# Spectrum-efficient Cooperation and Bargaining-based Resource Allocation for Secondary Users in Cognitive Radio Networks

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Dissertation submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Doctor of Philosophy
in
Electrical Engineering

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October 21, 2015
Blacksburg, Virginia

Keywords: Cooperative communication, Dynamic spectrum access,
Cognitive radio, Bargaining theory

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(ABSTRACT)

Dynamic spectrum access (DSA) is a promising approach to alleviate spectrum scarcity and improve spectrum utilization. Our work aims to enhance the utilization of the available white spaces in the licensed spectrum by enabling cooperative communication in the secondary networks. We investigate the ability of a two-hop cooperative transmission to reduce the effect of primary user interruption on secondary transmissions. We analyze the performance of a cooperative secondary transmission by modeling the interaction between primary user and secondary user transmissions using a discrete time Markov chain (DTMC). The analysis shows a significant enhancement in the secondary transmission efficiency and throughput when cooperative transmission is utilized compared to that of direct transmission, especially at high levels of primary user activity. We extend our study to model secondary cooperative transmission in realistic scenarios. We evaluate the throughput performance enhancement in the secondary infrastructure network analytical and by simulation. A simple scenario is modeled analytically by a DTMC that captures the probability of finding intermediate relays according to nodes' density and by discrete event simulation where both results confined each other. We introduce a dedicated cooperative and cognitive Media Access Control (MAC) protocol named CO$^2$MAC to facilitate secondary users transmissions in infrastructure-based secondary networks. The proposed MAC enables utilizing cooperative Multi-Input-Multi-Output (MIMO) transmission techniques to further enhance the throughput performance. By using the proposed MAC, we quantify the enhancement in the throughput of secondary infrastructure networks via simulation for complex scenarios. The results show an enhancement in cooperative transmission throughput compared to that of direct transmission, especially at crowded spectrum due to the ability of cooperative transmissions to reduce the negative effect of primary user interruptions by buffering the data at intermediate relays. Also, the cooperative throughput performance enhances compared to that of direct transmission as the nodes' density increases due to the increase in the probability of finding intermediate relays.

After that, we answer two questions. The first question is about the way a secondary user pays the cooperation price to its relay and what are the conditions under which the cooperation is beneficial for both of them. The second question is about how to pair the cooperating nodes and allocate channels in an infrastructure based secondary network. To answer the first question, we model the cooperation between the secondary user and its relay as a resource exchange process, where the secondary user vacates part of its dedicated free spectrum access time to the relay as a price for the energy consumed by the relay in forwarding the secondary user's packets. We define a suitable utility function that combines

the throughput and the energy then we apply axiomatic bargaining solutions, namely Nash bargaining solution (NBS) and egalitarian bargaining solution (EBS) to find the new free spectrum access shares for the secondary user and the relay based on the defined utility in the cooperation mode. We show that under certain conditions, the cooperation is beneficial for both the secondary user and the relay where both achieve a higher utility and throughput compared to the non-cooperative mode.

Finally, based on the bargaining based shares of the cooperating nodes, the node pairing and channel allocation are optimized for different objectives, namely maximizing the total network throughput or minimizing the maximum unsatisfied demand. Our bargaining based framework shows a comparable performance with the case when the nodes' free spectrum access time shares are jointly optimized with the pairing and allocation process, at the same time, our cooperation framework provides an incentive reward for the secondary users and the relays to involve in cooperation by giving every node a share of the free spectrum that proportional to its utility. We also study the case of using multiple secondary access points which gives more flexibility in node pairing and channel allocation and achieves a better performance in terms of the two defined objectives.

# Dedication

*This dissertation is dedicated to the memory of my father, Medhat Tawfik AbdelRaheem.*

# Acknowledgments

All praise is due to Allah (God), I thank him and seek his help, guidance, and forgiveness. At the beginning, I would like to thank my parents for their help and kindness. No words can express my gratitude to my father Medhat for the unlimited support he provided to me so I can travel abroad and start my Ph.D. journey. I really miss him at this moment which he always dreamed to see. For my mother, I cannot do any thing for her that, partially, can be compared to what she has sacrificed for me and for our family. Thanks for her prayers and kindness for her patient and generosity. I would thank my beloved wife Fatma for her unlimited help, support, and encouragement. She was always there for me and for our kids Rahma and Youssef. She never complained about being very busy with my work, especially near its end. May Allah help me to be a good husband and father.

I would like express my gratitude and appreciation to my advisor Prof. Scott Midkiff for his academic and personal support. During my stay in the United States I faced a lot of difficult situations that negatively affected my work schedule and without his understanding and support, I would not be able to finish my work. His advices and comments were my guidelines through my Ph.D. journey. Beside being my academic advisor, I was lucky to work with him as graduate teaching assistant.

I'd like to thank Prof. Mustafa ElNainay for his academic help since I started my Ph.D. back in EGYPT. Also I'd like to thanks Dr. Mohammad Abdel-Rahman for his technical help and advices. I'd like to thank my committee members for their comments in my work. Special thanks to Prof. Allen B. MacKenzie for hosting me in his lab for the last three years. My thanks also for Prof. Patrick Koelling and Prof. Yaling Yang for agreeing to server on my Ph.D. committee. Special thanks for Prof. Sedki Riad for his help through VTMENA program.

At the end, I'd like to thank the EGYPTIAN community at the beautiful town of Blacksburg. Special thanks to Mostafa Taha who was more than a brother for me and to my lab-mates Abdallah S. Abdallah and Amr Hilal for their help.

This work is supported by the Egyptian Cultural Affairs and Missions Sector, and the VTMENA program.

# Contents

# List of Figures

# List of Tables

# Part I

# Introduction & Background

# Chapter 1

# Introduction

The In this chapter, we present a high level overview about dynamic spectrum access approach in solving spectrum scarcity problem. Then we present our idea of using cooperative communication in the secondary network to achieve a better utilization of the available white spaces in the licensed spectrum. Finally, the scope of our work and the dissertation outline and flow are presented.

## 1.1 Dynamic Spectrum Access and Cognitive Radio Network

‘ The rapid growth of using wireless services created an unsatisfied demand on the limited wireless spectrum. Many research studies has been targeting this problem. The fundamental finding is that, the problem is mainly because regulatory authorities’ policy of assigning dedicated spectrum for individual owners has resulted in many underutilized spectrum bands. The under utilization and unequal distribution of the spectrum are clearly shown in Fig 1.1 [1][1].

This fact motivated the research community as well as the regulatory authorities to search for a new spectrum access scheme that is able to utilize the unused spectrum and reduce spectrum scarcity.

Dynamic Spectrum Access (DSA) [2] [3] was proposed as a promising solution for the spectrum scarcity problem. In DSA, an unlicensed user called Secondary User (SU) is able to access the licensed spectrum in a way that does not interfere with the licensed user named the Primary User (PU). In order to facilitate DSA, the wireless radio transceivers must be intelligent and capable enough to carry out additional tasks that may not be required in

[1] This research work was done at Illinois institute of technology (IIT) and Turku university.

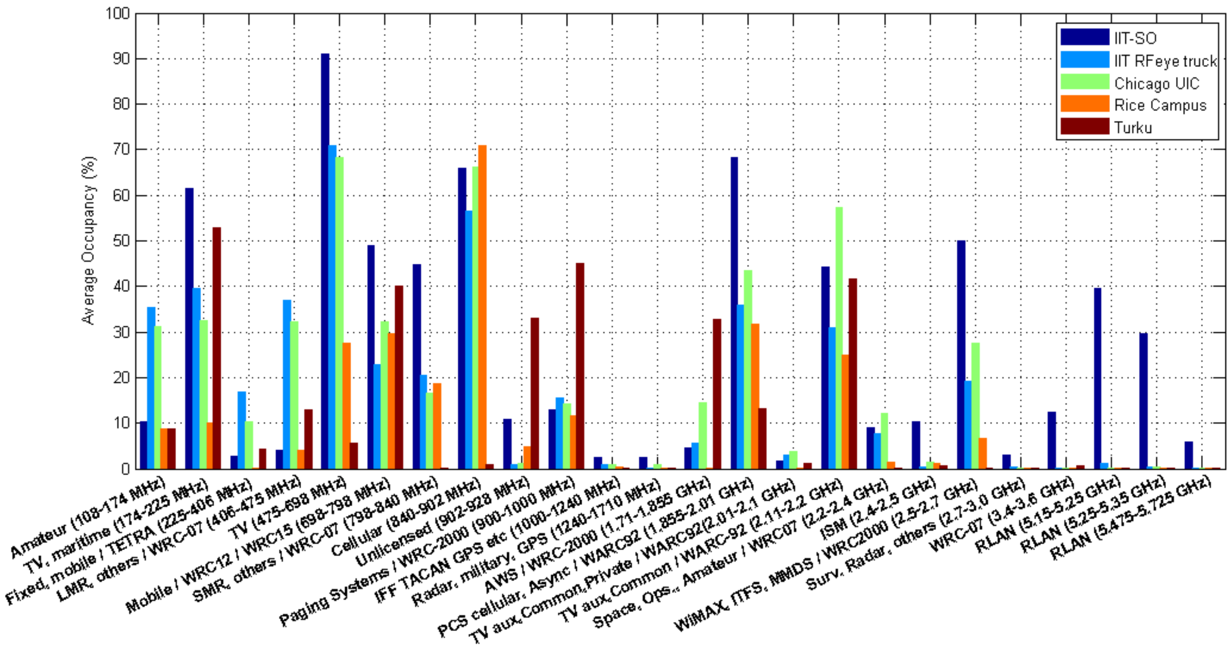



Figure 1.1: Average spectrum bands occupancy at different locations. Average spectrum bands occupancy at different locations. T. Taher, R. Attard, A. Riaz, D. Roberson, J. Taylor, K. Zdunek, J. Hallio, R. Ekman,J. Paavola, J. Suutala, J. Roning, M. Matinmikko, M. Hoyhtya, and A. MacKenzie, Global spectrum observatory network setup and initial ndings. Proceedings of the International Conference on Cognitive Radio Oriented Wireless Networks (CRWON-COM), pp. 79-88, 2014. Used with permission of Dr. Tanim M. Taher, 2015.

conventional radio transceivers Cognitive Radio (CR) [4] [5] is a context-aware radio that is able to reconfigure itself to adapt to the surrounding communication environment. The CR is built over the Software Defined Radio (SDR) which refers to multi-band and multi-protocol radio that is reconfigurable through software [6]. Wireless transceivers powered by CR technology keep sensing the available spectrum bands and switches between them to avoid interfering with the PU's transmission.

Cognitive Radio Network (CRN) is proposed to provide wireless users with high bandwidth via heterogeneous wireless architecture and DSA mechanism. CRN can be classified into two groups: The primary network which has the license to operate at a specific spectrum band (for exampl,e TV station or Radar) and the secondary network which does not have a licensed spectrum band to use (for example WiFi network). The secondary network nodes are equipped with CR technology to access the licensed spectrum of the primary network without interfering with the primary transmission. The secondary network may have a centralized architecture (infrastructure network) with Secondary Access Point (SAP) or Secondary Base Station (SBS) or distributed architecture (ad-hoc network) where there is no central controller in the network. Spectrum management is a challenging issue in CRN which includes four main functions [7]:

1. *Spectrum sensing:* SU must detect the presence of the PU to avoid interfering with the primary transmission. To handle this function, SU must be equipped with a powerful sensing mechanism.

2. *Spectrum decision:* The SU chooses available spectrum band (channel) to use based on the sensing information it obtains about the presence of the PU. Other factors may control the SU choice like the quality of the wireless channel and how frequently the PU utilizes this band. The PU availability depends on the spectrum sharing schemes where in some schemes the SU transmits only when the PU is absence where as in other schemes, the SU can coexist with the PU if its transmission will not cause harmful interference at the PU receiver.

3. *Spectrum sharing:* As the CRN consists of many SUs that may want to access the available spectrum simultaneously, the network should utilize a media access mechanism to prevent secondary transmissions collision.

4. *Spectrum mobility:* The SUs must be able to switch between the available spectrum bands according to the PUs activity to avoid harming the PU.

## 1.2 Cooperative Communication for Dynamic Spectrum Access

SUs can collaborate with each other to achieve better performance. The collaboration can be used to enhance the sensing results or to enhance the secondary transmission by using cooperative communication.

Cooperative sensing among SUs can take one of two forms [8]. The first is the centralized sensing where SUs send their sensing results to a centralized unit which identifies the free spectrum and broadcasts this information back to the SUs. The second method is the distributed sensing where SUs share their sensing information but each one takes the decision individually.

Cooperative communication [9] is also used to enhance the secondary transmission characteristics. In cooperative communication, the source node may recruit one or more relays to forward its data to the final destination in case the Direct Transmission (DT) from the source to destination is not available or to achieve better transmission performance. If two or more relays are used to forward the data, the relays share their antenna and form a virtual Multi-Input-Multi-Output (MIMO) system to gain MIMO benefits like space diversity and spatial multiplexing.

Cooperation in DSA networks can be categorized int:

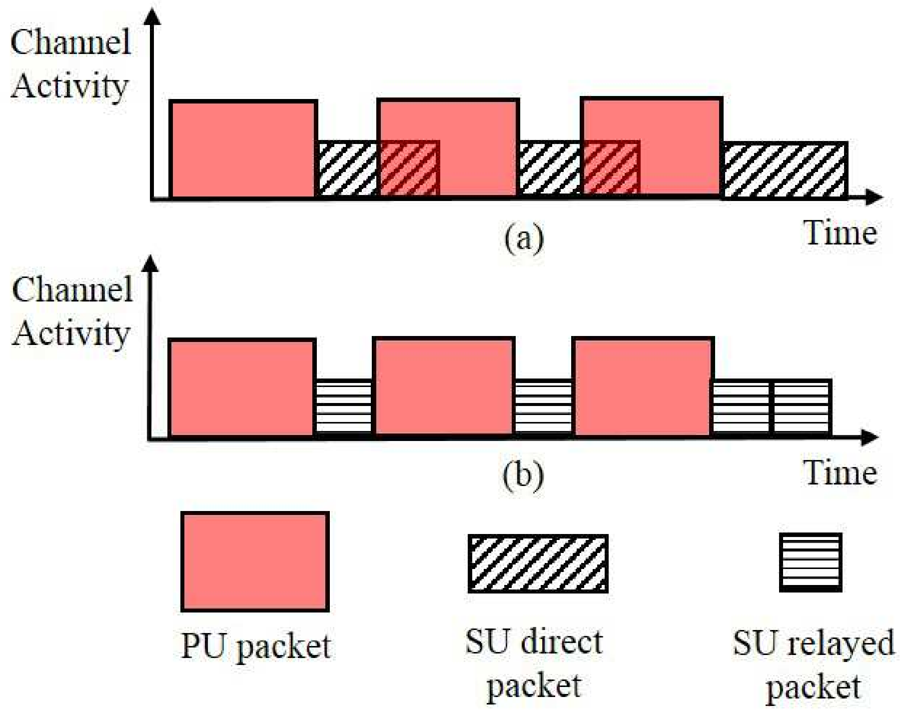



Figure 1.2: SU direct transmission and relayed transmission spectrum occupancy

- **Cooperation between SUs**–SUs cooperate with each other either (i) to enhance the sensing accuracy ( for example, [8]) or (ii) to enhance the transmission characteristics, such as throughput (for example, [10–12]).
- **Cooperation between PUs and SUs**–The authors in [13–24] modeled the cooperation between PUs and SUs as a market-driven spectrum trading.

## 1.3 Scope of the Work

In our study, we will start by investigating the ability of the two hop cooperative communication to mitigate the interruption caused by the presence of the PU. If the SUs employ cooperative communication techniques, they can enhance their spectrum occupancy by efficiently filling smaller empty spectrum holes that cannot be successfully filled by the DT. The SU can achieve this goal by transmitting the data over high data rate two hops using intermediate relay(s). The cooperative secondary transmission over the two hops is carried out at a higher data rate and, thus, it consumes a shorter time than that of the DT, as a result it can reduce the effect of PU interruption. Fig. 1.2 illustrates the previous idea. If the SU uses DT, it has to abort its first two transmission attempts due to the appearance of the PU before it can achieve a successful transmission in the third attempt. If the SU uses cooperative relaying, it can efficiently utilize the available spectrum holes by sending its data at a higher rate (shorter time) to the relay in the first time hop. The relay buffers the packet until it finds a vacant spectrum slot to send the buffered data to the final destination. As can be inferred from Fig. 1.2, the SU with cooperative relaying can utilize the available spectrum holes more efficiently than with the DT.

To quantify the enhancement in the secondary transmission characteristics, like the throughput, when cooperative communication is enabled between the SUs, we develop a new discrete-time Markov chain (DTMC) model to formulate the interactions between the PU and the cooperating SUs, assuming an interweave spectrum sharing paradigm. In contrast to existing Markov models (e.g., [25–27]), our DTMC model explicitly captures the ability of SUs to transmit cooperatively. We use our DTMC model to derive different transmission characteristics, such as the spectrum occupancy distribution, the spectrum efficiency, and the SUs' throughput.

