2.50306	2.71054
7	0.72314	2.82249	2.50172	2.73096
8	0.73473	2.8492	2.49735	2.75582
9	0.74167	2.87852	2.50173	2.77411
10	0.74856	2.89443	2.50302	2.77741
11	0.75472	2.91356	2.50315	2.80404
12	0.75824	2.92736	2.50183	2.80965
13	0.76216	2.93891	2.49867	2.82252
14	0.7655	2.95806	2.49874	2.82814
15	0.76821	2.96407	2.50049	2.83383
16	0.7699	2.97734	2.50131	2.84378
17	0.77335	2.99275	2.50018	2.85613
18	0.77497	2.99733	2.50219	2.85898
19	0.77557	3.00631	2.50051	2.86498
20	0.7772	3.00953	2.50165	2.86591
21	0.77979	3.0182	2.49657	2.87487
22	0.78057	3.03054	2.4996	2.87912
23	0.78113	3.03224	2.50065	2.88381
24	0.78337	3.03531	2.49769	2.88641
25	0.78367	3.04221	2.4998	2.8891

Parameter	**Value**
N	10
B	1
T	25
α	0.1
β	0.9
Number of collaborated users	5
ζ	0.3
Probability of selected channel (p) for DMCSS	0.2
SNR	Varied

SNR = 0 dB

T	Single	CMCSS	Random	DMCSS
1	0.50163	2.49237	2.50035	2.48292
2	0.54059	2.506675	2.5003	2.523355
3	0.55808	2.52747	2.499623	2.56103
4	0.57584	2.56139	2.49816	2.589555
5	0.590332	2.570172	2.498488	2.616528
6	0.59729	2.586982	2.502605	2.633902
7	0.603174	2.595664	2.499717	2.653177
8	0.60928	2.600941	2.500896	2.658354
9	0.611756	2.613434	2.499461	2.674274
10	0.617169	2.617174	2.501356	2.673812
11	0.620964	2.620403	2.497005	2.679125
12	0.62211	2.623865	2.500553	2.685321
13	0.623782	2.634719	2.50075	2.697335
14	0.625001	2.63506	2.500673	2.704046
15	0.628714	2.633842	2.498667	2.704991
16	0.627591	2.639118	2.502984	2.704999
17	0.629065	2.644972	2.499882	2.710981
18	0.630904	2.645914	2.499351	2.716542
19	0.632592	2.653541	2.498458	2.721416
20	0.633658	2.654221	2.498962	2.721316
21	0.633939	2.66135	2.501031	2.72124
22	0.634636	2.654625	2.498547	2.723523
23	0.636135	2.659611	2.500284	2.727571
24	0.637602	2.663815	2.499587	2.723726
25	0.636073	2.667037	2.501621	2.726061

SNR = 1 dB

T	Single	CMCSS	Random	DMCSS
1	0.49865	2.47404	2.50173	2.49394
2	0.5462	2.50933	2.49294	2.52759
3	0.56983	2.53801	2.49792	2.57006
4	0.58729	2.56542	2.50002	2.60292
5	0.60026	2.58194	2.49872	2.63343

6	0.60975	2.60347	2.49806	2.64721
7	0.62043	2.61915	2.49979	2.66371
8	0.62325	2.62343	2.50066	2.68158
9	0.62891	2.62828	2.50141	2.6978
10	0.63246	2.64422	2.50024	2.70182
11	0.63561	2.64205	2.49982	2.71124
12	0.63792	2.64978	2.50239	2.71917
13	0.64137	2.65617	2.49944	2.72632
14	0.64381	2.6586	2.50454	2.72548
15	0.64507	2.66463	2.50187	2.7308
16	0.64607	2.66784	2.49928	2.73923
17	0.64687	2.67089	2.5002	2.74159
18	0.64888	2.67132	2.50092	2.746
19	0.64981	2.68126	2.50095	2.74835
20	0.65144	2.6794	2.4995	2.7469
21	0.65134	2.68529	2.49806	2.75852
22	0.65367	2.68664	2.50011	2.75571
23	0.65361	2.6882	2.4975	2.75915
24	0.65496	2.68981	2.49974	2.76096
25	0.65465	2.6948	2.5004	2.7618

SNR = 2 dB

T	Single	CMCSS	Random	DMCSS
1	0.49865	2.47188	2.50181	2.48971
2	0.55345	2.50826	2.49261	2.53402
3	0.58039	2.54346	2.49817	2.57163
4	0.59636	2.57221	2.50023	2.61601
5	0.61163	2.59781	2.49884	2.63694
6	0.62153	2.61602	2.49787	2.65132
7	0.62912	2.63265	2.5003	2.67834
8	0.63453	2.64644	2.50053	2.69147
9	0.64226	2.65887	2.50183	2.70703
10	0.64626	2.66888	2.50054	2.71426
11	0.64921	2.66887	2.49957	2.73408
12	0.65181	2.67882	2.50241	2.74147
13	0.65498	2.68375	2.4992	2.74767

14	0.65659	2.68821	2.50411	2.74784
15	0.65876	2.69773	2.50213	2.75337
16	0.66093	2.69916	2.49939	2.76446
17	0.66019	2.70129	2.50001	2.76671
18	0.66376	2.71066	2.5006	2.77502
19	0.66452	2.71147	2.50114	2.77243
20	0.66587	2.71452	2.49998	2.78005
21	0.66558	2.72078	2.49775	2.78542
22	0.66703	2.72555	2.5005	2.78531
23	0.66808	2.72963	2.49757	2.78561
24	0.66878	2.73051	2.49971	2.78779
25	0.66882	2.73338	2.50016	2.7892