We modified our DTMC model to simulate a realistic infrastructure network. We model a simple scenario using the DTMC model after modifying it to include the probability of utilizing the cooperative transmission or direct transmission according to the network node density. The same scenario is modeled using discrete event simulation for confirmation. We introduce a cooperative and cognitive MAC protocol named $CO^2MAC$ to facilitate the cooperative transmission in secondary infrastructure network. The MAC operations is modeled using OPNET network simulator. A realistic secondary infrastructure network that utilize cooperative communications and multi-antenna techniques is simulated and the throughput performance is evaluated against the network node density and the PU activity.

In order for the cooperation to be beneficial for all involved nodes (the source and the relay) we develop a pair-wise (SU-SU) cooperation framework that controls the benefit of each of the cooperating nodes. We model the cooperation between a source and its relay in secondary network as a resource exchange process, where the source sacrifices part of its free spectrum access time share to the relay as a price for its energy consumed in relaying the source packets. We define the utility of each of the cooperating nodes in a way that combines both the throughput ant the energy consumption. Bargaining solutions, namely Nash bargaining solution (NBS) and Egalitarian bargaining solution (ES), are used to find the cooperation free spectrum shares of each node according to its utility and disagreement point. The bargaining process is applied for the entire original free spectrum time share of the two nodes so the result of the cooperation should not affect other nodes in the network not involved in the cooperation. The enhancement of the utility and throughput of both the source and the relay is evaluated and the conditions under which the cooperation is beneficial for all nodes are stated.

Based on the bargaining based shares, we formulate the node pairing and channel allocation in secondary infrastructure network problem as optimization problems with objectives to maximize the total network data rate or to minimize the minimum unsatisfied demand. For the sake of comparison, we formulate two variants of the problem; the first one, aims to find the optimum nodes pairing and channels allocations, by jointly optimizing the shares of the cooperating nodes. In this formulation the share of any of the nodes cannot exceed the original share of itself and its cooperation partner. The other problem also optimizes the share of every node without being bounded by the original shares of the nodes. We extend our problem to the case when multiple secondary access points are coordinating the channel allocation and node pairing. The presence of multiple secondary access points gives more flexibility in the pairing and allocation process and results in a better performance.

## 1.4 Research Outline and Work-flow

In this section we highlight the topics included in our research and describe the relation between them. The dissertation is organized into three parts. In Part I, we provide an introduction and a background about the research field and the research problem we are targeting. In Part II, we introduce and analyze the basic idea of the ability of cooperative communication to enhance the spectrum utilization of the secondary users. In Part III, we develop our cooperation and resource allocation framework based on bargaining theory. Finally, we conclude our work and provide some future research directions.

- Part I
  - **Introduction (Chapter 1)** In this chapter, we provide a high level overview of dynamic spectrum access, cooperative communication and the problem statement of the potential benefit of using cooperative communication in secondary networks.
  - **Background (Chapter 2)** This chapter provides a technical background about Muli-Input-Multi-Output techniques and its integration with cooperative communication, and the dynamic spectrum access as well as a literature review about each topic.
- Part II
  - **Data Rate Enhancement Using Cooperative MIMO Communications in Infrastructure Networks (Chapter 3)**

    This work uses simulation to study the benefit of using cooperative communication on the achieved throughput of infrastructure networks. The study includes a comparison between using direct transmission, single-relay assisted transmission, and multi-relay assisted transmission and their achieved average throughput. For multi-relay assisted transmission, the performance of spatial multiplexing and space time coding techniques are compared. The average throughput is evaluated against the number of potential relays and against the distance from the access point. This work provides basic results that are used in the later research.

  - **Spectrum Occupancy Analysis of Cooperative Relaying Technique for Cognitive Radio Networks(Chapter 4)**

    In this chapter, the interaction between the primary and secondary users in interweave spectrum sharing is modeled using a DTMC . The effect of the cooperation mechanism on the spectrum occupancy of the secondary user, especially with crowded spectrum, is highlighted. Also, the effect of DTMC time resolution (the number of time slots per data transmission) and the PU and SU's packets size ratio are studied.

  - **Analytical and Simulation Study of the Effect of Secondary User Cooperation on Cognitive Radio Networks (Chapter 5).**

    This research includes analytical and simulation studies of the effect of using cooperative transmission by SUs on the achieved throughput in infrastructure networks. A simple scenario of a secondary infrastructure network with downlink single-relay assisted transmission is modeled using DTMC. We model the same is simulated using OPNET [28] where the results of the analytical and simulation studies confirmed each other. The benefits of using cooperative transmission with respect to average throughput in the secondary network is highlighted. The $CO^2$ MAC protocol is designed to facilitate the secondary network cooperative transmissions. The $CO^2$ MAC design and operation details are provided and the performance of the protocol with different capabilities is shown.

- Part III

  - **Cooperation Price in Cognitive Radio Network: A Resource Exchange Model (Chapter 6).**

    In this chapter, we propose the bargaining based cooperation framework between the SUs. We start by introducing the presence of an active relay beside the secondary and primary users. For the secondary nodes' free spectrum access mechanisms, we introduce three different non-cooperative access methods that give equal access probability, or equal transmission time, or equal successful time for all secondary users. We show the limitation on applying the same non-cooperative access mechanisms in the cooperative mode and how these access mechanism will not be beneficial for the relay in most cases. To incentivize the relay to cooperate, we propose our cooperation framework as a resource exchange process in which the relay power is exchanged by transmission time. The new shares are incentive for the relay and beneficial for the source. We define the utility function such that it combines the achieved throughput and the consumed energy. We apply two different axiomatic bargaining solution to find the new shares. The performance of the proposed framework in terms of different nodes' utility and throughput is evaluated for different parameters and different scenarios.

  - **Bargaining-based Node Pairing and Channel Allocation in Secondary Infrastructure Networks (Chapter 7)**

    In this research topic, we investigate the optimal way to pair cooperating nodes and allocate channels based on the cooperation shares found using bargaining solutions. We formulate two optimization problem, one aims to maximize the total network throughput and satisfies every node's minimum demand, and the other aims to minimize the minimum unsatisfied demand among all the nodes. We evaluate the performance of the two problems in terms of throughput against the demand, primary user activity level, and nodes density.

    We compare our bargaining based shares problem with two other formulated variants where the shares of the cooperating nodes are also optimized within the limits of total nodes' shares or for the entire available share.

- **Conclusion and Future Directions (Chapter 8)**

Fig. 1.3 shows the relations between the different chapter contained in this dissertation.

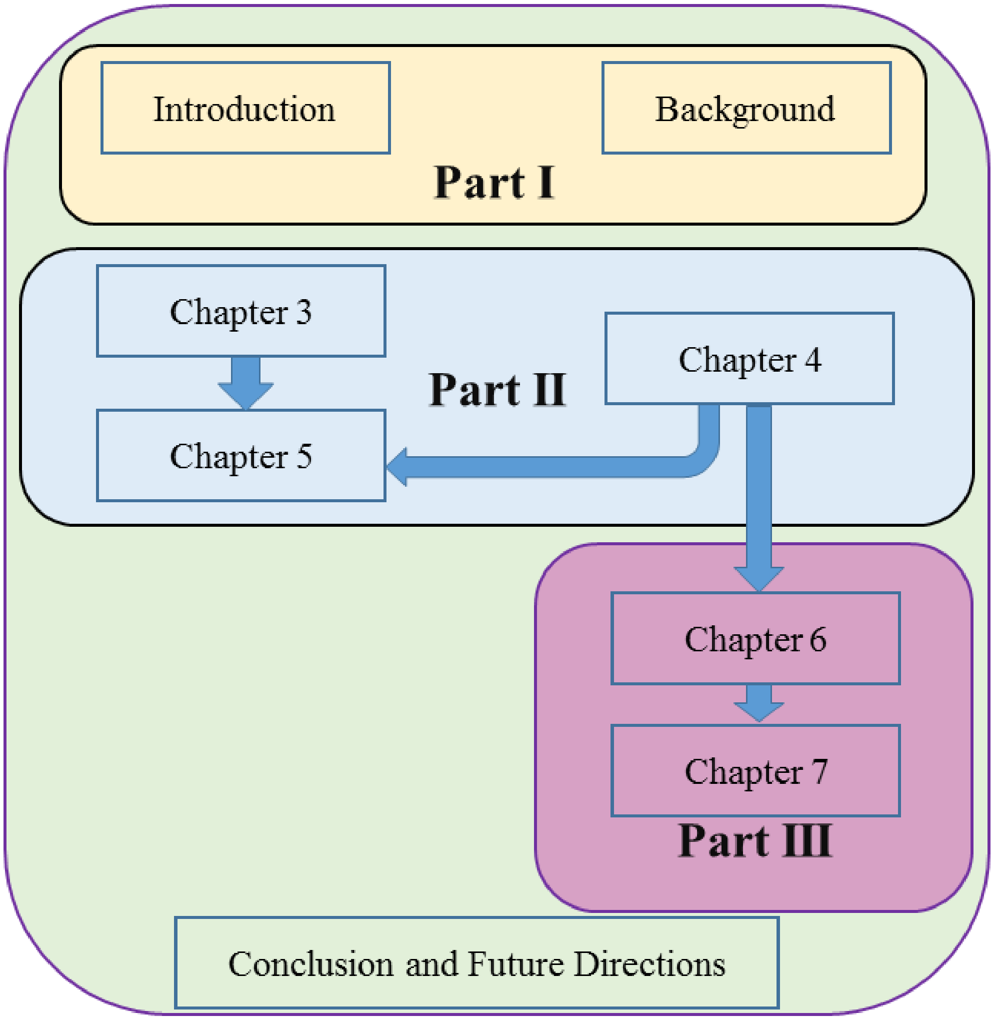



Figure 1.3: The dissertation organization.

## 1.5 Summary

In this chapter, the idea of using the cooperative transmission in secondary cognitive radio network to achieve a better spectrum occupancy is discussed. Based on this idea we introduce our research contributions and the dissertation organization and outline are listed.

# Chapter 2

# Background

This chapter covers the technical background and literature review related to the dissertation topic. The governmental and research community efforts in spectrum sharing are also discussed.

## 2.1 Cooperative Communications and Cooperative MIMO

The wireless channel suffers from fading, which means that the transmitted signal attenuation can vary significantly. Spatial diversity can combat the effect of fading in which multiple copies of the transmitted signal are transmitted from different locations(antennas) that travel over independent wireless channels. Multi-antenna techniques[29] like Space Time Block Coding (STBC) and spatial multiplexing are efficient transmission techniques to overcome the fading effect in the wireless channel or increase the channel capacity. However, it is not always feasible to equip wireless nodes with multiple antennas due to node's size, hardware complexity and antenna separation requirements especially, for end use devices. Cooperative communications [9] [30] is a paradigm where nodes can recruit one or more relays to forward their data to the final destination in case the direct transmission is not possible or to achieve better performance than that of direct transmission. This section discusses the basic backgrounf of multi-antenna transmission and cooperative communication systems.

MIMO system achieved a successful progress in combating the fading effect and increase the transmission range by using spatial diversity or increasing the channel capacity via spatial multiplexing. However, this required additional Radio Frequency (RF) front ends which may not be feasible for end use devises due to the cost and space limitation. As a solution for this obstacle, cooperative communication was introduced as a communication paradigm where nodes share their antennas to form virtual MIMO system and gain the MIMO benefit.

There are many forms of cooperative communications, the most famous are: Amplify and Forward (AF) and Decode and Forward (DF) [31].

- *Amplify and forward (AF):*
  In this scheme, relay(s) receives the noise version of the transmitted signal from the source then amplifies and transmits it to the final destination. The draw back of this scheme is the that the noise is amplified as well as the transmitted signal.

- *Decode and forward (DF)*
  In DF, the relay(s) first fully decodes the source signal then re-encodes it in the same modulation or a different one and transmits it to the final destination. By this way, the noise amplification effect is removed.

  A hybrid system was proposed in [32] that enable the relay to choose between AF and DF according to its ability to decode the signal correctly. The results show better performance than both schemes alone.

The receiver can combine the two signals (from the source and the relay(s)) and gain receiver diversity or use only the one received from the relay(s) in the second time slot.

As mentioned before one or more relays may be used to forward the source data. In one relay case, the transmission can be enhanced by extending its range or rate as the relay may have better channels (source-relay and relay-destination) than the direct one from the source to the destination due to fading or the distance. The same benefit can be found if multiple relays are used in addition to the MIMO benefits.

To enhance the performance of the relayed transmission the two signals are coded at the different transmitters by using Alamouti coding as in conventional MIMO. The deference between coding in the cooperative communication and in conventional MIMO is that the codeword is constructed in a distributed way where different parts of the codeword are transmitted over independent channels by different nodes. The coding schemes used in conventional MIMO can be applied for relay network. However, the distributed manner by which cooperative communication works addresses new design and practical challenges.

Example of the problems challenging the distributed manner of the cooperative communication are relays synchronization and Carrier Frequency Offset (CFO). Synchronization between relays can cause a problem if the relative delay between relays is not negligible. Another implementation problem is CFO which is resulted due to the variation in frequency between relays local oscillators.The two problem were addressed and solved in the practical implementation presented in [33]. The synchronization problem is solved by triggering the second transmission after a fixed time period from the first transmission ( Tx $\rightarrow$ Tx) or after a fixed time from the first reception (Rx $\rightarrow$ Tx). The CFO at the relays are ensured to be identical to that of the transmitter so the receiver observe only one CFO.

In this study, DF cooperative communications is used to increase the transmission rate higher than that of direct transmission. The direct transmission data rate between the source and the destination is $R_{sd}$, and by using cooperative communications, the source first transmits the data packet to the relay(s) using data rate $R_{sr}$ in time $T_{sr}$ and then the relay(s) re-forward the data to the destination with data rate $R_{rd}$ that consumes time $T_{rd}$. Assuming that the receiver does not combine the two signals, and by ignoring the encoding/decoding time at the relay, the net cooperative transmission time and net cooperative data rate for the two-hop communication are equal to:

$$T_{CC} = T_{sr} + T_{rd} \tag{2.1}$$

and

$$R_{CC} = \frac{1}{R_{sr}^{-1} + R_{rd}^{-1}} \tag{2.2}$$

To benefit from cooperative communications, the net data rate for the two hop communication must be higher than that of direct transmission.

$$R_{CC} > R_{sd}$$

Source can recruit more than one relay to forward its data to the final destination. Relays will cooperate with each other and share their antenna to form a virtual MIMO transmitter. Relays will encode the original message using space time coding as in MIMO system. Also if the destination is equipped with multi-antenna, relays can use spatial multiplexing in the second hop transmission and achieve a higher data rate.

## 2.2 Spectrum Sharing and Dynamic Spectrum Access

Spectrum sharing attracted the regularity agencies as the problem of spectrum scarcity becomes more severe. Different regularities started to set their own prospective to spectrum sharing and the general framework of spectrum sharing schemes to use.

In Europe, the European Commission identified two possible sharing approaches, which are:

- *Licensed Shared Access (LSA):*
  In the LSA, the PU is able to share its licensed spectrum with one or more SU (called LSA licensee) under a set of negotiated conditions and under the control of National Regularity Authorities (NRA).

- *Collective Use of Spectrum (CUS):*
  In CUS a devise can access a spectrum band that it finds to be vacant using its own capabilities. That means there is no control over spectrum access which makes these bands useless for some sensitive application. Additionally Quality of service (QoS) in CUS depends on spectrum congestion and for that, certain levels of QoS cannot be guaranteed.

The Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) investigated the technical requirement for White Space operation in the UHF (470-790 MHz) TV band. CEPT also studies spectrum sharing according to LSA concept. Two main projects are currently active. The first team focus on studying the regulatory framework of LSA and the other team studies the applicability of LSA sharing concept for Mobile Network Operators (MNOs) in the band between 2.3 and 2.4 GHz.

The prospective of spectrum sharing in the United States is represented in the Spectrum Policy proposal document prepared by the President's Council of Advisers on Science and Technology (PCAST). In this prospective, sharing depends on using geo-location database to enable dynamic sharing of spectrum bands. The proposed system is called the Federal Spectrum Access System (SAS) in which, a three tier hierarchy of spectrum usages is defined including:

1. *The primary licensee:*
   The federal service that owns the current license of the spectrum band (like Radar and TV channels). This user has the priority to access the spectrum at any time and location.

2. *The secondary licensee:*
   The secondary user (Like cellular service provider) is given a priority to access the license spectrum through the SAS, only if it is not used by the primary user.

3. *The tertiary user:*
   The tertiary user (like WiFi user) is an opportunistic user who obtains authorization to access the spectrum band if both the primary and secondary user are absent.

TV White Space (TVWS) is a perfect candidate for the geo-location based sharing approach. Where the first tier is the TV station and the second tier user is the one who is allowed to use the TV spectrum in a specific areas where there is no TV coverage. To ensure the maximum utilization, the third tier is also considered. The Federal Communications Commission (FCC) also investigating sharing the 3550-3650 MHz band, which is currently dedicated to the Naval Radar system, with tier two secondary systems cellular small cell deployment and low power systems as tier three tertiary users. A comprehensive survey and comparison between different regularity agencies contributions in spectrum sharing and DSA can be found in [34].