SNR = 3 dB

T	Single	CMCSS	Random	DMCSS
1	0.49858	2.47762	2.49551	2.48391
2	0.55683	2.54897	2.50448	2.53766
3	0.60121	2.60747	2.49962	2.58148
4	0.62223	2.64694	2.49637	2.62098
5	0.64306	2.67992	2.49618	2.64842
6	0.65533	2.70925	2.50058	2.66982
7	0.66321	2.7376	2.50083	2.68242
8	0.67288	2.74952	2.50331	2.71231
9	0.67921	2.76423	2.5037	2.71947
10	0.68169	2.77437	2.49842	2.7283
11	0.68531	2.7891	2.49977	2.74558
12	0.68907	2.80221	2.50194	2.75002
13	0.69226	2.80564	2.50147	2.75829
14	0.69443	2.81574	2.49777	2.77402
15	0.69685	2.82326	2.50036	2.77575
16	0.69899	2.82628	2.49787	2.7795
17	0.69961	2.83541	2.50041	2.78308
18	0.70044	2.84069	2.50494	2.78883
19	0.70249	2.83795	2.50224	2.79387
20	0.70393	2.84754	2.49988	2.80099
21	0.70512	2.85267	2.50047	2.80657

22	0.70569	2.85545	2.50276	2.80446
23	0.70696	2.86333	2.49775	2.81109
24	0.70764	2.86164	2.49527	2.81361
25	0.70836	2.86618	2.50148	2.81974

SNR = 4 dB

T	Single	CMCSS	Random	DMCSS
1	0.5004	2.47283	2.5007	2.48182
2	0.56316	2.53959	2.50263	2.52767
3	0.60557	2.61628	2.50399	2.58358
4	0.6365	2.66144	2.49717	2.61794
5	0.65476	2.70015	2.4954	2.63955
6	0.66956	2.72974	2.50038	2.67487
7	0.68001	2.75401	2.50211	2.69183
8	0.69134	2.77304	2.50001	2.70936
9	0.69845	2.79028	2.49729	2.73417
10	0.70335	2.80885	2.50339	2.74346
11	0.70859	2.82293	2.50009	2.75781
12	0.71217	2.83068	2.50127	2.7626
13	0.71479	2.84445	2.4993	2.7748
14	0.71655	2.85206	2.50141	2.77329
15	0.71921	2.85433	2.49926	2.78638
16	0.7218	2.85982	2.49764	2.79406
17	0.72371	2.87171	2.49915	2.79997
18	0.72612	2.87586	2.49775	2.80248
19	0.72667	2.88166	2.49871	2.81122
20	0.72793	2.89339	2.50226	2.81311
21	0.72791	2.89274	2.49813	2.82156
22	0.72932	2.89574	2.49906	2.82577
23	0.73171	2.8974	2.5002	2.82209
24	0.73221	2.90368	2.50014	2.82796
25	0.73314	2.91056	2.49996	2.83167

SNR = 5 dB

T	Single	CMCSS	Random	DMCSS
1	0.49924	2.47712	2.49838	2.48448

2	0.5648	2.5541	2.50145	2.53925
3	0.61322	2.62329	2.50072	2.58158
4	0.64425	2.67449	2.4993	2.62733
5	0.66536	2.71452	2.49884	2.65588
6	0.68287	2.74472	2.49657	2.6845
7	0.69533	2.7767	2.49899	2.69412
8	0.70315	2.79808	2.50126	2.71791
9	0.71255	2.82068	2.49794	2.73374
10	0.71759	2.83541	2.50254	2.73572
11	0.722	2.84439	2.50021	2.75863
12	0.72594	2.86	2.4993	2.76994
13	0.73104	2.87341	2.49983	2.77596
14	0.73467	2.87658	2.50172	2.7828
15	0.73662	2.89265	2.50059	2.7916
16	0.73879	2.89672	2.49806	2.79516
17	0.74082	2.90036	2.49745	2.7968
18	0.74349	2.90822	2.50067	2.80843
19	0.74379	2.91422	2.50121	2.81601
20	0.74541	2.92269	2.49753	2.81998
21	0.74747	2.92452	2.49748	2.81889
22	0.74811	2.93387	2.49814	2.83446
23	0.74912	2.92815	2.50143	2.82839
24	0.75035	2.93932	2.49846	2.83234
25	0.75117	2.94253	2.49987	2.83684

SNR = 6 dB

T	single	CMCSS	Random	DMCSS
1	0.5005	2.48258	2.49339	2.48908
2	0.56815	2.55414	2.49422	2.53757
3	0.61349	2.62352	2.49908	2.58157
4	0.64789	2.67806	2.50309	2.61548
5	0.67137	2.71781	2.50112	2.65379
6	0.68882	2.75498	2.50084	2.67458
7	0.7029	2.78957	2.496	2.69694
8	0.71038	2.80939	2.49739	2.71183
9	0.72011	2.82537	2.49987	2.72792

10	0.72664	2.84382	2.50193	2.74811
11	0.73185	2.86116	2.50007	2.75514
12	0.73597	2.87629	2.50186	2.76097
13	0.73897	2.88291	2.49827	2.77388
14	0.74303	2.8925	2.50033	2.78206
15	0.74575	2.91248	2.5	2.79369
16	0.74747	2.91278	2.49907	2.79526
17	0.75006	2.91647	2.50022	2.80703
18	0.75214	2.93316	2.50129	2.80733
19	0.75397	2.93869	2.50202	2.81561
20	0.75489	2.93932	2.49948	2.82186
21	0.75728	2.94909	2.49838	2.82252
22	0.75782	2.95467	2.49888	2.82873
23	0.75951	2.95852	2.49831	2.83176
24	0.75958	2.96307	2.50072	2.83432
25	0.76155	2.96635	2.49967	2.83197