Spectrum sharing scheme describes the interaction between the primary and secondary users. Different classifications are found in the literature. For example, [3] classifies spectrum sharing to underlay and overlay spectrum sharing where, in overlay the SU transmits only in the absence of the PU, while in underlay spectrum sharing the SU transmission can coexist with the one of PU given that the interference resulted from the secondary transmission at the PU receiver is below a certain threshold. Another classification is found in [2] where underlay has the same definition as in [3] but its definition for overlay scheme generally includes any scheme where the SU cooperates with the PU by forwarding its data and in return the PU rewards the SU by giving it authorization to access to the licensed spectrum. The scheme where the secondary user is allowed to access the licensed spectrum only at the absence of the PU is called interweave spectrum sharing. In our study we will use the same definition used in[2].

## 2.3 Literature Review

In this section, we review the research work related to our problem statement including dynamic spectrum access, cooperative communication, cooperative communication for DSA, and spectrum trading and resource allocation in DSA networks.

### 2.3.1 Dynamic Spectrum Access and Cognitive Radio

Research in DSA [2][3] and CR [4] [5] spans many different areas from physical layer to network layer. In physical layer research includes areas like sensing the PU's presence [8] and PU's activity modeling and estimation [35]. In MAC layer, many research studies were conducting to develop MAC protocols for Cognitive Radio Network CRN [36] where most of them are considered cross layer protocol that use sensing and adaptive modulation to facilitate DSA. the research in MAC layer leads to IEEE 802.22 the first IEEE standard MAC protocol for Cognitive Radio Wireless Regional Area Networks (WRANs) [37]. In network layer, many routing protocols were designed to benefit from the CR in multi-hop network. A survey on the CR routing protocol and routing metrics can be found in [38]. Many research studies were conducted in the spectrum sharing schemes using Markov chain. In [25], Wang et al. proposed a prioritized Markov chain to model the interaction between the PU and more than one SU which can access the PU's vacant spectrum simultaneously. The authors optimized the access probabilities of the Markov chain to achieve fairness among the SUs. The evaluation showed that the proposed scheme achieves higher throughput than the Carrier Sense Multiple Access (CSMA) scheme. Ngallemo et al. in [26] computed the coexistence probability between the PU and multiple SUs under an interference constraint in underlay sharing scheme. Nair et al. [39] used overlay and underlay hybrid spectrum sharing low-complexity access model that improves the SU's throughput.

### 2.3.2 Cooperative Communication and Cooperative MIMO

Multi-Input Multi-Output (MIMO) techniques [29] like STBC and spatial multiplexing are successful techniques to combat the fading effect in the wireless channel or increase the channel capacity. However, equipping the wireless node with multi-antenna is not always feasible due to antenna-separation requirements, hardware constraints, and cost especially for consumer devices like cellular phones.

Cooperative communications [30] is a paradigm where nodes can recruit one or more relays to forward their data to the final destination to extend the transmission range or to increase the data rate. Multi-relay can be used to forward the data and in this case the relays share their antennas to benefit from MIMO capabilities. Several research studies were conducted in cooperative communications using one or more relays. Lui et al. [40] developed a MAC protocol that chooses between direct transmission and one relay transmission so that nodes with high data rate transmission can assist those with slow data rate. In this paper cooperation is limited to a single relay case only. In [41], Jakllari, et al. designed a cross layer framework that enables using more than one relay to forward source data and mimic Multi-Input Single-Output (MISO) transmission to achieve transmitter diversity. Sirkeci-Mergen and Scaglione [42] developed a new Space Time Block Coding (STBC) technique named Randomized Distributed Space Time Coding (RDSTC) that enables recruiting any number of relays on the fly. This code was used in [43] to develop cross layer multi-relay multi-hop cooperative MAC protocols that increases the network throughput. The source can recruit one or more relay according to the node density. Nodes share their antennas to form a virtual MIMO system and forward the source packet using RDSTC. The MAC protocol uses two methods to decide which relays to use; one through exchange information between nodes which will result in a more accurate information but large overhead, the other is based on the relay density where the source guesses the average number of relays that can forward its packet.

In [44], authors developed a RDSTC based cross layer protocol for infrastructure network. The proposed protocol handles the handshaking process as well as the relay(s) selection *on the fly*. The protocol enables utilizing any number of intermediate relays and thus reduces outage due to relay failure and reduces the signaling overhead.

In [45], author developed a cross layer multi-hop cooperative protocol named RECOMAC. In RECOMAC, packets are forwarded via opportunistically formed cooperative sets within the region.RECOMAC employs RDSTC and cooperative forwarding which depends on the availability of node location information. By this, the coded packet are forwarded from a cooperative set to a consecutive set is a direction towards the destination without any need of selecting relays. In this way, the end-to-end route is defined as a series of regions in which the relays reside, as opposed to traditional routes that take the shape of string of predetermined relays

Another research direction showed that cooperative transmission achieves better power efficiency than direct transmission as shown in [46] where the energy performance of COOPMAC [40] was investigated. In [47] author developed a generalized energy model for relay-enabled MAC protocol with rDCF MAC protocol [48] was used as a case study.

Cooperative communication can help the SUs by enhancing the secondary transmission characteristics. In [10], Amplify and Forward relaying with beamforming was used by the SUs in underlay DSA to enhance the secondary transmission and reduce the interference at the PU's receiver. If there is no common channel between the secondary transmitter and the secondary receiver, a cooperative relay with common channels with each of them can act as a bridge [12]. In [49] nodes with extra Orthogonal Frequency Division Multiplexing Access (OFDMA) sub-channels can help those with limited bandwidth by relaying their data at a higher rate.

### 2.3.3 Spectrum Trading in Cognitive Radio Networks

Cooperation between the PUs and the SUs mainly takes one form in which the SU gains access to some of the PU's resources and in return, offers a price or help for the PU. Market driven spectrum trading is an efficient way to facilitate spectrum sharing between different users. The basic idea is to provide an incentive reward for the different nodes to cooperate and achieve a better performance. Most of the previous work focuses on the cooperation between the PU and the SU. In this model, the trade is done using money exchange or resource exchange. A sample of the related work is listed below.

In the money exchange type, the trade between the SUs and the PUs can be modeled as an auction which is useful when the seller has no information about the buyer evaluation of the resources. In [15], TODA, a general framework for truthful online double auction for spectrum allocation is proposed. A central auctioneer upon the arrival of a new SU decides which PU and SU will win the auction and how much the SU should pay for the PU and how much time the PU will sublease its channel to the SU. Another double auction model is proposed in [14], where the hierarchical multi-tier spectrum sharing framework [34] is used as a network model. In this work, the double auction between the sellers (tier 1 PUs) and buyers (tier 2 SUs) for multi auctioneer (Shared Spectrum Manager ) is proposed to maximize the profit achieved by the buyer and the seller as well as the Shared Spectrum Manager. Another way to model the money exchange is the contract based trade. The Contract method is useful when the sellers has a limited information about the buyers evaluation for the resources. In [13], the spectrum trade between a single PU and multiple SUs is modeled using contract theory. The spectrum owner (PU) act as a monopolist who wants to sell its spectrum for a certain price and qualities. The SUs act as consumers who want to buy spectrum with appropriate price and quality. The PU designs a feasible contract that contains quality and price conditions for every buyer type.

Another approach to deal with the money-exchange type of spectrum trading is the pricing based model which is useful when the seller knows the value of the resources it sold. In [16] the authors modeled the problem as competition game between two operators who compete to sell the spectrum to secondary users to maximize their individual profit. In [17], the authors modeled the cooperative spectrum sharing between one PU and several SUs in a relay assisted network using Stackelberg game. In the first stage, the leader (the PU) selects the several parameters including its own transmission power, the SUs and relay powers, and the price vector. In the second stage, each SU selects its transmission power. The goal is to find a Nash equilibrium between the PU's utility (includes its QoS and revenue) and SUs' achieved throughput.

The other model of spectrum trading is the resource exchange model, where the leased spectrum price is paid in terms of other resources. The resource exchange model is more useful when the seller has limited resources or high demand so there is no free resources to sell. In such case, the seller (PU) can lease part of its spectrum time to the buyer (SU) who pays the price in terms of power by serving as a relay for the PU. By this way the PU's performance is improved and thus it can lease part of its time to the SU. In [18], authors modeled the cooperative spectrum sharing between the SU and the PU using contract theory. The paper studied the optimal contract design at different information availability including complete, weakly complete and incomplete information. In [19], SU helps the PU by performing successive interference cancellation and in return the PU allows the SU to access its medium. Contract theory was used to design the cooperation contract between the PU and the SU. Authors of [20] studied the spectrum sharing between the PU and SU using contract theory in case the SU tends to cheat to achieve a higher utility. Matching theory is also used to study cooperative spectrum sharing. Feng et. al. [21] used matching theory to study the cooperative spectrum sharing among multiple PUs and multiple SUs. The authors derived the necessary conditions for stable matching and developed a distributed matching algorithm to achieve equilibria at different information availability cases. Namvar et. al. [22] used Stakelberg game between the PUs and the SUs to find the optimal time allocation of the different cooperative transmission faces; then they used matching theory to find the best one-to-one matching partners by designing a stable distributed matching algorithm.

In [23] and [24], the cooperative spectrum sharing between the PUs and SUs was modeled using Stackelberg game and the unique Nash equilibrium was found analytically.

### 2.3.4 Bargaining Theory Application in Dynamic Spectrum Access

Bargaining theory has been used in wireless communications for many applications. In [50], the authors modeled the cooperation between a source and a relay as a bargaining problem. A bandwidth allocation strategy using NBS was proposed to choose between to cooperate or not to cooperate and to determine the amount of bandwidth to allocate for cooperation. Authors of [51] solved the same problem using KalaiSmorodinsky bargaining solution which was proven to be fairer than the NBS based bandwidth allocation. Cooperation between the PU and the SUs was studied as a bargaining problem in [52] to stimulate the PU to lease part of its spectrum to the SUs which act as relays to forward the PU data. The NBS based model achieved a fair share for each SU according to its contribution in the cooperation. In [53], a PU (Mobile operator) leases a portion of its licensed spectrum to a SU (WiFi AP) and in return the SU acts as a relay to offload the cellular data. The resource allocation among players was analyzed as a bargaining problem and solved using NBS, where the utilities were determined based on the achieved throughput. The resources allocation problem in secondary ad-hoc network with imperfect PU sensing was investigated in [54]. A dynamic subchannel and power allocation algorithm was developed based on NBS that achieved a better performance than max-min and min-max approaches.

Xu et al. [55] proposed a two tier market for decentralized dynamic spectrum access. In the first tier, the PU lease part of the spectrum to the SUs in a relatively large scale. In the second tier, according to the traffic demand, the SUs redistribute the leased spectrum between themselves in a fine scale.

### 2.3.5 Resource Allocation In Cooperative Cognitive Radio Networks

Resource allocation in cooperative cognitive radio network include relay(s) selection, channel allocation, access time and frequency bands allocation. In [56], authors investigated the jointly relay and channel selection for location based CRN. The optimal selection and allocation was formulated as a combinatorial optimization problem with the objectives to maximizing the number of cooperating pairs and reduce the transmission power and interference using power control. Authors of [49] formulated the relay selection in OFDMA secondary network with overlay access scheme using non-transferable utility coalition graph game to improve throughput and achieve fairness between nodes. SUs with more available sub-channels (bandwidth) can help those with less number of sub-channels by acting as relays. The problem is solved by obtaining the balanced core of the coalition graph. Authors of [57] provided a spectrum sharing mechanism in multi-hop cognitive network. SUs pay for the PU for the leased spectrum and for other SU for their relaying help. Optimal power allocation and relay selection are investigated for different pricing function. Nash equilibrium were found when all secondary nodes use multi-hop relaying. In [58], a joint relay selection, spectrum allocation and rate control problem is formulated to achieve user Quality of Service (QoS) and maximize the system throughput. The sub-optimal solution is found using a heuristic algorithm. Authors of [59] modeled the relays selection and power control in one source and multiple relays for Amplify and Forward cooperative communications. The problem was solved as a mixed integer programming. The same problem was solved by a Biogeography-based optimization algorithm where the resulted performance is comparable to the optimal one. The subcarrier allocation and multi-relay selection in OFDMA based cognitive radio network is investigated in [60] where the problem is solved using Estimation of Distribution Algorithm (EDA). The same problem of subcarrier allocations and relay selection was solved in [61] using swarm algorithm with low computational complexity. With each SU equipped with multiple antennas, the optimal subcarrier allocation and node pairing problem in MIMO-OFDM based cognitive radio network was studied in [62]. A suboptimal low complexity algorithm was also developed. Authors of [63] modeled the spectrum allocation and relay selection as a truthful auction mechanism. Authors of [64] provide a comprehensive survey on resource allocation in cooperative and cognitive radio networks.

## 2.4 Summary

This chapter discussed the technical background used in the rest of the dissertation. The MIMO and cooperative communication concept were illustrated. The regularity agencies and research efforts in DSA were listed and the cooperation models in the DSA networks were discussed.

# Part II

# Cooperative Communication for Efficient Spectrum Utilization in Secondary Networks

# Chapter 3

# An Experimental Study of Data Rate Enhancement Using Cooperative and Multi-Antenna Communications in Infrastructure Networks

This chapter[1] studies the upper bounds on data rate in infrastructure networks, especially for low rate nodes, using cooperative communications. Different simulated experiments were conducted to quantify the enhancement of data rate.

## 3.1 Introduction

This chapter presents simulated experiments to quantify upper bounds on rate enhancement in infrastructure networks with a more realistic assumption of having an Access Point (AP) with two antennas and a number of user nodes, each equipped with a single antenna. Equipping the AP with two antennas and using multi-relays in data forwarding enables utilizing different multi-antenna communication techniques like 1x2 MRC, 2x1 STBC, 2x2 STBC and 2x2 spatial multiplexing.

The relay(s) and transmission technique are chosen by a centralized algorithm that has full knowledge of Channel State Information (CSI) between different nodes. The algorithm examines this information and searches for the relay(s) and transmission technique combination that achieve the highest data rate and meets a specific Bit Error Rate (BER) threshold at the receiver. As the algorithm has full knowledge about the network and carries out an exhaustive search over all combinations, the result from this selection can be considered an

[1]This chapter is based on work presented in [65].

upper bound and can be used to compare the performance of any other selection mechanism that may not have full knowledge of the network CSI.

## 3.2 Multi-Antenna Systems

In multi-antenna systems, the transmitter and/or the receiver are equipped with more than one antenna, which leads to a data rate increase within the same bandwidth or achieves diversity gain that can improve transmission characteristics. Different multi-antenna communication techniques are descried below including Single-Input-Single-Output (SIMO), Multi-Input-Single-Output(MISO) and Multi-Input-Multi-Output(MIMO). For all of them, the receiver is able to perfectly estimate the transmitting channel state information.

- *SIMO with Maximal Ratio Combining:*
  A receiver with multiple antennas can combine the received signals over different antennas using different techniques. The optimal combining technique is called Maximal Ratio Combining (MRC) [66]. In MRC, the received signal at different antennas can be expressed as:

  $$\mathbf{r} = \mathbf{h}x + \mathbf{n}. \tag{3.1}$$

  here, $\mathbf{r}$ is the received signal vector, $\mathbf{h}$ is the channel coefficients vector, $x$ is the transmitted symbol and $\mathbf{n}$ is the noise vector.

  To estimate the original symbols, the received signal at each antenna is multiplies by a weight equals to the channel fading observed by this antenna. After the weighting process, the received signals are combined together before sending them to maximum likelihood detector.

  $$\tilde{\mathbf{x}} = \mathbf{h}^H \, \mathbf{r} \tag{3.2}$$

  The signal to noise ratio (SNR) for N antennas at the receiver is equal to the sum of SNRs of individual antennas.

  $$\gamma = \sum_{i=1}^{N} \gamma_i. \tag{3.3}$$

  By this technique, the receiver achieves a receiver diversity gain of $N$ fold and SNR gain of $3dB$ for each antenna.

- *MISO/MIMO with Alamouti Space Time Block Coding*

  In Alamouti STBC [67] the transmitter is equipped with two antennas and the receiver is equipped with one or more antennas. The transmitter groups every two consecutive symbols and sends an orthogonally-coded version of them using the two antennas over two time slots which can be expressed as:

$$\begin{pmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{pmatrix}.$$

  Where rows represent antennas and columns represent time slots.

  The receiver may be equipped with one or more antenna to form MISO or MIMO respectively.

  - **Single antenna receiver**

    In the case of single-antenna receiver, the received signals can be expressed as:

$$r_1 = h_1 x_1 + h_2 x_2 + n_1, \tag{3.4}$$

    and

$$r_2 = -h_1 x_2^* + h_2 x_1^* + n_2, \tag{3.5}$$

    where $r_1$ and $r_2$ are the received signals at the first and second time slot respectively. $h_1$ and $h_2$ are the channel coefficients between the transmitter antennas and the receiver. $n_1$ and $n_2$ are the noise components associated with each time slot. The previous equations can be represented in matrix notations as:

$$\begin{bmatrix} r_1 \\ r_2^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2^* \end{bmatrix} \tag{3.6}$$

    or

$$\mathbf{r} = \mathbf{H}\mathbf{x} + \mathbf{n}. \tag{3.7}$$

    **H** is 2x2 orthogonal channel matrix.
    The transmitted symbol can be estimated by zero forcing

$$\tilde{\mathbf{x}} = \mathbf{H}^{-1}\mathbf{r}. \tag{3.8}$$

    The estimated signals are sent to a maximum likelihood detector. The previous configuration forms a 2x1 MISO transmission scheme with transmit diversity of 2 and no receive diversity.

- **Multi-antenna receiver**

  In case of multi-antenna receiver $N_r$ ($N_r = 2$ for Alamuti STBC described below), the received signal at the first time slot can be expressed as:

$$r_1^1 = h_{11}^1 x_1 + h_{12}^1 x_2 + n_1^1, \tag{3.9}$$

and

$$r_2^1 = h_{21}^1 x_1 + h_{22}^1 x_2 + n_2^1, \tag{3.10}$$

and at the second time slot as

$$r_1^2 = h_{11}^2 x_1^* - h_{12}^1 x_2^* + n_1^2, \tag{3.11}$$

and

$$r_2^2 = h_{21}^2 x_1^* - h_{22}^1 x_2^* + n_1^2, \tag{3.12}$$

where $r_i^t$ is the received signal at receiver $i$ and time $t$, $n_j^t$ is the noise signal at receiver $j$ and time $t$, and $h_{ji}^t$ is the channel gain between transmitter $i$ and receiver $j$.

By assuming that $h_{ij}^{t_1} = h_{ij}^{t_2}$ the previous equation can be combined in matrix form as

$$\begin{bmatrix} r_1^1 \\ r_2^1 \\ r_1^{2*} \\ r_2^{2*} \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \\ h_{11}^* & -h_{12}^* \\ h_{21}^* & -h_{21}^* \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} n_1^1 \\ n_2^1 \\ n_1^{2*} \\ n_2^{2*} \end{bmatrix}. \tag{3.13}$$

or

$$\mathbf{r} = \mathbf{H}\,\mathbf{x} + \mathbf{n}. \tag{3.14}$$

the estimated transmitted signal is calculate as

$$\tilde{\mathbf{x}} = \mathbf{H}^{+}\mathbf{r} \tag{3.15}$$

where $H^+$ the pesudo inverse of $H$.

The estimated signals $\tilde{\mathbf{x}}$ is sent to a maximum likelihood detector. The previous configuration forms a 2x2 MIMO transmission scheme. The same configuration can be easily generalized for any $N_r$ antennas at the receiver to achieve a total of $2Nr$ diversity order.

- Spatial Multiplexing

  By using spatial multiplexing[68], the system achieves a higher data rate by dividing the data stream at the transmitter into sub streams and transmitting each sub stream

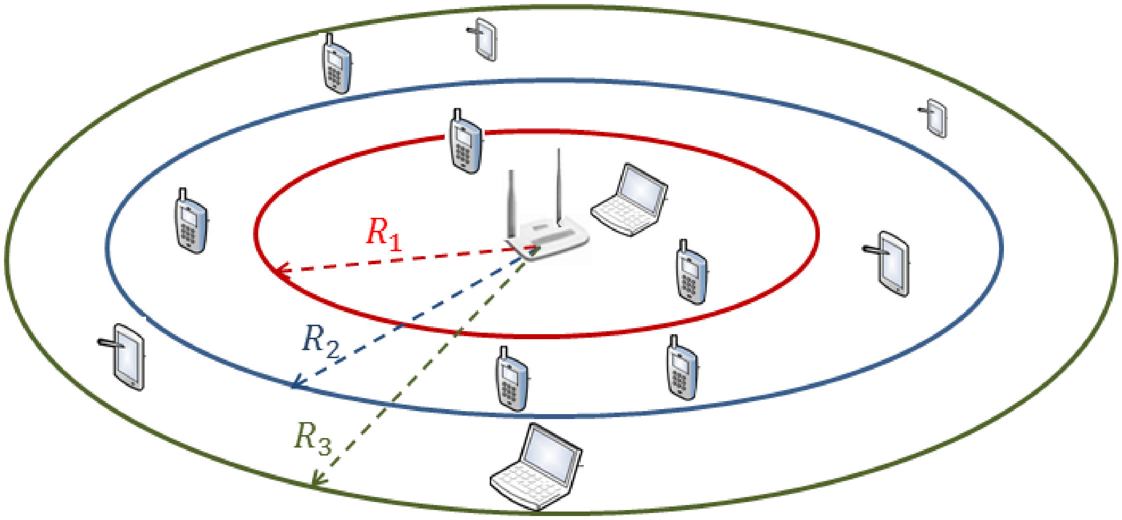



Figure 3.1: Infrastructure network with different direct transmission rate ranges

independently over a different antenna. At the receiver, the data streams are detected and decoded using several techniques, for example, maximum likelihood detector. The maximum likelihood detector chooses the symbol set with the smallest Euclidean distance from the received signal.

$$\tilde{\mathbf{x}} = \operatorname*{argmin}_{x} ||\mathbf{r} - \mathbf{H}\sqrt{E_s}\mathbf{x}||^2 \tag{3.16}$$

The receiver must estimate the channel matrix $\mathbf{H}$ and requires a brute force search over $2^{m.N_t}$ different combinations, where $m$ is the modulation order and $N_t$ is the number of transmitting antennas. The system can successfully decode up to $min\,(N_t, N_r)$ data streams where $Nr$ is the number of receiver antennas.

## 3.3 System and Network Model

In this section, details are provided about the characteristics of the wireless channel, the network model, and the transmission techniques used in our study.

*1) Channel Model:* The flat fading Rayleigh channel model is used with independent identically distributed zero mean, unit variance complex Gaussian distributed random variables. Each node can estimate the CSI between itself and other nodes using embedded pilot tones in the data packet.

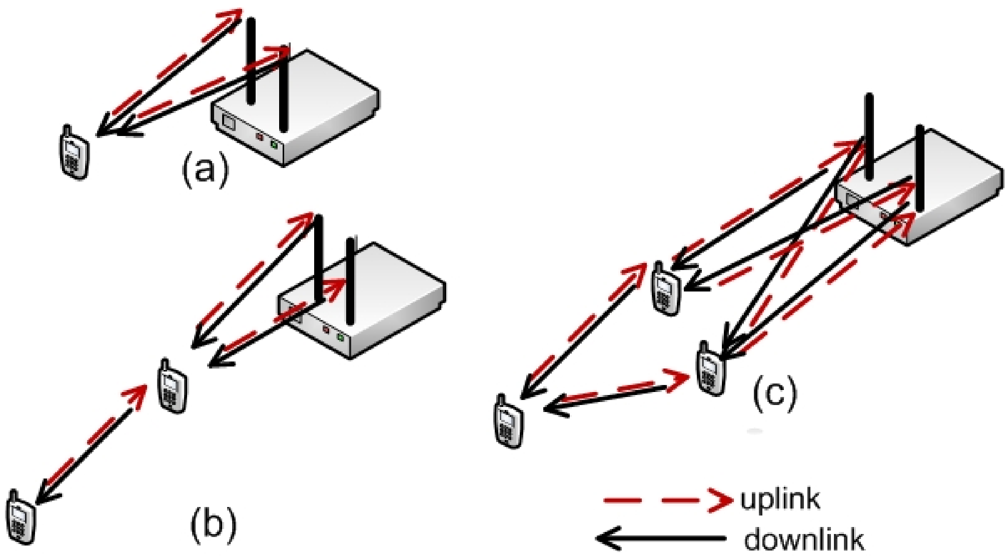



Figure 3.2: Different transmission techniques

*2) Network Model:* The network model is an infrastructure network with a single Access Point (AP) in the center of the network and a number of stationary user nodes as shown in Fig. 3.1. The AP is equipped with two antennas and the rest of the nodes are equipped with a single antenna. Each node has a powerful transceiver that is able to transmit and receive at different transmission schemes with different data rates using a set of modulation techniques. Nodes are assumed to have a transmitting power threshold per antenna that cannot be exceeded. The AP can transmit to any node at the network using at least a basic rate and vice versa. Nodes can communicate directly with the AP in an adaptive way by changing the modulation scheme and so the transmission rate is determined according to the distance from the AP. Nodes and AP can use cooperative communication by using intermediate relay(s) instead of using direct transmission (DT). In this study, cooperative communication is used to increase the transmission rate for slow nodes within the same range of communication. Decode and Forward (DF) cooperative communication is used by all relays with perfect synchronization. It is assumed that nodes run a MAC protocol that facilitates media access and handshaking. The MAC protocol handshaking carries the necessary information for the AP to build a complete channel knowledge for the selection process. Bidirectional flows in the uplink and downlink directions are assumed to be of equal priority among all nodes.

*3) Transmission modes:* Different transmission modes are implemented in this study depending on the type of transmission (DT or relayed transmission), the number of relays used and if nodes utilize space diversity or spatial multiplexing. These modes are the result of the integration of cooperative and multi-antenna communications when the AP is equipped with two antennas and user nodes are equipped with single antenna.

Fig. 3.2 (a) represents the direct transmission between the user node and the AP. In the uplink direction, the AP uses 1x2 MRC to combine the two signals received by its antennas from the source. In the downlink direction, the AP transmits to the user node using 2x1 Alamouti STBC. The modulation technique and the rate used depends on the channel status between the node and the AP. The transmission power combined with the reception method makes the data rate identical in the uplink and in the downlink.

Single relay cooperative communications is shown in Fig. 3.2 (b). In the first hop, the user node transmits directly to the relay in ordinary Single-Input Single-Output (SISO) transmission. In the second hop the relay forwards the data to the AP, which combines the received signal using MRC. In the downlink direction, the AP transmits the data using 2x1 Alamouti STBC to the relay, which forwards it in the next hop using SISO transmission. The selection of each hop data rate depends on the channel status between the transmission pair.

Multi-relay cooperative communications is depicted in Fig. 3.2(c). In the uplink direction, the source transmits to the two relays using SISO transmission, and in the second hop the relays jointly forward the data to the AP using 2x2 STBC or 2x2 spatial multiplexing. In the downlink direction, the AP sends data to the each relays using 2x1 STBC in the first hop and the relays jointly forward the data to the user node using 2x1 STBC.

For relayed transmission, Decode and Forward (DF) is used. The selection algorithm choose to use relay(s) to forward the data if it will lead to a higher data rate than that of the direct transmission.

## 3.4 Network and Simulation Setup

In this section, the network and simulation setup is discussed.

The infrastructure network consists of N stationary user nodes randomly (i.i.d) uniformly located within a circle with radius of 90 meters and the AP is located at the center of the circle. The transmission power is chosen such that the bidirectional direct transmission between any user nodes and the AP is guaranteed using at least the basic (slowest) data rate.

Each node is able to transmit and receive at different modulation techniques (BPSK,QPSK, 16QAM, 64QAM and 256QAM). For each node's transceivers following transmission capabilities were defined.

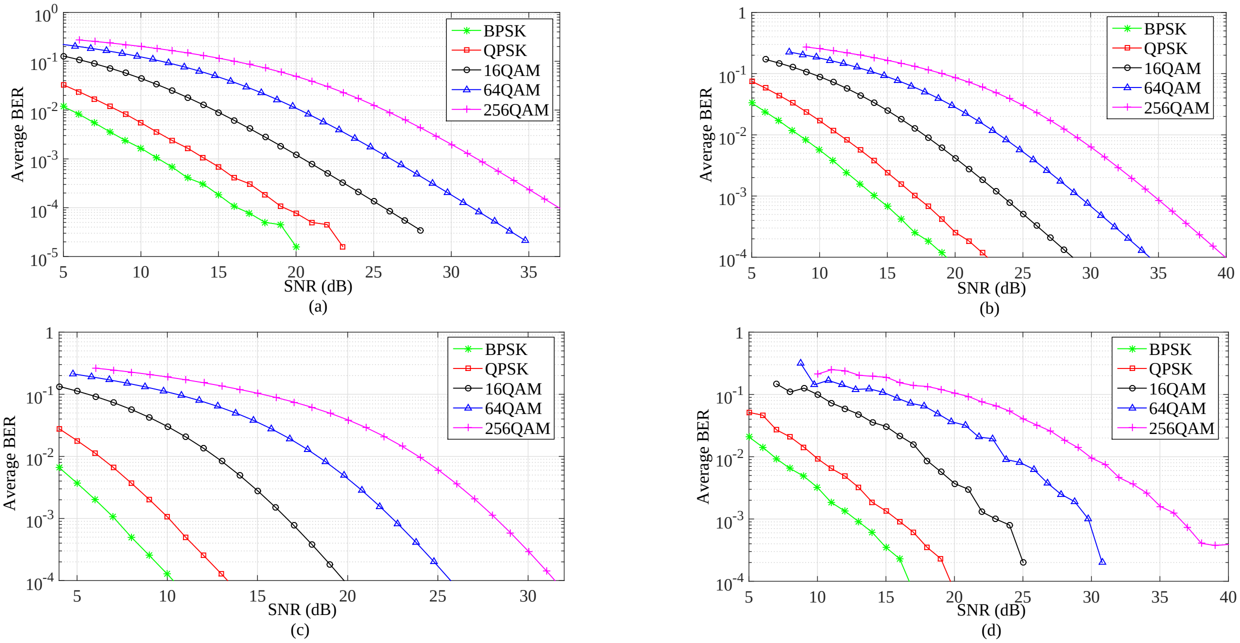



Figure 3.3: Average BER performance for different modulation techniques at (a) 1x2 MRC, (b) 2x1 STBC, (c) 2x2 STBC, and 2x2 spatial multiplixing.

- *Direct Transmission (DT):* One hop transmission without relaying
- *Single Relay Assisted Transmission (SRAT):* Switches between DT and single relay transmission according to the achieved data rate
- *Multi-Relay Assisted Transmission (MRAT):* Switches between DT, single relay and multi-relay transmission according to the achieved data rate

Fig. 3.3 shows the average BER for different modulations at different transmission techniques. These curves are obtained through Monte Carlo simulation using MATLAB [69].

As mentioned before, the maximum likelihood detector required a brute force search over $2^{m.N_t}$ combinations. This is considered to be practical limitation that limits using higher order modulations. For this reason, the modulation techniques used with spatial multiplexing are limited to BPSK, QPSK and 16QAM.

The selection of relay(s) and transmission technique is based on the highest achievable data rate that satisfies the BER requirement at the receiver. This requirement is set to be lower than $10^{-3}$ in the simulation. The selection process is done using a centralized algorithm that has full knowledge of all CSI between different nodes and examines this information to calculate the average data rate for every relay(s) and transmission technique. From these

Table 3.1: Simulation Parameters

| **Simulation Parameter** | **Value** |
|---|---|
| Modulation | BPSK, QPSK, (16,64,256)QAM |
| Data rate | 6,12,24,36,48 Mbps |
| Path loss exponent | 3 |
| Symbol duration | 1/6 micro sec. |
| Max. Transmission Power per Antenna | 0.25 mW |
| Center Frequency | 2.4 GHz |
| Channel BW | 20 MHz |
| Successful reception BER threshold | $10^{-3}$ |

combinations, the algorithm chooses the one with the highest data rate that meets the BER requirement. Table 3.1 lists the different parameters and their values used in the simulation.

## 3.5 Performance Evaluation

This section includes the results of different simulation experiments. The experiments focus on the enhancement of the data rate of slow nodes. A slow node is defined as the node with a direct transmission rate equals to 6 or 12 Mbps. Other nodes with higher DT rates will not benefit from cooperation as the cooperative rate will be always less than that of DT regardless of the two hop rates used. For multi-relay transmission, two scenarios were studied: The First one, when the two relays forward data using normalized power so the total power transmitted by the two relays is equal to that if only single relay is used. This way gives a fair comparison between single relay and multi-relay performance. In the second scenario, we show how much better the performance will be when relays forward the data with full transmission power.

### 3.5.1 Transmission Rate Versus Number of Nodes

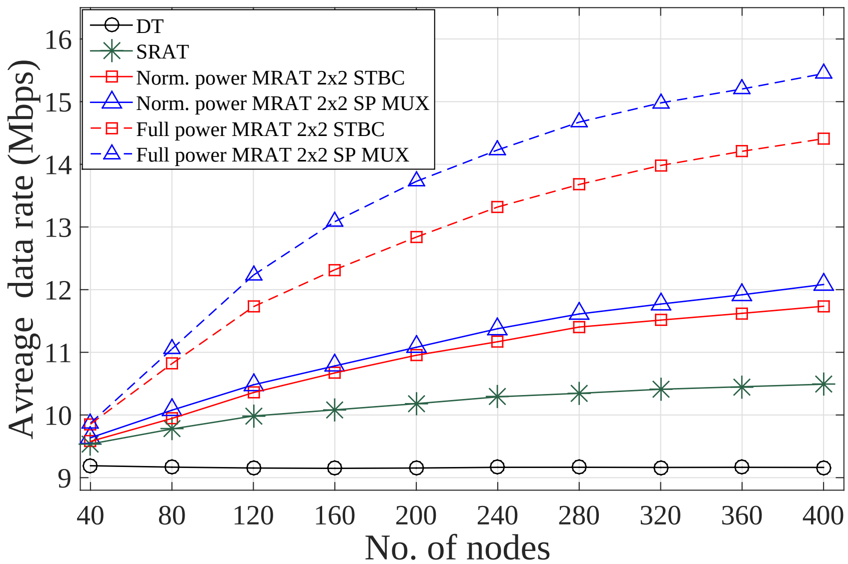



Figure 3.4: Slow nodes average data rate vs. number of nodes in uplink direction

This experiment shows the relation between the average transmission rate per packet and the number of nodes (relays) available in the network in uplink and downlink directions. The transmission rate performance was averaged over 100 realizations of network nodes distribution.