SNR = 7 dB

T	Single	CMCSS	Random	DMCSS
1	0.49959	2.48326	2.49517	2.48807
2	0.56832	2.55104	2.49457	2.53871
3	0.61621	2.61893	2.49938	2.58212
4	0.64966	2.6764	2.5025	2.61685
5	0.67533	2.71863	2.50148	2.65259
6	0.69271	2.7594	2.50082	2.6736
7	0.70625	2.79116	2.49623	2.69375
8	0.71436	2.80831	2.49721	2.71318
9	0.72416	2.83069	2.49999	2.72776
10	0.72925	2.85293	2.50233	2.74753
11	0.73416	2.86769	2.50037	2.75636
12	0.73993	2.88227	2.50162	2.76354
13	0.74372	2.89163	2.49829	2.77645
14	0.74705	2.90062	2.50031	2.77793
15	0.75032	2.91654	2.50011	2.79166
16	0.7521	2.92379	2.49922	2.79798
17	0.7552	2.93136	2.50006	2.80506

18	0.75698	2.9409	2.50081	2.80913
19	0.75817	2.94886	2.50216	2.81627
20	0.76	2.95525	2.49972	2.82151
21	0.76097	2.96002	2.49852	2.82151
22	0.76151	2.96571	2.49907	2.82614
23	0.76327	2.97038	2.49819	2.83407
24	0.76537	2.97196	2.5006	2.83258
25	0.7651	2.98048	2.49953	2.83431

SNR = 8 dB

T	Single	CMCSS	Random	DMCSS
1	0.50007	2.47955	2.49984	2.4863
2	0.57	2.55731	2.50321	2.53219
3	0.61983	2.62442	2.49498	2.58865
4	0.64976	2.67737	2.49789	2.61471
5	0.67466	2.71847	2.5049	2.64802
6	0.69333	2.75728	2.50215	2.67039
7	0.70646	2.78739	2.49638	2.69633
8	0.71438	2.8156	2.49805	2.71424
9	0.72343	2.83908	2.50542	2.7287
10	0.73105	2.85772	2.49702	2.74841
11	0.73662	2.86917	2.50291	2.75674
12	0.74101	2.88241	2.5017	2.77044
13	0.74472	2.89455	2.49988	2.7718
14	0.74678	2.91251	2.49894	2.78892
15	0.75141	2.91793	2.50118	2.79815
16	0.75364	2.93314	2.50382	2.79928
17	0.7567	2.93365	2.49813	2.79986
18	0.7576	2.93835	2.50082	2.80795
19	0.75929	2.94615	2.49934	2.81587
20	0.7602	2.95627	2.50039	2.8249
21	0.76235	2.96149	2.50008	2.82328
22	0.7638	2.96109	2.50056	2.82653
23	0.76431	2.97212	2.49991	2.83083
24	0.76573	2.97966	2.50031	2.83193
25	0.76653	2.98681	2.50048	2.83591

SNR = 9 dB

T	Single	CMCSS	Random	DMCSS
1	0.49793	2.476	2.50593	2.48267
2	0.56653	2.55328	2.50008	2.53592
3	0.62	2.62002	2.49565	2.58471
4	0.65176	2.67711	2.49928	2.62069
5	0.67444	2.71898	2.50134	2.65525
6	0.69201	2.75898	2.49867	2.67287
7	0.70479	2.79018	2.50183	2.6979
8	0.71583	2.8075	2.49858	2.72136
9	0.72425	2.83526	2.49859	2.73571
10	0.73213	2.85263	2.49777	2.74963
11	0.73516	2.87009	2.49887	2.7575
12	0.74031	2.883	2.49832	2.76632
13	0.7454	2.90014	2.49908	2.77619
14	0.74717	2.90808	2.49733	2.7901
15	0.75077	2.92087	2.49928	2.79619
16	0.75409	2.92404	2.49969	2.80031
17	0.75654	2.93184	2.49816	2.8058
18	0.75818	2.94948	2.49563	2.81219
19	0.75952	2.94883	2.49853	2.81698
20	0.76134	2.95543	2.50084	2.82122
21	0.76252	2.96046	2.50001	2.82271
22	0.76446	2.96873	2.50029	2.83037
23	0.76512	2.9742	2.50305	2.82539
24	0.76645	2.97882	2.50019	2.84092
25	0.76752	2.9771	2.50011	2.83788

SNR = 10 dB

T	Single	CMCSS	Random	DMCSS
1	0.49966	2.47611	2.50524	2.48211
2	0.5673	2.55376	2.5003	2.53699
3	0.62	2.61828	2.49776	2.58405
4	0.6518	2.67759	2.49844	2.62039
5	0.67466	2.71953	2.50101	2.65455

6	0.69159	2.75955	2.49799	2.67225
7	0.70471	2.7907	2.50188	2.69659
8	0.71604	2.80665	2.49789	2.72219
9	0.72364	2.83642	2.49874	2.73563
10	0.73248	2.85308	2.49881	2.75081
11	0.73575	2.87037	2.49821	2.75773
12	0.74004	2.88621	2.49834	2.76658
13	0.74551	2.90153	2.49912	2.77674
14	0.74734	2.90766	2.49778	2.78981
15	0.7507	2.92014	2.49901	2.79647
16	0.75434	2.92232	2.49984	2.80047
17	0.75696	2.93139	2.49816	2.80487
18	0.7583	2.94772	2.49596	2.81281
19	0.75924	2.94568	2.49836	2.81706
20	0.76117	2.95724	2.50106	2.8214
21	0.76252	2.9593	2.49989	2.82216
22	0.76439	2.96992	2.50061	2.82983
23	0.76523	2.97418	2.50301	2.82526
24	0.76681	2.97565	2.50007	2.84097
25	0.7675	2.98104	2.50027	2.8375