Fig. 3.4 and Fig. 3.5 show the data rate performance for slow nodes in uplink and downlink directions, respectively. For uplink direction, as expected, the DT is almost constant regardless of the availability of relays. SRAT data rate is slightly better than DT and increases as the number of nodes (potential relays) increases. For normalized MRAT with both 2x2 STBC and 2x2 spatial multiplexing, the data rate is much higher than the DT and the SRAT due to the diversity gain or multiplexing gain. For full power MRAT, the enhancement is significant and can reach up to 77% of that of DT. It also noted that 2x2 spatial multiplexing performs better than STBC. This can be justified by comparing the performance of 256 QAM 2x2 STBC and 16 QAM 2x2 spatial multiplexing in Fig. 3.3. From the curves we can observe that, at the target BER threshold 2x2 spatial multiplexing has much better performance than 256 QAM 2x2 STBC at the same transmission rate.

For the downlink direction, the DT is almost constant and there is a slight enhancement in SRAT and both are almost the same as in uplink direction. For full power STBC MRAT, there is enhancement in data rate of about 53% of that of DT.

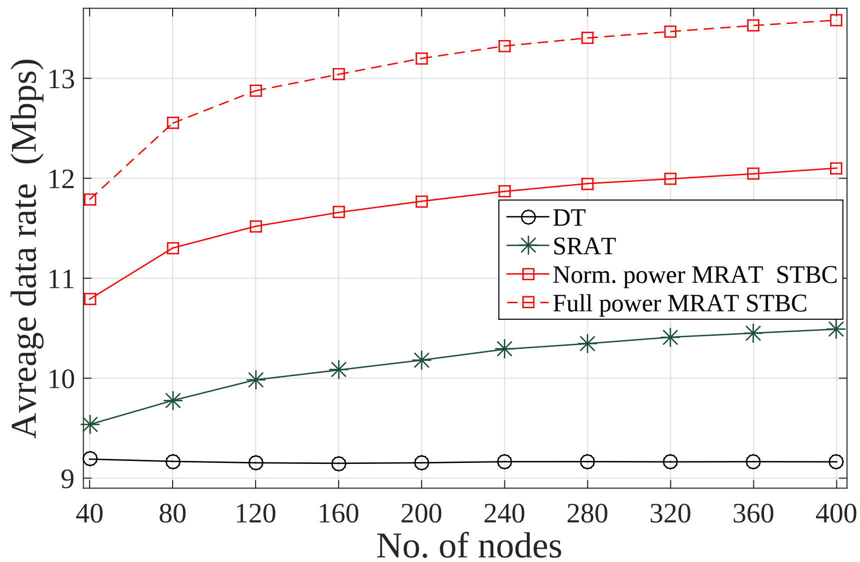



Figure 3.5: Slow nodes average data rate vs. number of nodes in downlink direction

### 3.5.2 Transmission Rate Versus Distance from the AP

In this experiment we study the average transmission rate against the distance between the user node and the AP. The node is first located at the outer network boundaries and then moved towards the AP until it cames very close to it.

Fig. 3.6 and Fig. 3.7 show the average transmission rate as a function of the distance to the AP in the uplink and downlink direction, respectively. As can be expected from the previous results, cooperation (with its different schemes and power levels) resulted in data rate enhancement for nodes that are far away from the AP. As the node comes closer to the AP, its transmission rate enhanced until it reached a distance where there is no additional benefit from the cooperation. This is intuitive as the node at a far distance has a low DT rate and it performs better with relaying. However, when it come closer to the AP, the DT dominates any two-hop communications.

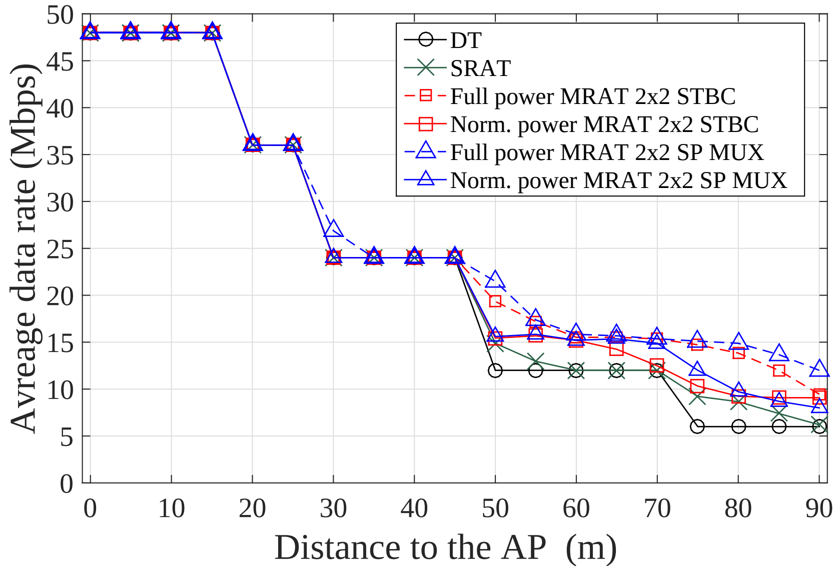



Figure 3.6: Average transmission rate vs. distance from the AP in uplink direction

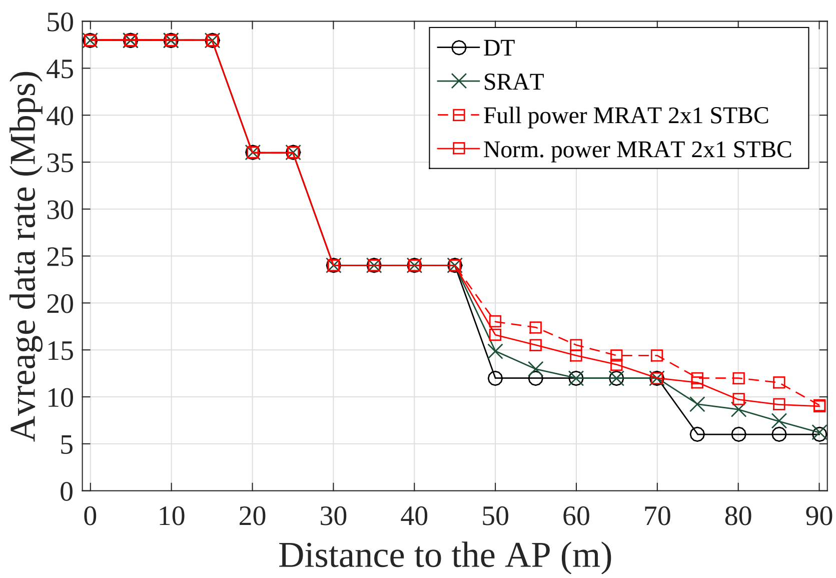



Figure 3.7: Average transmission rate vs distance from the AP in downlink direction

## 3.6 Conclusion

This chapter examined the data rate performance limits of cooperative communications with multi-antenna transmission techniques in infrastructure network. The selection of relay(s) and transmission technique is based on full knowledge of the network. The results show an enhancement for multi-relay transmission over single relay and direct transmission as it reaches up to 77% in the uplink and 53% in the downlink compared to direct transmission. In multi-relay, 2x2 spatial multiplexing gives better results than 2x2 STBC in the uplink direction.

# Chapter 4

# Spectrum Occupancy Analysis of Cooperative Relaying Technique for Cognitive Radio Networks

This chapter [1] analyzes the benefits of using the cooperative relaying technique on the spectrum occupancy for the unlicensed transmissions. A slotted access with interweave spectrum sharing is modeled using stationary Discrete Time Markov Chains (DTMC) for both non-cooperative and cooperative unlicensed transmissions. Furthermore, the effect of the cooperation level among the unlicensed users on the achieved throughput is investigated. The results show that the mechanism of cooperative relaying is more efficient in utilizing the unused spectrum, especially in the crowded spectrum. Moreover, the relative average throughput increases as the cooperation increases due to efficient utilization of the spectrum holes. The effect of the number of time slots per packet and the SU's and PU's packet size ratio are also studied.

## 4.1 Introduction

Spectrum scarcity has emerged as a problem of primary interest in the past years because of the high demand on new wireless services. Efficient spectrum sharing mechanisms are needed to better utilize the licensed spectrum. Dynamic Spectrum Access (DSA) techniques provide solutions for this problem. DSA allows unlicensed users called Secondary Users (SUs) to gain access to the licensed spectrum without interfering with the Primary User (PU), who owns the spectrum.

The interweave spectrum sharing scheme for single PU and multiple SUs was analyzed

[1] This chapter is based on work published in [70].

by Wang et al. in [71]. The PU band is divided into N sub-bands so $N$ SUs can coexist simultaneously in the absence of the PU. The scenario is modeled using Continues Time Markov Chain (CTMC) and important statistics are obtained like SUs' blocking rate, utilization ratio of the spectrum and SU deprivation rate(the rate by which the SUs are forced to evacuate the spectrum in case of the PU arrival). The work was extended to two PUs and $2N$ band by Patil et al. in [72]. In [73], Yao et al. represented a CTMC model that takes into consideration the effect of SU's sensing error and its effect on the PU QoS. The optimal access probability was calculated and the effect of SU buffers on the achieved throughput was shown.

Authors of [74] developed a CTMC model for interweave spectrum sharing scenario where in addition to the Primary Channel (PC) that SU can share there are number of unshared Secondary Channels (SCs) dedicated to the SUs usage. The performance of the system was evaluated in terms of SU call blocking and dropping probabilities. The model provided an accurate estimation of maximum Number of Secondary User Per Second (NSPS).

In [25], Wang et al. proposed a prioritized Markov chain to model the interaction between the PU and more than one SU which can access the PU's vacant spectrum simultaneously. The authors optimized the access probabilities of the Markov chain to achieve fairness among the SUs. The evaluation showed that the proposed scheme achieves higher throughput than the carrier sense multiple access (CSMA) scheme. Ngallemo et al. in [26] computed the coexistence probability between the PU and multiple SUs under an interference constraint in underlay sharing scheme. Nair et al. [39] used overlay and underlay hybrid spectrum sharing, low-complexity access model that improved the SU's throughput.

As discussed in Chapter 1, cooperative relaying can be more efficient in utilizing the available white spaces in the licensed spectrum better than direct transmission(DT) as it uses two hops transmission. Each of the two time slots consumes smaller time than the DT, and the relay can buffer the data after the first hop in case that the PU appeared again. After the PU become idle, it is only required to transmit the second hop by the relay instead of retransmitting the data all over again as in the case of DT.

In this chapter, the interaction between the PU and the SU in a slotted access with interweave spectrum sharing is modeled. Here, we considered a passive relay that does not transmit its own packets and do not ask for a price for its help.

The effect of using cooperative relaying by the SUs on the spectrum occupancy is analyzed using DTMC and the spectrum occupancy distribution of the SU is computed. Moreover, the effect of the SUs cooperation levels on the achieved throughput is evaluated.

## 4.2 System Model

In this section, details are provided about the system model including the PU and SU activity models and the medium access mechanism. The communication model consists of one PU and one SU[2]. The SU wants to gain access to the unused spectrum in interweave sharing scheme. The PU and the SU use synchronized slotted MAC to access the spectrum, where the data transmission time spans an integer number $M$ of time slots. The SU is assumed to be equipped with an efficient sensing capability to detect the presence of the PU at the beginning of every time slot and evacuate the medium immediately to avoid interfering the PU's transmission. The SU can use direct transmission (DT) or cooperative communication by using the help of a secondary relay.

In the cooperation mode, the SU employs Decode and Forward (DF) cooperative communication technique. In this mode, the SU first transmits its data to an intermediate relay using rate $R_{sr}$ in transmission time $T_{sr}$. The relay decodes the data then forwards it to the final destination using rate $R_{rd}$ in transmission time $T_{rd}$. Neglecting the decoding time, the overall transmission time and data rate are given by equations (4.1) and (4.2) respectively [40].

$$T_{CC} = T_{sr} + T_{rd}, \tag{4.1}$$

and subsequently,

$$\frac{1}{R_{CC}} = \frac{1}{R_{sd}} = \frac{1}{R_{sr}} + \frac{1}{R_{rd}}. \tag{4.2}$$

## 4.3 PU/SU Interaction DTMC Model

In this section we present and discuss the DTMC models of the interaction between the PU and the SU in cooperative and non-cooperative modes[3]. From the DTMC models different performance metrics like throughput and efficiency can obtained at different PU and SU activities and packet size ratio.

### 4.3.1 Stand-alone Models

First, we model the PU and SU transmissions separately using "stand-alone" DTMCs. Stand-alone means that the PU and the SU behave independent of each other. Every state in the DTMC represents one time slot[4]. The state space of the stand-alone DTMC consists of one idle state (denoted by $I$) and $M$ active states (denoted by $A_1, A_2, \ldots, A_M$), where $M$

[2] our model assumes the existence of a passive relay that does not transmit packets for itself

[3] Cooperative or non-cooperative mode refer to the cooperation between the secondary user and the relay.

[4] In this paper, we use the words 'state' and 'time slot' interchangeably.

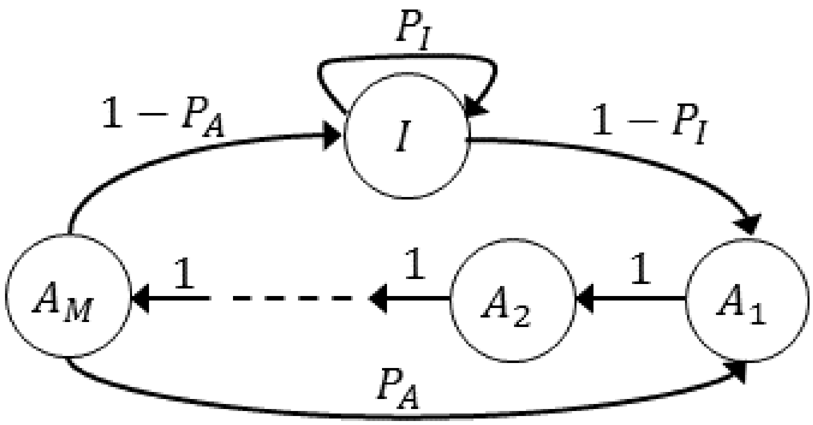



Figure 4.1: Stand-alone Markov chains for PU and SU when transmission consumes $M$ time slots.

is the number of time slots required to transmit a certain packet. In Fig 4.1, we depict the stand alone DTMC for $M$ states followed by both, the PU and SU.

The steady-state occupancy distribution, denoted by $\boldsymbol{\pi}$, can be derived from the transition diagram of the DTMC (shown in Figure 4.1). The steady-state probability of being in state $j \in \{A_1, A_2, \ldots, A_M, I\}$, denoted by $\pi_j$, represents the percentage of time the given user (PU or SU) stays in state $j$. Because the DTMC is irreducible, $\boldsymbol{\pi}$ is obtained by solving the following two equations [75]:

$$\boldsymbol{\pi} = \boldsymbol{\pi} \times \boldsymbol{P}, \tag{4.3}$$

$$1 = \boldsymbol{\pi} \times \mathbf{1}, \tag{4.4}$$

where $\boldsymbol{\pi} = [\pi_{A_1}, \ldots, \pi_{A_M} \pi_I]$, $\boldsymbol{P}$ is the $(M+1) \times (M+1)$ transition probability matrix, and $\mathbf{1} = [1, 1, \ldots, 1]_{(M+1)\times 1}$. Let $\pi_A \stackrel{\text{def}}{=} \sum_{i=1}^{M} \pi_{A_i}$, then $\pi_I = 1 - \pi_A$, and $M = (N-1)$, the values of $P_A$ and $P_I$ are calculated by solving equations (4.3) and (4.4) giving that $(\pi_I = 1 - \pi_A)$. The value of $P_A$ is chosen to satisfy equation (4.5) and $P_I$ is calculated by substituting the value of $P_A$ in (4.6)[5].

$$1 \geq P_A \geq 1 - \frac{M(1-\pi_A)}{\pi_A} \tag{4.5}$$

$$P_I = 1 - \frac{\pi_A(1-P_A)}{M(1-\pi_A)}. \tag{4.6}$$

The values of $P_A$ and $P_I$ will be used to calculate the transition probabilities of the interaction DTMC in the next sections.

[5]Profs of (4.5) and (4.6) are provided in appendix A

$$\boldsymbol{P} = \begin{array}{c} \\ II \\ AI \\ A_2I \\ A_2I^* \\ AA^* \\ IA \\ IA_2 \end{array} \begin{array}{ccccccc} II & AI & A_2I & A_2I^* & AA^* & IA & IA_2 \\ \hline P_{(PU_I)}.P_{(SU_I)} & \left(1-P_{(PU_I)}\right).P_{(SU_I)} & 0 & 0 & \left(1-P_{(PU_I)}\right).\left(1-P_{(SU_I)}\right) & P_{(PU_I)}.\left(1-P_{(SU_I)}\right) & 0 \\ 0 & 0 & P_{(SU_I)} & \left(1-P_{(SU_I)}\right) & 0 & 0 & 0 \\ \left(1-P_{(PU_A)}\right).P_{(SU_I)} & P_{(PU_A)}.P_{(SU_I)} & 0 & 0 & P_{(PU_A)}.\left(1-P_{(SU_I)}\right) & \left(1-P_{(PU_A)}\right).\left(1-P_{(SU_I)}\right) & 0 \\ 0 & 0 & 0 & 0 & P_{(PU_A)} & \left(1-P_{(PU_A)}\right) & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & \left(1-P_{(PU_I)}\right) & 0 & P_{(PU_I)} \\ P_{(PU_I)}.\left(1-P_{(SU_A)}\right) & \left(1-P_{(PU_I)}\right).\left(1-P_{(SU_A)}\right) & 0 & 0 & \left(1-P_{(PU_I)}\right).P_{(SU_A)} & P_{(PU_I)}.P_{(SU_A)} & 0 \end{array} \quad (4.7)$$

### 4.3.2 PU and SU Interaction DTMC Model

In this section, the DTMC models for PU-SU interaction for both SUs cooperative and non-cooperative modes in an interweave spectrum sharing scheme are presented. The interaction DTMC consists of $N$ states representing all possible cases resulted from the interaction between the PU and SU stand alone DTMCs. Again, each state represents one time slot and each state is represented by the two letters $(XY)$ where $X$ represents the PU's status and $Y$ represents the SU's status.

As an example, state $II$ means that both the PU and the SU are idle. The DTMC moves from state $II$ to state $AI$ if in the next time slot, the PU becomes active with transition probability $(1 - P_{(PU_I)})$ and the SU remains idle with probability $P_{(SU_I)}$, where $P_{(PU_I)}$ is the stand alone idle transition probability of the PU and $P_{(SU_I)}$ is the stand alone SU's idle state transition probability calculated by equations (4.5) and (4.6). Subsequently, the transition probability from $II$ to $AI$ equals $(1 - P_{(PU_I)}).P_{(SU_I)}$

#### Non-cooperative PU-SU DTMC Model

Fig. 4.2 shows a 7 states DTMC that represents the interaction between PU and non-cooperative SU. In this DTMC, $M_{PU} = M_{SU} = 2$ which means that both the SU and PU transmission spans two time slots. The SU can buffer up to one packet only.

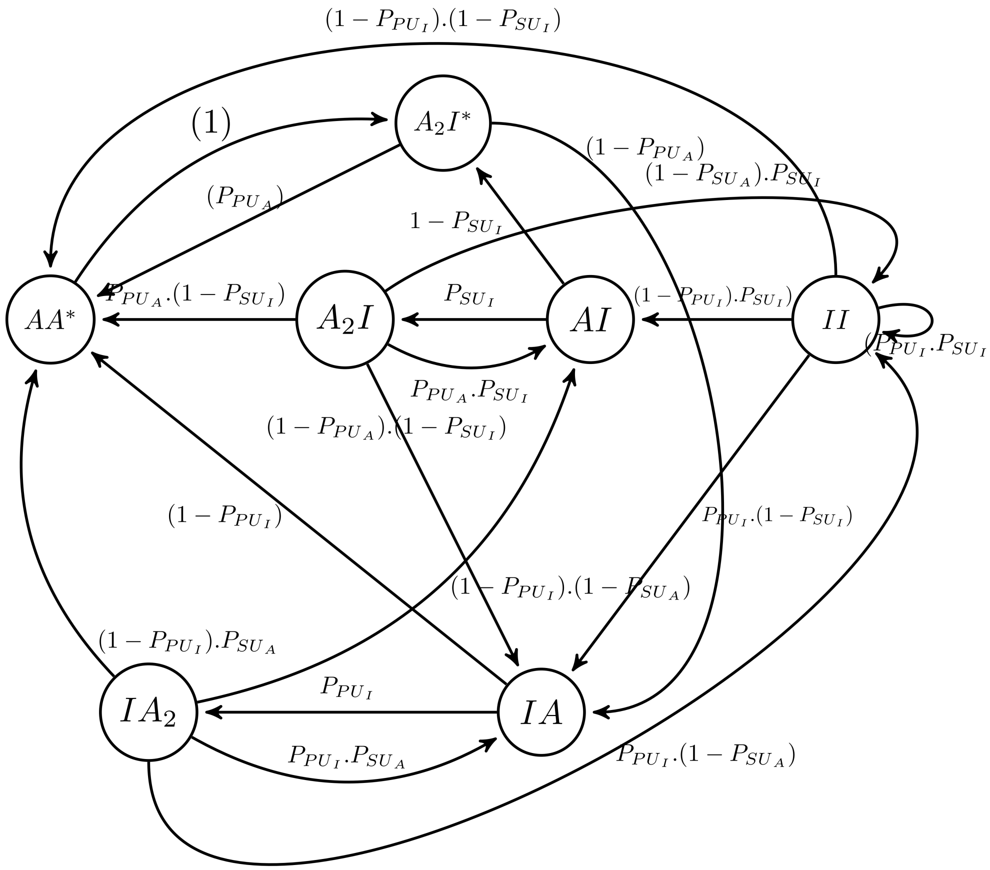



Figure 4.2: DTMC for PU/SU interaction in non-cooperative mode with $M = 2$.

In the SU non-cooperative mode, both the PU and SU need two consecutive time slots to send their data. Starting from state $II$, the DTMC remains in the same state for the next time slot or moves to one of the following states $AI$, $IA$ or $AA^*$. State $AI$ means that the PU is active by transmitting the first half of its data while the SU is idle. From state $AI$, the DTMC moves to $A_2I$ or $A_2I^*$. In both states, the PU remains active as they represent the second slot needed to transmit the PU's data (assuming $M = 2$). However, state $A_2I$ means that the SU stays idle as the previous state, but state $A_2I^*$ means that SU has data to transmit but con not turn to active state as it senses that the PU is still active. Thus, it buffers the data and stays idle. State $AA^*$ means that both the PU and SU moved to the active state, but as the SU detects the presence of the PU at the beginning of the time slot, it buffers the data and remains idle waiting for the PU to the move to idle state. From state $AA^*$, the DTMC can move only to state $A_2I^*$. The DTMC moves from $A_2I^*$ to $AA^*$ if the PU is active again with transition probability $P_{(PU_A)}$ or moves to $IA$ if the PU becomes idle with transition probability $1 - P_{(PU_A)}$. If the DTMC moves to state $IA$, it means that the SU transmitted half of the data without being interrupted by the PU. In the next time slot, there is a probability of $P_{(PU_I)}$ that the SU successfully completes the transmission by moving to state $IA_2$. Otherwise, it moves to state $AA^*$ and loses the transmission due to the PU's presence with the probability of $1 - P_{(PU_I)}$. The SU will successfully transmit its data only if it moves directly from state $IA$ to state $IA_2$.

The transition probability matrix $\boldsymbol{P}$ for the DTMC shown in Fig. 4.2 is given by equation (4.7). By substituting the value of the transition matrix $\boldsymbol{P}$ into equation (4.3), where $\hat{\boldsymbol{\pi}} = [\hat{\pi}_{II}\ \hat{\pi}_{AI}\ \hat{\pi}_{A_2I}\ \hat{\pi}_{A_2I^*}\ \hat{\pi}_{AA^*}\ \hat{\pi}_{IA}\ \hat{\pi}_{IA_2}]$ and solving equations (4.3) and (4.4), the occupancy distribution for different states can be calculated. The overall PUs active state occupancy distribution $\hat{\pi}_{PU_A}$ is calculated by summing over all states when the PU is active[6].

$$\hat{\pi}_{PU_A} = \hat{\pi}_{AI} + \hat{\pi}_{A_2I} + \hat{\pi}_{A_2I^*} + \hat{\pi}_{AA^*} \tag{4.8}$$

The value of $\hat{\pi}_{PU_A}$ must be equal to the active state occupancy distribution of the PU stand alone DTMC. The SUs active state occupancy distribution $\hat{\pi}_{SU_A}$ is equal to the sum of the distributions of state $IA_2$ and state $IA$ that comes directly before $IA_2$, or equivalently twice the distribution of state $IA_2$.

$$\hat{\pi}_{SU_A} = 2\ \hat{\pi}_{IA_2}. \tag{4.9}$$

This value should be less than that of the SUs stand alone DTMC counterpart due to the lost packets resulted from the presence of the PU. The difference between $\hat{\pi}_{IA}$ and $\hat{\pi}_{IA_2}$ gives the distribution of the states the SU wasted in unsuccessful transmissions.

### Cooperative PU-SU DTMC Model

Fig. 4.3 represents a 9 states DTMC for PU and cooperative SU interaction. The main difference between this DTMC and the non-cooperative SUs DTMC is that, in cooperative SUs DTMC, when the DTMC reached state $IA$ that means that the SU has successfully forwarded the data to the relay(s) in first time slot. In the next state, if the PU becomes active, the SU relay(s) will wait until the spectrum is free (PU is idle) and forward the data to the final destination in the next time slot (state $IA_2$ ) without the need to retransmit the data again. The PU and SUs active states occupancy distribution are calculated in the same way as in the previous case where $\hat{\pi}_{PU_A}$ equals to:

$$\hat{\pi}_{PU_A} = \hat{\pi}_{AI} + \hat{\pi}_{A_2I} + \hat{\pi}_{A_2I^*} + \hat{\pi}_{AA^*} + \hat{\pi}_{\overline{A_2I^*}} + \hat{\pi}_{\overline{AA^*}} \tag{4.10}$$

and $\hat{\pi}_{SU_A}$ equals to:

$$\hat{\pi}_{SU_A} = \hat{\pi}_{IA} + \hat{\pi}_{IA_2} \tag{4.11}$$

[6] We will refere to the PU active state occupancy distribution by the term "PU activity" and the symbol ($\rho$).

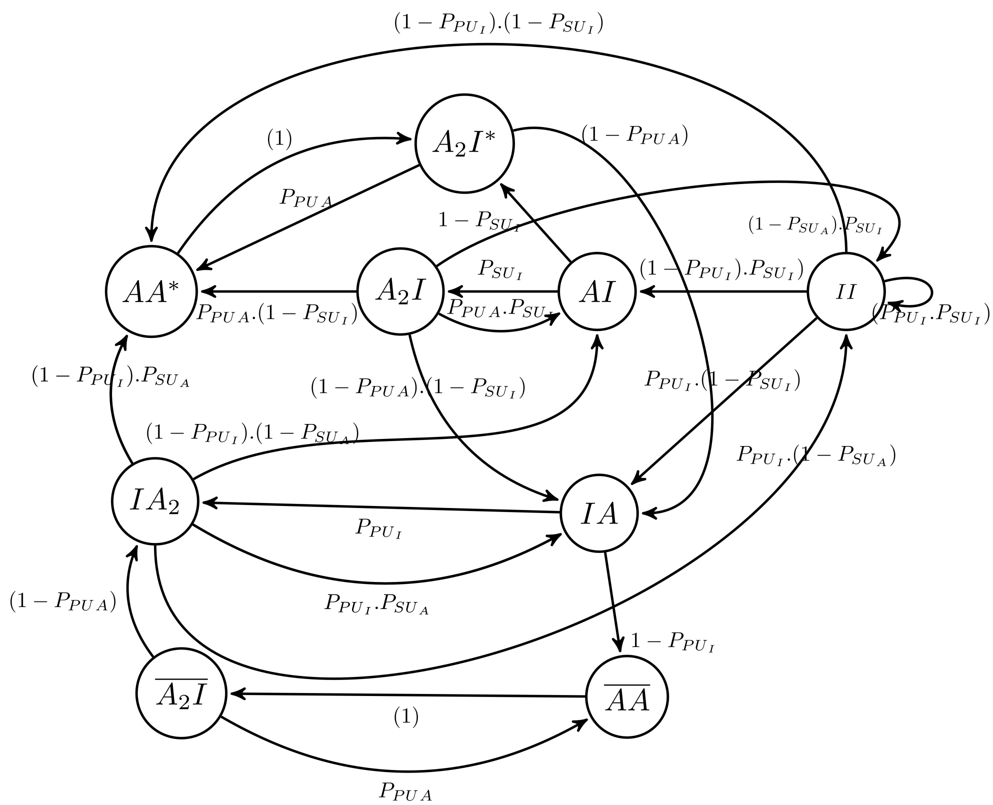



Figure 4.3: DTMC for PU/SU interaction in cooperative mode with $M = 2$.

### 4.3.3 Various SU cooperation levels DTMC model

In this section, different SUs cooperation levels are modeled using DTMC. In the previous section, the SUs cooperative transmission was modeled such that it consumes the same number of time slots as the Direct Transmission (DT). However, one of the main goals of cooperative communication techniques is to decrease the transmission time by increasing the overall throughput. This goal is fulfilled if $R_{CC} > R_{DT}$ where $R_{CC}$ is the overall cooperative data rate in equation (4.2) and $R_{DT}$ is the DT rate. As an example, if the DT rate $R_{DT} = 6Mbit/sec$ and the cooperative rates are $R_{sr} = 24Mbit/sec$ and $R_{rd} = 12Mbit/sec$, the cooperative transmission will achieve a higher overall throughput than that of the DT as $R_{CC} = 8Mbit/sec > R_{DT}$.

Fig. 4.4 shows DTMC for cooperative SUs and PU interaction model corresponding to the previous example. The stand alone SU's DTMC is modeled with three active states $M_{SU} = 3$. Without loss of generality, It is assumed that $M_{SU} = 3$ means that the transmission from the SU source to the relay(s) consumes two time slots and the transmission from the relay(s) to the destination consumes one time slot. The PUs stand alone DTMC is modeled with

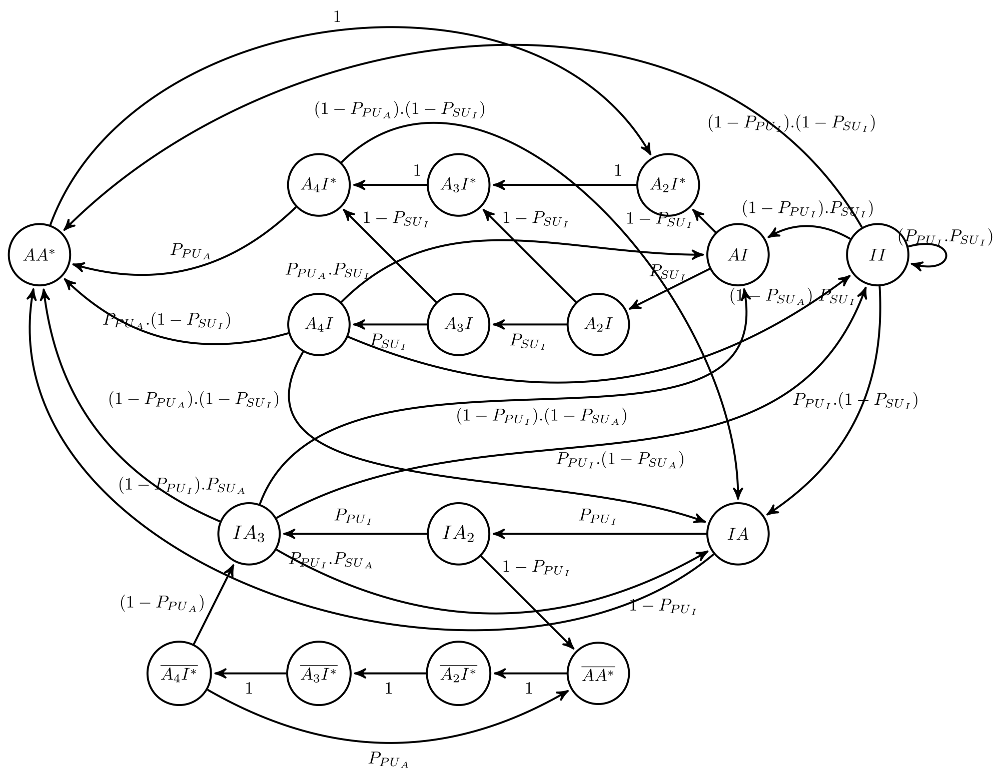



Figure 4.4: DTMC for cooperative SU/ PU interaction with $M_{SU} = 3$ and $M_{PU} = 4$.

four active states $M_{PU} = 4$ which means that the PU sends its data in four consecutive time slots. The same method will be used to model other levels of cooperation between SUs in the results section.

## 4.4 Performance Evaluation

In this section, the effect of SUs cooperation on the spectrum occupancy and the throughput performance of different cooperation levels are evaluated and discussed.