Parameter	Value
N	10
B	1
T	25
α	0.1
β	0.9
Number of collaborated users	5
ζ	0.7
Probability of selected channel (p) for DMCSS	0.2
SNR	Varied

SNR = -5 dB

T	Single	CMCSS	Random	DMCSS
1	0.49931	2.48871	2.49637	2.50216

2	0.51429	2.5021	2.50067	2.50836
3	0.51953	2.50501	2.49952	2.51749
4	0.5202	2.51895	2.4966	2.52829
5	0.52815	2.53274	2.50075	2.53934
6	0.52722	2.54247	2.50437	2.54346
7	0.52949	2.54333	2.4979	2.54183
8	0.53057	2.54353	2.49631	2.55934
9	0.53157	2.54798	2.50099	2.55693
10	0.53507	2.54893	2.49678	2.56112
11	0.53292	2.56153	2.49545	2.56476
12	0.53341	2.55817	2.49777	2.56556
13	0.53317	2.55723	2.50102	2.56971
14	0.53499	2.56594	2.5005	2.5703
15	0.53584	2.56927	2.49952	2.56938
16	0.53531	2.57316	2.50026	2.57292
17	0.53527	2.56377	2.50167	2.57191
18	0.53749	2.5693	2.50344	2.57919
19	0.53719	2.5712	2.49926	2.57564
20	0.53793	2.56887	2.49957	2.58253
21	0.53808	2.57534	2.49894	2.57803
22	0.53731	2.57282	2.50109	2.58154
23	0.53796	2.57612	2.49956	2.58533
24	0.53858	2.57355	2.49852	2.58089
25	0.53738	2.57011	2.49824	2.59092

SNR = -4 dB

T	Single	CMCSS	Random	DMCSS
1	0.50009	2.49616	2.49269	2.4989
2	0.51874	2.50707	2.50583	2.50656
3	0.52371	2.50601	2.49847	2.5159
4	0.52624	2.52398	2.49915	2.53187
5	0.52894	2.53495	2.49602	2.54187
6	0.53261	2.54169	2.50039	2.54923
7	0.53109	2.55554	2.50557	2.55527
8	0.53416	2.56358	2.49991	2.56785
9	0.53485	2.56589	2.49645	2.5675

10	0.5374	2.5667	2.50064	2.57123
11	0.53818	2.57246	2.49984	2.57623
12	0.53898	2.57475	2.49698	2.57727
13	0.54032	2.57457	2.49982	2.58245
14	0.53914	2.57902	2.49923	2.58222
15	0.53898	2.57722	2.50159	2.58056
16	0.5401	2.58101	2.49627	2.5844
17	0.54185	2.58139	2.50226	2.58782
18	0.5417	2.58429	2.49878	2.59044
19	0.54274	2.59074	2.50041	2.59496
20	0.54197	2.59123	2.49859	2.59758
21	0.54373	2.59035	2.50043	2.59779
22	0.54338	2.58992	2.50118	2.60156
23	0.54301	2.59217	2.4989	2.60117
24	0.54367	2.59178	2.50172	2.59991
25	0.54362	2.58979	2.50107	2.60043

SNR = -3 dB

T	Single	CMCSS	Random	DMCSS
1	0.49952	2.4906	2.49699	2.49854
2	0.5189	2.51285	2.4959	2.50483
3	0.5338	2.53835	2.49812	2.52753
4	0.5457	2.55036	2.49538	2.53305
5	0.55528	2.56207	2.5029	2.5443
6	0.56247	2.58031	2.50153	2.55966
7	0.56739	2.58448	2.5013	2.56518
8	0.57243	2.59192	2.50136	2.56928
9	0.57533	2.59911	2.49812	2.57541
10	0.57833	2.60201	2.49794	2.58725
11	0.58197	2.61264	2.49726	2.58623
12	0.58313	2.61165	2.49687	2.58761
13	0.58469	2.61314	2.49912	2.58877
14	0.58569	2.62035	2.50031	2.59747
15	0.58727	2.62271	2.49849	2.6069
16	0.58951	2.61908	2.49968	2.60659
17	0.58954	2.6245	2.49856	2.60374

18	0.59001	2.61775	2.50135	2.60499
19	0.59244	2.62994	2.49896	2.61226
20	0.59224	2.62846	2.50125	2.61662
21	0.5935	2.62912	2.50041	2.61242
22	0.59274	2.63089	2.49699	2.6225
23	0.59562	2.63255	2.49904	2.62175
24	0.59492	2.63146	2.50123	2.62472
25	0.59564	2.63091	2.49758	2.61815

SNR = -2 dB

T	Single	CMCSS	Random	DMCSS
1	0.50016	2.4946	2.49697	2.50232
2	0.52312	2.51435	2.49176	2.51316
3	0.53785	2.54213	2.49373	2.5258
4	0.55256	2.55916	2.49493	2.54635
5	0.5649	2.57583	2.50234	2.55304
6	0.57097	2.58627	2.49355	2.56411
7	0.57905	2.59855	2.49913	2.56561
8	0.58201	2.61121	2.49958	2.57143
9	0.58668	2.60895	2.50334	2.5791
10	0.59163	2.61245	2.5018	2.59496
11	0.59337	2.63073	2.49735	2.59403
12	0.59693	2.62678	2.49835	2.59854
13	0.59814	2.63486	2.50109	2.61152
14	0.60091	2.64011	2.50216	2.60312
15	0.60275	2.64165	2.50053	2.61655
16	0.60406	2.63775	2.49932	2.61808
17	0.60588	2.65041	2.4983	2.61634
18	0.60685	2.64747	2.49923	2.61921
19	0.60664	2.65238	2.50059	2.62867
20	0.60835	2.65254	2.49876	2.63002
21	0.6084	2.65302	2.49991	2.62945
22	0.60956	2.65624	2.5011	2.63668
23	0.60926	2.65861	2.50199	2.62688
24	0.61077	2.65905	2.49954	2.63707
25	0.61083	2.66044	2.49919	2.63897

SNR = -1 dB

T	Single	CMCSS	Random	DMCSS
1	0.49997	2.48786	2.49721	2.49807
2	0.52577	2.52665	2.50015	2.51565
3	0.54347	2.54672	2.49882	2.53599
4	0.55786	2.56437	2.49708	2.54176
5	0.56804	2.58192	2.50305	2.55737
6	0.57823	2.59985	2.49808	2.57163
7	0.58773	2.6014	2.49979	2.57456
8	0.59349	2.61429	2.4982	2.5821
9	0.59992	2.62486	2.50404	2.59657
10	0.60437	2.63498	2.50105	2.60327
11	0.60608	2.64575	2.49756	2.60579
12	0.6081	2.64945	2.49916	2.60943
13	0.6118	2.6528	2.4985	2.61131
14	0.61345	2.66238	2.50171	2.62319
15	0.61579	2.66361	2.49935	2.625
16	0.61892	2.66324	2.49804	2.63283
17	0.62	2.66766	2.49788	2.63075
18	0.6209	2.67345	2.50012	2.63761
19	0.62354	2.67121	2.49718	2.6368
20	0.62307	2.68192	2.49958	2.63983
21	0.62483	2.67578	2.50104	2.64623
22	0.62491	2.68181	2.49814	2.64952
23	0.62473	2.67973	2.50123	2.64936
24	0.62693	2.68366	2.50244	2.65315
25	0.62824	2.68397	2.49816	2.65185

SNR = 0 dB

T	Single	CMCSS	Random	DMCSS
1	0.50111	2.48551	2.50515	2.49081
2	0.52552	2.51275	2.49201	2.51067
3	0.55006	2.55753	2.49596	2.52863
4	0.56375	2.56906	2.49751	2.53781
5	0.57631	2.59338	2.50003	2.55614

6	0.58739	2.61264	2.50107	2.56262
7	0.59609	2.62511	2.50321	2.57938
8	0.60209	2.63188	2.50057	2.59408
9	0.61003	2.64173	2.50104	2.59738
10	0.61145	2.64873	2.499	2.6083
11	0.61673	2.65778	2.49956	2.61411
12	0.61928	2.66939	2.49927	2.62111
13	0.62292	2.67328	2.49944	2.62137
14	0.62572	2.67033	2.5009	2.62477
15	0.62787	2.68718	2.50081	2.63793
16	0.63146	2.68395	2.50116	2.63168
17	0.63111	2.6968	2.50009	2.64764
18	0.63433	2.69313	2.50072	2.64439
19	0.63504	2.69751	2.49936	2.64992
20	0.63647	2.70034	2.50227	2.65557
21	0.63832	2.69629	2.50041	2.65094
22	0.6386	2.70377	2.4971	2.65899
23	0.64047	2.70419	2.49781	2.6568
24	0.64089	2.70903	2.50046	2.66097
25	0.64074	2.70933	2.49917	2.66034

SNR = 1 dB

T	Single	CMCSS	Random	DMCSS
1	0.50139	2.48715	2.49754	2.49753
2	0.52871	2.52542	2.50039	2.51395
3	0.54987	2.54813	2.49735	2.53701
4	0.56702	2.57606	2.50286	2.54551
5	0.58111	2.59855	2.49942	2.56235
6	0.59266	2.61631	2.50234	2.56794
7	0.60208	2.63024	2.49947	2.58728
8	0.61007	2.64722	2.49671	2.5896
9	0.61643	2.65758	2.49666	2.60851
10	0.62368	2.66622	2.49829	2.61373
11	0.62458	2.67333	2.49864	2.61522
12	0.62963	2.68029	2.49856	2.62776
13	0.63167	2.68911	2.49889	2.6315

14	0.63428	2.69773	2.49665	2.63134
15	0.63813	2.69764	2.50023	2.64438
16	0.63956	2.70514	2.49969	2.64033
17	0.642	2.70751	2.4996	2.65291
18	0.64285	2.71214	2.49842	2.64824
19	0.6446	2.71259	2.4987	2.65717
20	0.64716	2.72081	2.50065	2.65772
21	0.64818	2.72421	2.49924	2.66181
22	0.65071	2.7248	2.50117	2.6638
23	0.65051	2.73139	2.49833	2.66476
24	0.65123	2.72522	2.49906	2.66465
25	0.65203	2.73219	2.49999	2.6703