### 4.4.1 SU Spectrum Occupancy Ratio

In this section, the SUs spectrum occupancy ratio with and without cooperation are compared. The DTMC models are those shown in Fig. 4.2 and Fig. 4.3 with $M_{PU} = M_{SU} = 2$ in both cases. The occupancy ratio is evaluated against the SU activity (SU stand alone spectrum occupancy ratio) at different PU spectrum occupancy ratios.

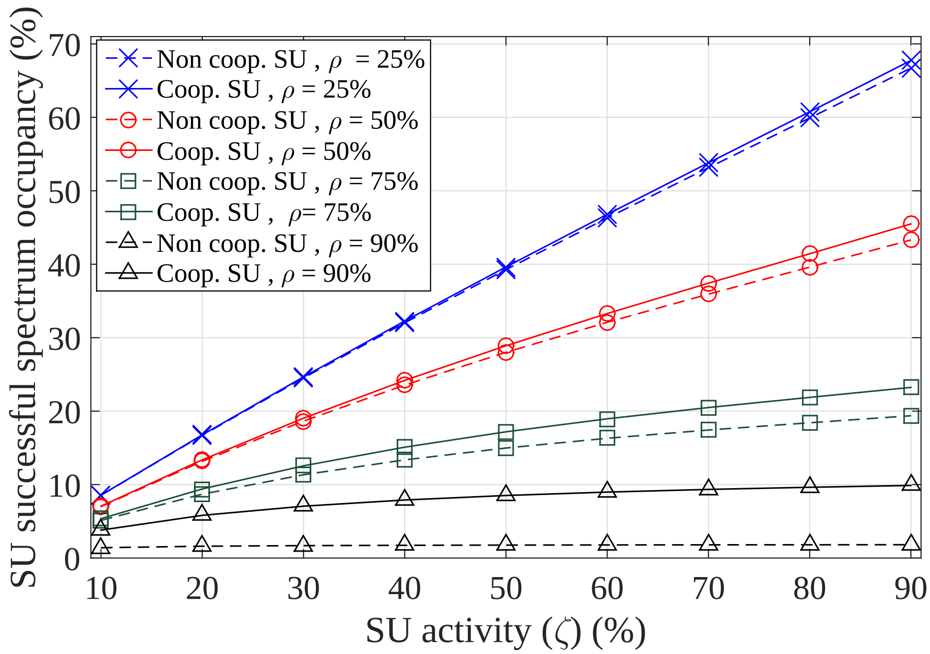



Figure 4.5: SU successful spectrum occupancy.

Fig. 4.5 shows the performance of the SUs' spectrum occupancy. From the figure, it can be noticed that at low PU's activity the difference between the cooperative and non-cooperative SU occupancy ratio is very small as the SUs do not face frequent interruption by the PU. As the PU's activity increases, the effect of cooperation becomes more noticeable as the cooperative transmission efficiently utilizes the spectrum holes. For high PU's activity, the SU without cooperation has no opportunity to access the spectrum for the PU activity of 90%.

### 4.4.2 The Effect of SUs Cooperation on The Achieved Throughput

This section measures the SUs' average normalized throughput performance at different levels of cooperation. The cooperation level is modeled by controlling the number of states required to transmit the data. For example, $M_{PU} = M_{SU} = 4$ means that both the PU and SU need 4 slots to transmit the data and $M_{SU} = 2$ means that the SU needs only two slots to transmit the data.

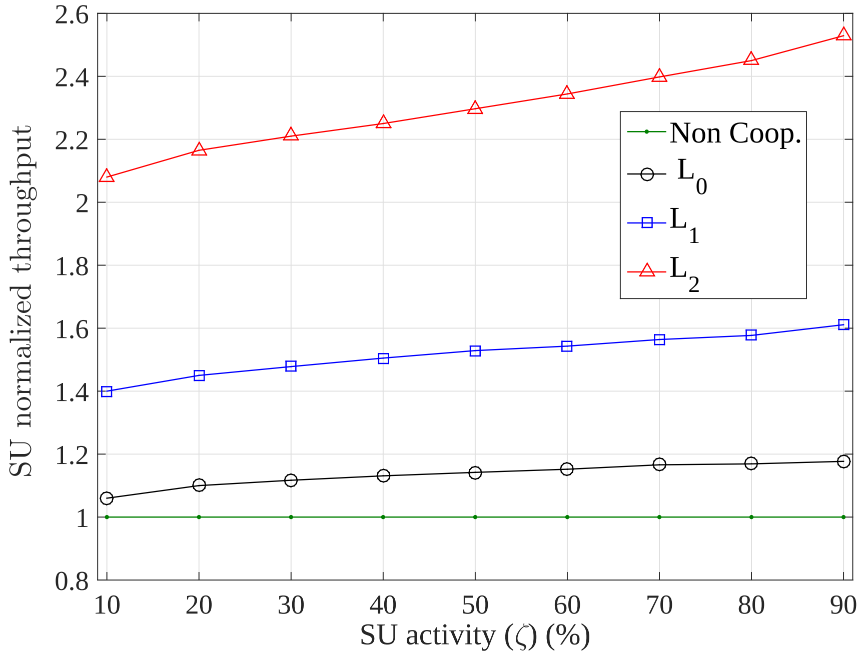



Figure 4.6: SU normalized throughput at different cooperation levels and PU activity ($\rho$) of 75%.

The following four levels of SU cooperation are used:

1. L0: cooperative relaying with $M_{PU} = M_{SU} = 4n$
2. L1: cooperative relaying with $M_{PU} = 4, M_{SU} = 3n$
3. L2: cooperative relaying with $M_{PU} = 4, M_{SU} = 2n$

where $n$ is a number that represents the DTMC time resolution. The performance is evaluated for PU spectrum occupancy ratio of 75%. The throughput of every cooperation level is normalized to the corresponding throughput of the non cooperative case to neutralize the throughput enhancement due to the SU activity $\zeta$ increase. As shown in Fig. 4.6, the slope of the normalized throughput increases as the SUs cooperation level increases. For example for L2, the normalized average throughput increases from nearly double that of the DT at low SU activity to achieve an additional 25% enhancement at high SU activity of 90%. This means that as the level of cooperation increases, the SU becomes more efficient in transmitting data through utilizing the available spectrum holes, and this is more noticeable at the crowded spectrum.

The SU spectrum occupancy ratio is evaluated at different PU's activity levels for different SU cooperation levels. Again, the results are normalized to the corresponding throughput of the non cooperative case. Fig. 4.7 shows the normalized SU's throughput at different PU activities. The results show significant enhancement due to cooperation, especially at high PU activity.

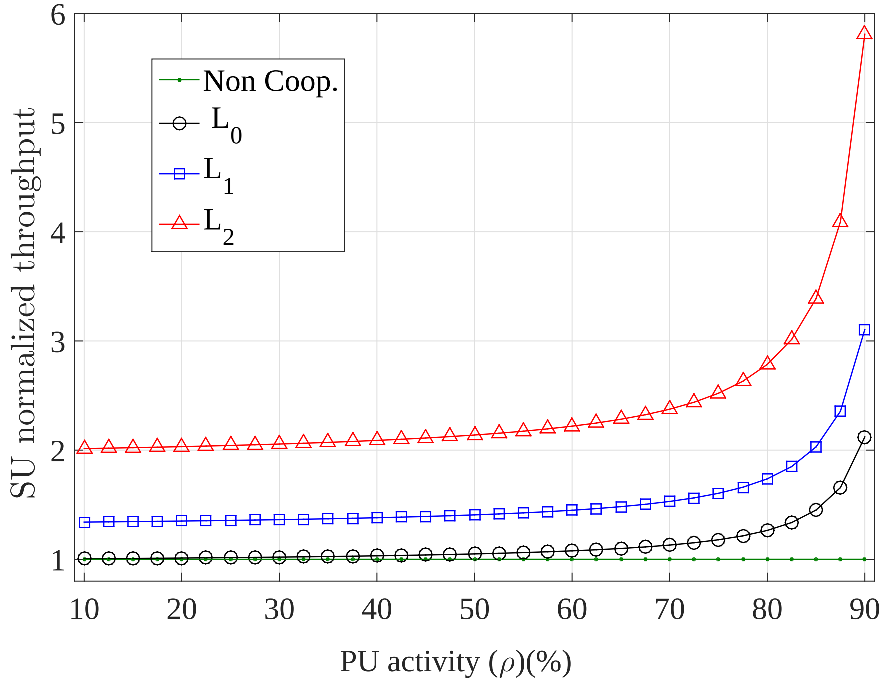



Figure 4.7: SU normalized throughput at different PU activity and SU activity of 90 %

### 4.4.3 The Effect of Number of time Slots Per Transmission

This section investigates the effect of number of time slots per data transmission. Fig. 4.8 shows the effect of time resolution on the spectrum occupancy of the SU. The results show that the effect of time resolution is mainly constant after $M = 20$

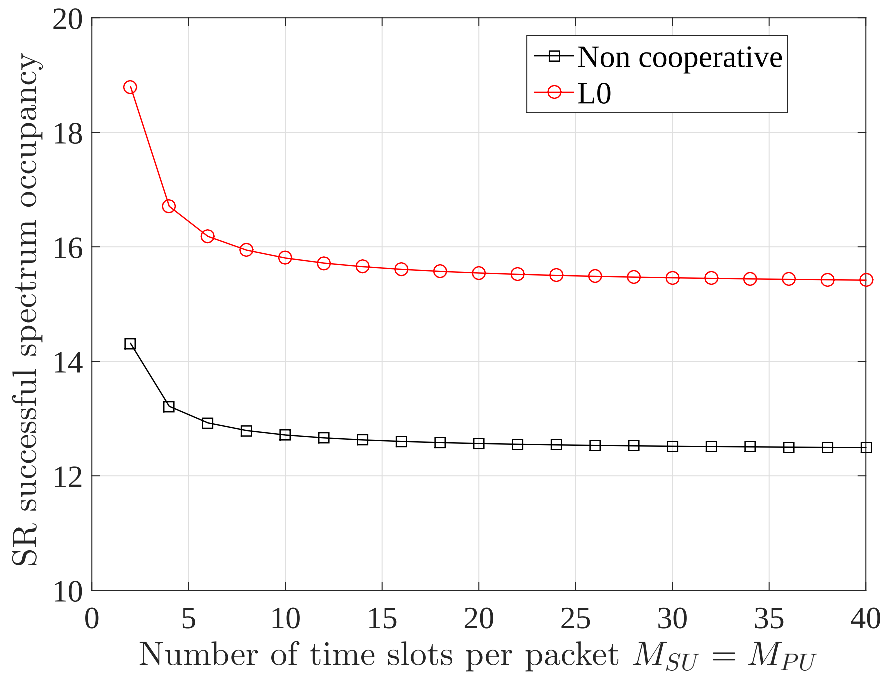



Figure 4.8: SU spectrum occupancy percentage at different time resolution for L1 cooperation and SU activity = 90 % and PU activity = 80%.

### 4.4.4 The Effect of PU/SU Packet Size Ratio on SU Throughput

In this experiment, the effect of the SU and PU's packets size on the SU throughput is studied. The SU's packet size is assumed to be constant and consumes 48 time slots while the PU's packet size is variable over the range $S_{pu} = \{12, 24, 36, 48, 60, 72, 84, 96\}$ time slots per packet. These configuration gives packet size ratios $\frac{PU}{SU}$ equals to $\{\frac{1}{4}, \frac{1}{2}, \frac{3}{4}, 1, \frac{5}{4}, \frac{6}{4}, \frac{7}{4}, 2\}$. The normalized throughput for the SU is calculated for the different cooperation levels at different PU activity levels $\rho$. The throughput normalization is done by dividing each cooperation level throughput by its non cooperative throughput.

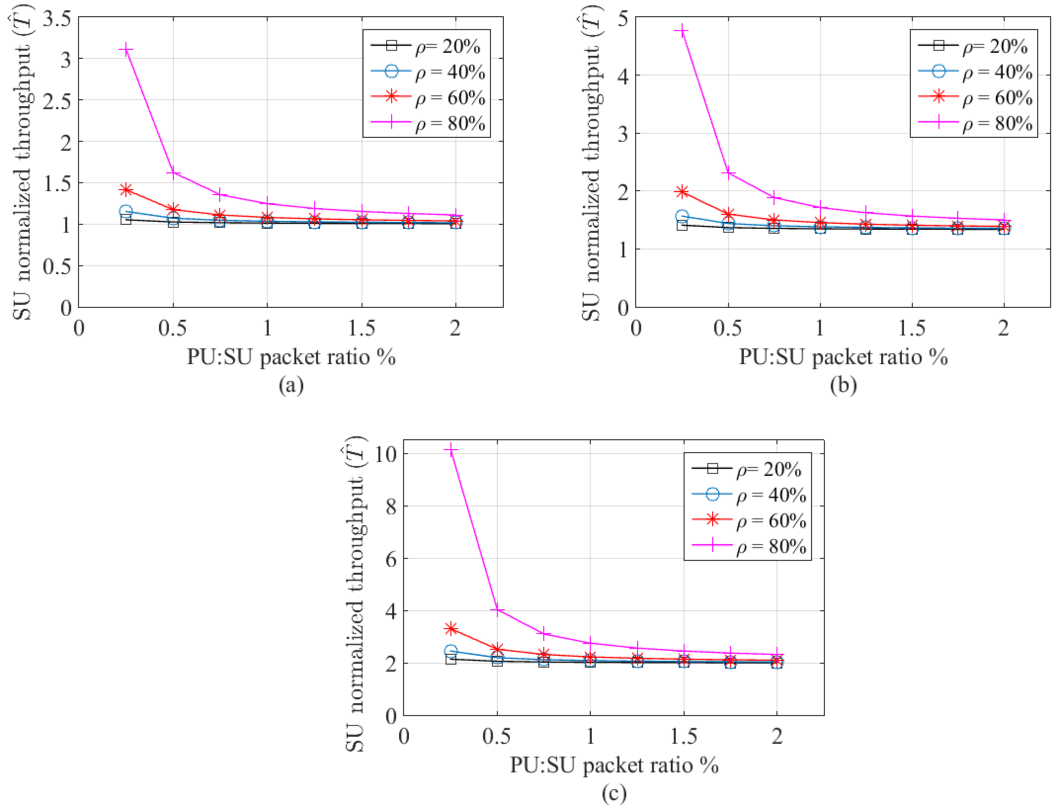



Figure 4.9: Effect of PU/SU's Packet Size on the SU's normalized Throughput at Different PU Activity for (a) L1 cooperation level, (b) L2 Cooperation level, (c) L3 Cooperation level

As can be inferred from Fig. 4.9, when the ratio $\frac{PU}{SU}$ is small, the cooperation is very beneficial and as the SU's packet size increases, the cooperation losses its power. The result can be justified as the following. When the PU's packet size is smaller than that of the SU, the PU frequent presence cause a harmful interruption to the SU's DT packet. However, using cooperation can mitigate this effect by sending the packet over two small transmission time hops. When the PU's packet is larger than that of the SU, the PU interruption is not harmful as before. That is because, for a given PU activity and with a large size PU's packet, the continuous time the PU remains idle is larger than that when the PU's packet is small.

## 4.5 Conclusion

This chapter studied the effect of using cooperative communication by the secondary users on the spectrum occupancy. Discrete time Markov chains were developed to model the interaction between the primary user and secondary user in a slotted access with interweave spectrum sharing scheme. The results show that the mechanism of sending the secondary transmissions using cooperative relaying is more efficient than the direct transmission in utilizing the licensed spectrum holes, especially at high levels of primary user activity where the secondary users opportunity to access the spectrum is limited. Furthermore, the effect of DTMC time resolution is investigated and results show that the time resolution has a negligible effect for $M \geq 20$.

# Chapter 5

# Analytical and Simulation Study of the Effect of Secondary User Cooperation on Infrastructure Cognitive Radio Networks

This chapter [1] presents an analytical and simulation study of the efficiency of using cooperative communication for Dynamic Spectrum Access (DSA) in secondary infrastructure networks. The licensed and unlicensed network transmissions are modeled using a Discrete Time Markov Chain (DTMC). The previous DTMC model is modified to include choosing between direct transmission and cooperative transmission according to the probability of finding a useful relay. The secondary network spectrum occupancy and throughput are evaluated analytically and by simulation. A COoperative and COgnitive MAC protocol ($CO^2MAC$) is developed to facilitate cooperative transmissions in secondary infrastructure networks. The results show significant performance enhancement for cooperative transmission over direct transmission, especially in the crowded spectrum where it achieves up to 80% enhancement in throughput compared to direct transmission.

## 5.1 Introduction

The previous chapter showed analytically that the mechanism of cooperative communication, in which data is sent over two high rate hops is more efficient in utilizing the shared spectrum than Direct Transmission (DT). This chapter studies the effect of SUs cooperation on the network throughput in secondary infrastructure networks. Interweave spectrum sharing scheme is used, where the SU can access the licensed spectrum only at the absence

[1] This chapter is based on work published in [76].

of the PU. A simple scenario represents the interaction between PU and Secondary Access Point (SAP) was modeled using DTMC and the analytical results are compared with those from the simulation of the same scenario. In order to facilitate the secondary network transmission. The $CO^2$MAC protocol was designed to operate in multi-channel secondary network environment and carries all the traditional MAC functions including sensing and media access, in addition to the selection of channel, relay(s) and transmission technique.