SNR = 2 dB

T	Single	CMCSS	Random	DMCSS
1	0.49946	2.48848	2.48811	2.50133
2	0.53029	2.52623	2.49897	2.51268
3	0.55281	2.55238	2.50601	2.53324
4	0.56841	2.58803	2.49928	2.54751
5	0.58488	2.60212	2.50487	2.56698
6	0.59691	2.62122	2.50372	2.57422
7	0.60743	2.6338	2.50167	2.58159
8	0.61269	2.64686	2.50298	2.59454
9	0.61985	2.66433	2.49695	2.61066
10	0.62636	2.67277	2.50469	2.61541
11	0.63107	2.68644	2.5007	2.61331
12	0.63536	2.68895	2.49941	2.62773
13	0.6376	2.6973	2.49937	2.63365
14	0.64097	2.70578	2.49886	2.63757
15	0.64415	2.71411	2.50107	2.64156
16	0.64637	2.71986	2.49969	2.64451
17	0.64822	2.72257	2.49825	2.64662
18	0.65049	2.72594	2.49987	2.65442
19	0.65108	2.72846	2.50042	2.65713
20	0.65383	2.73531	2.50214	2.65887
21	0.65282	2.73703	2.50071	2.66336

22	0.6556	2.74542	2.49978	2.67137
23	0.65641	2.74388	2.49964	2.67044
24	0.65815	2.74283	2.50266	2.67532
25	0.65899	2.74405	2.50296	2.67278

SNR = 3 dB

T	Single	CMCSS	Random	DMCSS
1	0.50197	2.48287	2.50104	2.49206
2	0.53197	2.52236	2.50522	2.515
3	0.55294	2.55962	2.49998	2.53281
4	0.57292	2.58232	2.4961	2.55226
5	0.58774	2.60637	2.49961	2.55828
6	0.60053	2.62965	2.50032	2.57599
7	0.60817	2.64533	2.50245	2.58569
8	0.61477	2.657	2.5005	2.5972
9	0.62224	2.66844	2.49883	2.60181
10	0.62939	2.67107	2.50544	2.6182
11	0.6339	2.68562	2.49857	2.61778
12	0.63804	2.70332	2.502	2.63002
13	0.64206	2.70599	2.50407	2.62793
14	0.64368	2.71035	2.50267	2.63818
15	0.64674	2.71297	2.50044	2.6474
16	0.64888	2.72533	2.49656	2.64789
17	0.65103	2.7273	2.50127	2.65394
18	0.65403	2.73236	2.49941	2.6602
19	0.65507	2.73582	2.50044	2.65477
20	0.6571	2.74169	2.49922	2.65852
21	0.65732	2.74375	2.50144	2.66712
22	0.65975	2.7487	2.49846	2.66722
23	0.65972	2.75004	2.4997	2.67119
24	0.66051	2.75962	2.49839	2.67095
25	0.66124	2.75624	2.49979	2.67572

SNR = 4 dB

T	Single	CMCSS	Random	DMCSS
1	0.49983	2.48952	2.49257	2.49567

2	0.52824	2.52523	2.49653	2.51859
3	0.5551	2.55892	2.50136	2.53416
4	0.57384	2.57373	2.50095	2.55231
5	0.58491	2.61169	2.50186	2.56292
6	0.59695	2.62535	2.49792	2.57492
7	0.61103	2.63637	2.49794	2.58527
8	0.61683	2.65445	2.50007	2.59784
9	0.62414	2.66716	2.49851	2.6023
10	0.62965	2.67259	2.50111	2.61751
11	0.63462	2.68961	2.49895	2.61828
12	0.63908	2.7038	2.49769	2.62682
13	0.64153	2.70856	2.50012	2.6345
14	0.64478	2.71804	2.49981	2.63429
15	0.64728	2.71584	2.50217	2.64375
16	0.65085	2.72471	2.49764	2.6502
17	0.65312	2.73522	2.50159	2.64933
18	0.6552	2.73841	2.49946	2.65389
19	0.65634	2.73881	2.50154	2.65673
20	0.65747	2.74001	2.49864	2.66695
21	0.66032	2.74859	2.50159	2.66757
22	0.66073	2.74898	2.50241	2.66965
23	0.66109	2.74821	2.49881	2.67683
24	0.66275	2.75525	2.5021	2.67384
25	0.66279	2.7583	2.49955	2.67947

SNR = 5 dB

T	Single	CMCSS	Random	DMCSS
1	0.50138	2.49315	2.4934	2.4989
2	0.5268	2.53227	2.50395	2.50835
3	0.55445	2.5538	2.50097	2.53415
4	0.5696	2.58202	2.49901	2.54967
5	0.58641	2.60227	2.50217	2.56142
6	0.59794	2.62161	2.49921	2.56784
7	0.60901	2.63573	2.4993	2.59318
8	0.61833	2.65997	2.50072	2.59777
9	0.62359	2.66554	2.49965	2.60688

10	0.63147	2.67944	2.49794	2.61896
11	0.63479	2.69066	2.50091	2.63224
12	0.639	2.70244	2.49686	2.62429
13	0.64345	2.70527	2.50156	2.63122
14	0.6466	2.7159	2.49817	2.63717
15	0.64905	2.71714	2.49914	2.64136
16	0.65104	2.72131	2.50123	2.6477
17	0.65388	2.72917	2.49591	2.65653
18	0.65585	2.73733	2.49803	2.65694
19	0.65593	2.73986	2.49884	2.66253
20	0.65833	2.74156	2.50156	2.65872
21	0.65882	2.74583	2.50155	2.6675
22	0.6602	2.74963	2.49949	2.66556
23	0.66187	2.75117	2.50102	2.67257
24	0.66326	2.75209	2.49817	2.67435
25	0.66396	2.76267	2.49768	2.68051

SNR = 6 dB

T	Single	CMCSS	Random	DMCSS
1	0.49942	2.49406	2.4998	2.49615
2	0.5312	2.52948	2.49699	2.51318
3	0.55514	2.55438	2.49461	2.52952
4	0.57284	2.5795	2.49955	2.5478
5	0.58832	2.60185	2.50071	2.55807
6	0.60038	2.62708	2.5017	2.57531
7	0.61146	2.64182	2.50252	2.58663
8	0.61815	2.65802	2.50406	2.5966
9	0.62353	2.66977	2.4999	2.60716
10	0.63002	2.68381	2.49842	2.61207
11	0.63546	2.69245	2.50015	2.61794
12	0.63901	2.6996	2.49987	2.62442
13	0.64221	2.706	2.49461	2.63336
14	0.64349	2.71646	2.50226	2.64452
15	0.64774	2.72171	2.5006	2.64849
16	0.65093	2.73003	2.49969	2.64828
17	0.65341	2.72844	2.50138	2.65237

18	0.65587	2.73202	2.50165	2.64863
19	0.65655	2.73682	2.50062	2.66017
20	0.65889	2.74003	2.4992	2.65977
21	0.65944	2.75214	2.49922	2.66585
22	0.66071	2.75551	2.49889	2.66867
23	0.66154	2.75033	2.50027	2.67623
24	0.66291	2.75945	2.49978	2.67456
25	0.66435	2.76062	2.50003	2.67871

SNR = 7 dB

T	Single	CMCSS	Random	DMCSS
1	0.49961	2.49652	2.49412	2.49839
2	0.53169	2.52528	2.49947	2.51666
3	0.55289	2.55697	2.50138	2.53511
4	0.5703	2.5937	2.5006	2.54636
5	0.58737	2.60543	2.5066	2.56547
6	0.59948	2.62165	2.49455	2.57582
7	0.61025	2.64743	2.4972	2.58921
8	0.61549	2.65336	2.50293	2.59822
9	0.62372	2.67126	2.49855	2.60236
10	0.63069	2.683	2.49948	2.61734
11	0.63465	2.6897	2.49957	2.62069
12	0.63715	2.69721	2.49632	2.62431
13	0.64327	2.71046	2.49784	2.63534
14	0.64626	2.7152	2.49877	2.63299
15	0.64771	2.71685	2.49841	2.65422
16	0.65224	2.72572	2.5003	2.65074
17	0.65419	2.73005	2.49858	2.65389
18	0.65353	2.73597	2.50042	2.65677
19	0.65704	2.74189	2.50246	2.65375
20	0.6588	2.74661	2.50081	2.66078
21	0.66055	2.74498	2.50085	2.66319
22	0.66064	2.7454	2.50159	2.66967
23	0.66183	2.75351	2.50283	2.67066
24	0.66398	2.75676	2.49887	2.67165
25	0.66387	2.76241	2.50144	2.67281

SNR = 8 dB

T	Single	CMCSS	Random	DMCSS
1	0.49922	2.48888	2.51084	2.4912
2	0.52923	2.52188	2.49847	2.51626
3	0.55483	2.56012	2.50428	2.5373
4	0.57238	2.58441	2.50202	2.54555
5	0.5878	2.60264	2.49814	2.56201
6	0.60139	2.62943	2.49777	2.57129
7	0.60984	2.64202	2.50203	2.59109
8	0.61654	2.65364	2.50126	2.59549
9	0.62447	2.66391	2.50017	2.60885
10	0.62873	2.68561	2.49812	2.61788
11	0.6349	2.69183	2.501	2.61185
12	0.63826	2.69648	2.49777	2.63152
13	0.64301	2.70457	2.49929	2.62891
14	0.64762	2.72029	2.49732	2.63483
15	0.64887	2.71979	2.50054	2.64181
16	0.65142	2.72241	2.50046	2.64786
17	0.65294	2.73327	2.50012	2.65481
18	0.65451	2.73724	2.50408	2.65203
19	0.65677	2.73615	2.49965	2.66416
20	0.65788	2.74491	2.49953	2.66177
21	0.66072	2.74898	2.50108	2.66719
22	0.65972	2.74713	2.50018	2.67216
23	0.66273	2.75802	2.50233	2.67063
24	0.6626	2.75328	2.50306	2.6752
25	0.66382	2.75535	2.49689	2.67147

SNR = 9 dB

T	Single	CMCSS	Random	DMCSS
1	0.49825	2.48784	2.50505	2.49286
2	0.5272	2.52788	2.49912	2.52172
3	0.55426	2.55546	2.49942	2.53187
4	0.57503	2.57723	2.49602	2.54796
5	0.58772	2.60796	2.49962	2.55685

6	0.59955	2.62792	2.50206	2.57765
7	0.60984	2.63586	2.49669	2.58352
8	0.61767	2.65363	2.50176	2.59757
9	0.62318	2.66854	2.49701	2.60443
10	0.62958	2.67855	2.50411	2.60682
11	0.63481	2.69005	2.50089	2.62143
12	0.63943	2.70048	2.49828	2.63291
13	0.6427	2.70455	2.49898	2.63039
14	0.64746	2.7115	2.5008	2.64025
15	0.648	2.71803	2.49889	2.64557
16	0.65236	2.7266	2.50025	2.6448
17	0.65387	2.73427	2.50169	2.65785
18	0.65477	2.74062	2.49867	2.65605
19	0.65677	2.73942	2.50106	2.65732
20	0.6584	2.74429	2.49894	2.66092
21	0.66024	2.74953	2.4996	2.66601
22	0.66077	2.74944	2.49966	2.66299
23	0.66227	2.74979	2.50276	2.66953
24	0.66229	2.76009	2.49739	2.67426
25	0.66357	2.76017	2.50184	2.67783

SNR = 10 dB

T	Single	CMCSS	Random	DMCSS
1	0.50232	2.49479	2.4996	2.50128
2	0.52813	2.53128	2.50414	2.51727
3	0.55473	2.55233	2.49476	2.52718
4	0.5736	2.58267	2.49864	2.55373
5	0.58762	2.60662	2.5055	2.5644
6	0.60033	2.62509	2.50065	2.57275
7	0.61018	2.64679	2.50179	2.58227
8	0.61939	2.65868	2.50199	2.58798
9	0.62342	2.67381	2.50452	2.60498
10	0.6319	2.68037	2.49666	2.61457
11	0.63444	2.69625	2.50017	2.6192
12	0.64071	2.70377	2.49702	2.6296
13	0.64254	2.70359	2.50086	2.63745

14	0.64506	2.70808	2.50007	2.63963
15	0.64825	2.71829	2.50153	2.64613
16	0.6516	2.72535	2.4994	2.64768
17	0.65284	2.72573	2.49923	2.65499
18	0.65533	2.7358	2.49931	2.66068
19	0.65703	2.73652	2.50198	2.66446
20	0.65948	2.74303	2.50234	2.66368
21	0.65951	2.74283	2.50262	2.65992
22	0.66043	2.75384	2.49915	2.67197
23	0.66249	2.75443	2.49976	2.6751
24	0.66228	2.74987	2.49654	2.67378
25	0.66341	2.7548	2.50131	2.67069

Throughput performance vs Arrival rate

Parameter	Value
N	10
B	1
T	25
α	0.1
β	0.9
Number of collaborated users	varied
ζ	0.3
Probability of selected channel (p) for DMCSS	0.2
SNR	5 dB

Number of SUs = 5

Arr.rate (λ)	CMCSS	Random	DMCSS
0.02	0.13667	0.11618	0.13244
0.04	0.26427	0.22047	0.25637
0.06	0.38895	0.31805	0.37574
0.08	0.50216	0.40899	0.48519
0.1	0.61209	0.49344	0.58863
0.12	0.71274	0.5683	0.6911

0.14	0.81168	0.64328	0.78176
0.16	0.89656	0.70642	0.86802
0.18	0.98641	0.77235	0.95673
0.2	1.0675	0.82871	1.03184
0.22	1.14043	0.88289	1.1037
0.24	1.21561	0.9356	1.17222
0.26	1.28404	0.98175	1.2375
0.28	1.34548	1.02513	1.30324
0.3	1.40955	1.06734	1.36332
0.32	1.47013	1.10626	1.41583
0.34	1.52347	1.14548	1.46365
0.36	1.57487	1.17731	1.5142
0.38	1.61902	1.21317	1.56544
0.4	1.66559	1.24369	1.61023
0.42	1.70957	1.27188	1.6534
0.44	1.75278	1.30131	1.69398
0.46	1.79612	1.32658	1.72742
0.48	1.83269	1.34974	1.76454
0.5	1.86505	1.3737	1.80236

Number of SUs = 7

Arr.rate (λ)	**CMCSS**	**Random**	**DMCSS**
0.02	0.13617	0.11592	0.13245
0.04	0.26721	0.22376	0.25785
0.06	0.39279	0.32519	0.37867
0.08	0.51353	0.42141	0.49398
0.1	0.63103	0.50855	0.6063
0.12	0.74523	0.59007	0.71423
0.14	0.84799	0.67414	0.81621
0.16	0.95153	0.74627	0.91587
0.18	1.04641	0.818	1.011
0.2	1.13947	0.8837	1.09884
0.22	1.22979	0.9456	1.18854
0.24	1.31629	1.00386	1.26717
0.26	1.40251	1.06014	1.34913

0.28	1.48204	1.11255	1.42873
0.3	1.55337	1.16222	1.50147
0.32	1.63052	1.20948	1.57137
0.34	1.70172	1.2581	1.6374
0.36	1.76142	1.29904	1.70137
0.38	1.83162	1.34107	1.76439
0.4	1.893	1.37964	1.82003
0.42	1.95229	1.41811	1.88081
0.44	2.009	1.45647	1.93389
0.46	2.06074	1.48635	1.98778
0.48	2.1188	1.51956	2.0408
0.5	2.16571	1.55144	2.08676

Throughput performance vs Number of SUs

Parameter	Value
N	10
B	1
T	25
α	0.1
β	0.9
Number of collaborated users	varied
ζ	0.3
Probability of selected channel (p) for DMCSS	0.2
SNR	5 dB

collaborated users	CMCSS	Random	DMCSS
2	1.1745	1.00028	1.12548
3	1.77721	1.5007	1.69301
4	2.36355	2.0007	2.26319
5	2.94221	2.4995	2.83717
6	3.50668	3.00003	3.37464
7	4.06016	3.49968	3.9262
8	4.617	4.00345	4.46509
9	5.18985	4.49401	5.033

10	5.7518	5.00135	5.58111
11	6.32434	5.50545	6.10338
12	6.88826	6.00419	6.63186
13	7.45653	6.49993	7.15862
14	8.00809	6.99992	7.67451
15	8.5965	7.49254	8.21139
16	9.17306	8.0036	8.71255
17	9.73238	8.50313	9.26219
18	10.31	8.99498	9.76577
19	10.8756	9.50796	10.2897
20	11.4592	10.0005	10.828
21	12.0275	10.5036	11.371
22	12.6078	11.0032	11.8739
23	13.1698	11.504	12.4047
24	13.7534	12.0004	12.9284
25	14.361	12.5004	13.4746
26	14.9219	12.9977	14.0156
27	15.5097	13.4985	14.5406
28	16.0852	13.9917	15.0899
29	16.6408	14.492	15.6222
30	17.237	14.9859	16.1345