## 5.2 System Model

In this section, details are provided about the network model and transmission techniques used in this study.

*1) Network Model:* The network model is a secondary infrastructure network with a single SAP and a number of stationary SUs. The network lies under the coverage of one or more PUs. The network area is such that the SAP can transmit to any SU using at least the basic rate and vice versa. The transmission channels are assumed to be flat fading Rayleigh channels. The SAP is equipped with two antennas while the SU is equipped with a single antenna. Each SU has a powerful transceiver that is able to transmit or receive at different transmission schemes with different data rates using a set of modulation techniques. Also, the transceiver can sense the available spectrum bands and chooses between them to avoid interfering with the PUs. The SAP has a number of Radio Front-end (RF) chains to handle transmissions over multiple channels simultaneously. The control messages are exchanged over a dedicated Common Control Channel (CCC) where each node has a dedicated transceiver tuned at this channel. It is assumed that nodes can estimate their Channel State Information (CSI) through embedded pilot tones in the data packets.

*2) Transmission Techniques:* SAP and SUs utilize number of cooperative and multi-antenna transmission systems. As shown in 5.1(a), when SUs use DT to transmit data to the SAP in the uplink direction, the SAP uses 2x1 Maximum Ratio Combining (MRC). In the DT downlink direction, the SAP uses 2x1 Alamouti STBC. The transmitting power for each antenna is adjusted such that the average DT ranges are the same for uplink and downlink directions.

A relay or two can be used to forward the data to the final destination if the direct channel between the SAP and the SU does not support high data rates. The Decode and Forward (DF) form of cooperative communication is used where, the relay(s) fully decode the source data then re-encode it before transmitting it to the final destination. As shown in Fig. 5.1 (b), if only one relay is used in the uplink direction, the SU sends the data to the relay using SISO transmission then, the relay re-forwards the data to the SAP that uses MRC to receive the data. For the downlink direction, the SAP uses 2x1 Alamouti STBC in the first hop, then the relay uses SISO in the second hop.

In the case of using two relays as shown in Fig. 5.1 (c), the two relays will mimic multi-

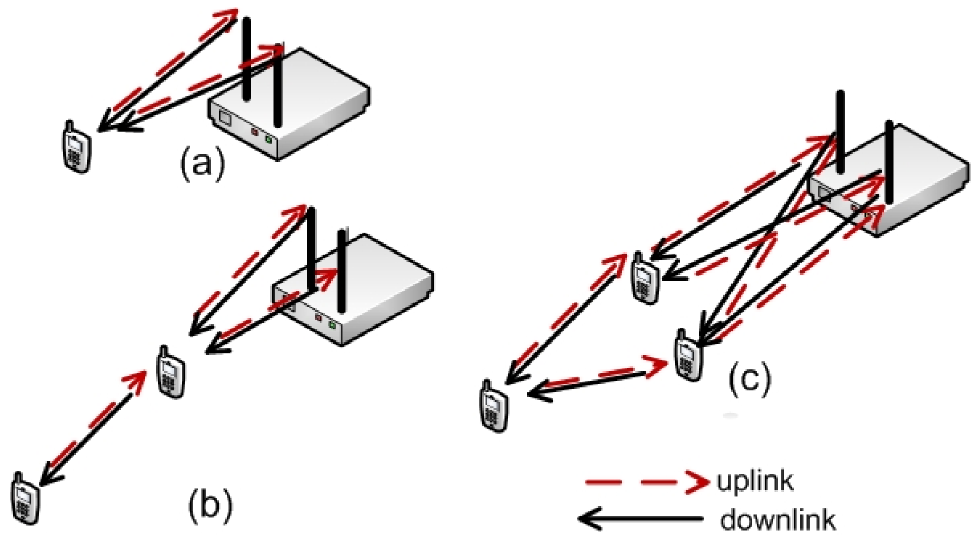



Figure 5.1: Different transmission techniques.

antenna system. In the uplink direction, each relay will receive the data from the sender in SISO transmission, and then the two relays will jointly transmit the data using 2x2 Alamouti STBC to the SAP. In the downlink direction, the first hop will be 2x1 Alamouti STBC then the two relays will jointly re-forward the data to the user node using 2x1 Alamouti STBC.

Cooperative communication is used to increase the transmission rate higher than that achieved by DT. By using cooperative communication, the source first transmits the data packet to the relay(s) using data rate equals to $R_{sr}$ and then the relay(s) re-forwards the data to the destination with data rate equals to $R_{rd}$. The net data rate for the two-hop communication is equal to:

$$R_{CC} = \frac{1}{R_{sr}^{-1} + R_{rd}^{-1}}. \tag{5.1}$$

Cooperative communications can be beneficial if the net data rate for the two hop communication is higher than that of DT.

## 5.3 Network DTMC model

In this section, the DTMC model for a simple scenario representing the interaction between the SAP and the PU is developed. The scenario consists of a SAP that shares the licensed media with a PU in interweave scheme. The SAP is assumed to be able to transmit to SUs using a DT with rate $R_{DT}$ or over two hops using an intermediate relay with rates $2R_{DT}$ and $4R_{DT}$ in the first and second hop, respectively. The medium access scheme is assumed to be slotted access and the PU and SAP are synchronized. The SAP senses the medium at the beginning of every time slot and evacuates the medium immediately if it detects the presence of the PU. The SAP is assumed to be able to buffer only one packet to transmit and ignores any packet if the buffer is full. By modeling the PU-SAP interaction, the time the SAP can access the medium and successfully transmit packets is determined and consequently, the average throughput can be calculated.

First, the PU and the SAP activities were modeled separately using two separate stand alone DTMC as described in Chapter 4. Then the interaction between the PU and the SU is modeled using the probabilities driven from the stand alone DTMC. In the interaction model between the PU and SU, we assume that both the PU and SU direct transmission consumes $M = 4n$ time slots, while the SU cooperative transmission consumes $3n$ time slots.

The transition diagram shown in Fig. 5.2 represents the interaction model between the PU and the SAP when $n = 1$. Each state is labeled by two letters $(XY)$, where, $X$ represents the PU status and $Y$ represents the SAP status. The dashed line states are shortcuts to the original states to simplify the transition diagram connections. It is assumed that the DT of both the PU and SAP spans four time slots (states) and by cooperation, the SAP transmission spans three time slots over the two hops. The transition probability from one state to another is calculated by the interaction between the two stand alone DTMCs of the PU and SAP. For example, to move from state $(II)$ to state $(AI)$, this implies that the PU moves from state $(I)$ to $(A)$ state and the SAP remains in the state $(I)$. This transition occurs with probability equals to $(1 - P_{PU_I}).P_{SU_I}$.

The interaction DTMC consists of five sets of states divided according to the PU and SAP status as shown on Fig. 5.2 . States set (0) contains only state $(II)$ where both the SAP and PU are idle. Starting from state $(II)$ in set (0), the DTMC can move to set (1) where the PU will be active at the first time slot. The DTMC can enter set (1) through state $(AI)$ if the SAP remained Idle or to state $(AA^*)$ if the SAP tried to access the spectrum in the same time of the PU. In the last case, the SAP will buffer the data and remain Idle waiting for the PU to finish its transmission. The DTMC in set (1) can move through two branches, one with states labeled $(A_xI)$ where $x = 2, 3$ or 4 if the SAP remains idle during the PU transmission. If the DTMC reached $(A_4I)$ it can move to any set according to the status of the PU and SAP in the next state. The DTMC can go through the other branch with states labeled $(A_xI^*)$ if at any state the SAP has a packet ready to be transmitted. In the last case, SAP will wait till the PU finished its transmission at state $(A_4I^*)$ to start its own transmission. After the PU finished its transmission, the SAP will try to send the buffered packet, however if the PU decides to transmit another packet, the DTMC will move to set (1) through state $(AA^*)$. If the PU becomes idle, the DTMC will move to set (2) through state $(IA_d)$ or to set (3) through state $(IA_r)$ according to the SAP decision of using relay cooperation or not.

If the SAP decides to use DT while the PU remained Idle, the DTMC will move to set(2).

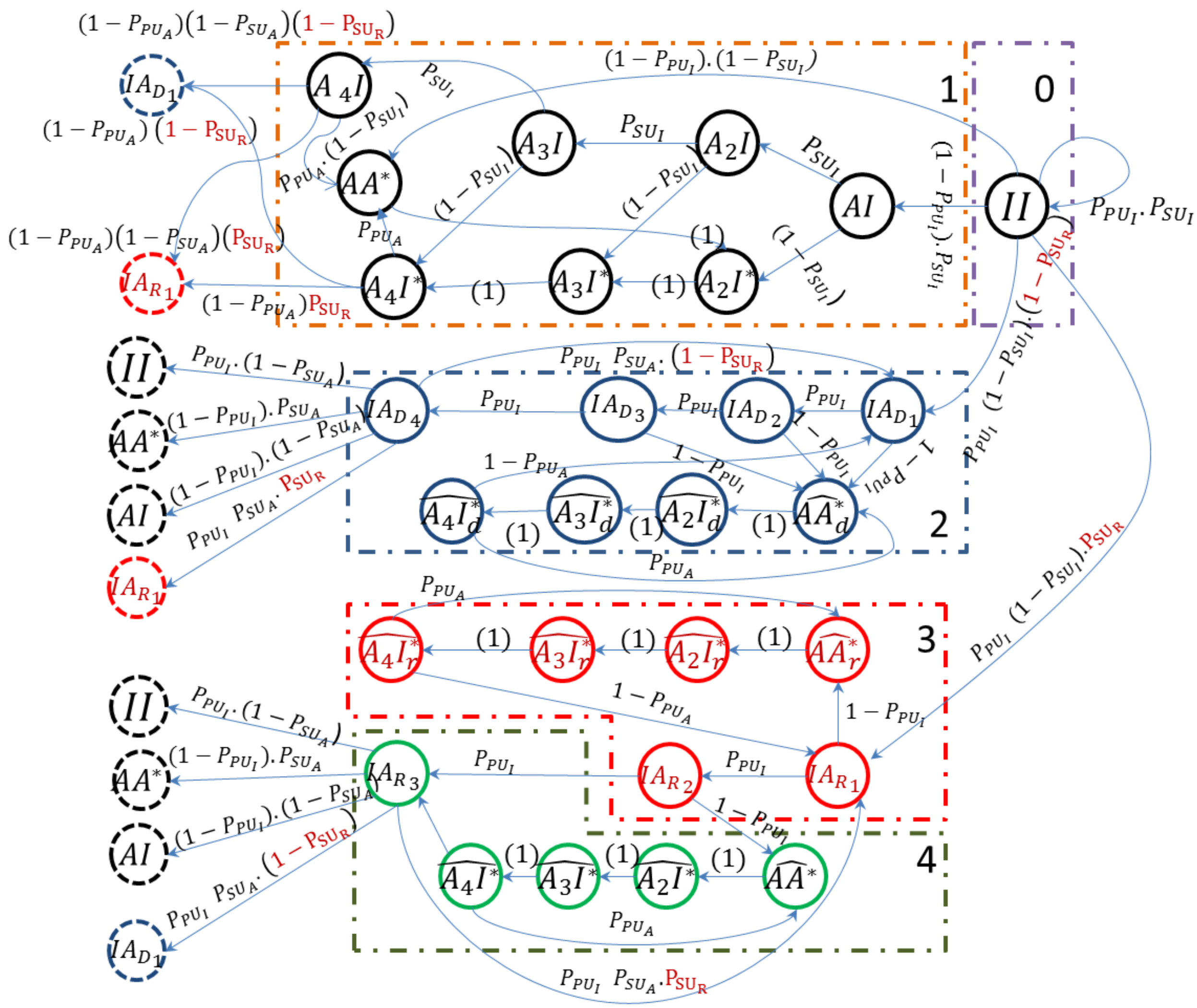



Figure 5.2: DTMC model for PU and SU interaction in infrastructure network for $n = 1$.

The SAP will start its DT that consumes four time slots from state $(IA_{d1})$ to $(IA_{d4})$. If at any transitions the PU becomes active, the DTMC will move to state $(AA_d^*)$ and the SAP has to wait until the PU finished its transmission then start again from state $(IA_{d1})$. The SAP transmission will be successful only if the DTMC moved from $(IA_{d1})$ to $(IA_{d4})$ without any interruption. If the SAP decides to use relayed transmission, the DTMC will move to set (3) through state $(IA_{r1})$. In this case, the transmission will be done over two hops, the first consumes two consecutive time slots that has to be done without any PU interruption and the second consumes one time slot. If the SAP successfully transmits the first transmission without PU interruption, the DTMC will move to set(4) for the second hop transmission. The relay will forward the data to the final destination through one time slot and if the PU appears the relay will wait until the PU finishes transmission then try to retransmit the relayed data without the need to retransmit the first hop again.

The transition probability matrix $\boldsymbol{P}$ can be constructed using the transition probabilities shown in Fig. 5.2 By substituting the value of $\boldsymbol{P}$ into equation (4.3), and solving equations (4.3) and (4.4), the occupancy distribution for different states can be calculated. The overall PU active state occupancy distribution $\hat{\pi}_{PU_A}$ can be calculated by summing over all active states of the PU in the different sets.

The successful SAP active state occupancy distribution $\hat{\pi}_{SU_A}$ equals to the summation of the successful states occupancy distribution which equals to,

$$\hat{\pi}_{SU_A} = 4n\ ot\hat{\pi}_{IA_{d4}} + 2n\ \hat{\pi}_{IA_{r2}} + n\ \hat{\pi}_{IA_{r1}}, \tag{5.2}$$

where successful means that the transmissions in this occupancy time were completed without PU interruption. The occupancy distribution can be translated to average throughput $R_{SAP}$ by multiplying each occupancy distribution by the corresponding rate

$$R_{SAP} = (4n\ \hat{\pi}_{IA_{d4}})\ R_{DT} + (2n\ \hat{\pi}_{IA_{r2}} + n\ ot\hat{\pi}_{IA_{r1}})\ \frac{2R_{DT}\ 4R_{DT}}{2R_{DT} + 4R_{DT}}. \tag{5.3}$$

The previous DTMC can model the case when the SAP decided to use only DT by setting $P_{SU_R}$ to zero or, to choose between DT and relayed transmission according to the value of $P_{SU_R}$.
The probability of finding a relay $P_{SU_R}$ depends on the nodes density and the intersection area of the two ranges of the cooperative transmissions. Fig. 5.3 represents a SU located at distance $d$ from the SAP. The circle with radius $R_1$ represents the transmission range of the first hop from SAP and $R_2$ represents the transmission range of the second hop but the center is moved to the SU's position to show the potential relays position. The shaded area represents the intersection between the two transmissions ranges and consequently the area of potential relays. From the shape geometry the intersection area of the two circles consists

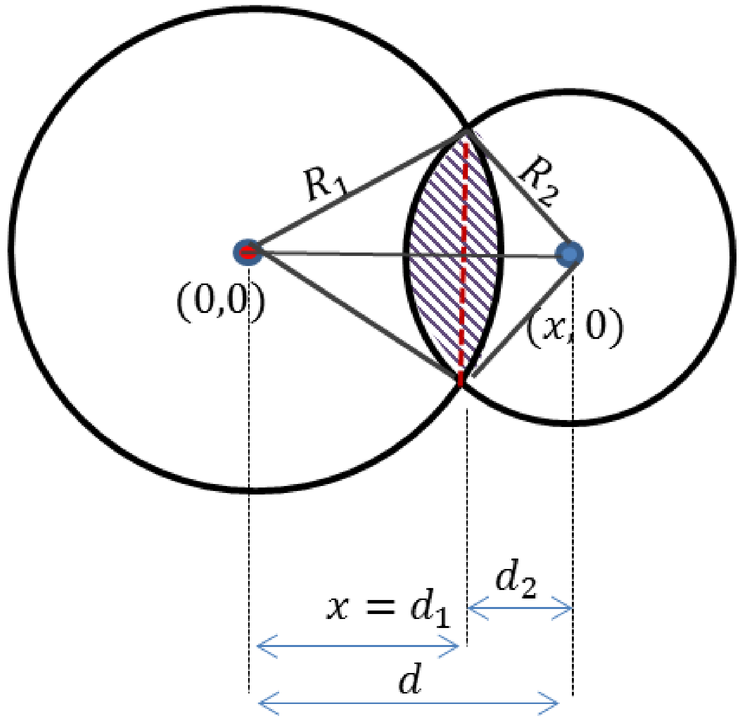



Figure 5.3: Intersection area of potential relays.

of the area of two half lenses which can be expressed as [77]

$$A_{(d,R_1,R_2)} = R_1^2\, cos^{-1}\left(\frac{d_1}{R_1}\right) - d_1\sqrt{R_1^2 - d_1^2} + R_2^2\, cos^{-1}\left(\frac{d_2}{R_2}\right) - d_2\sqrt{R_2^2 - d_2^2}, \quad (5.4)$$

where $d_1 = \frac{d^2+R_1^2-R_2^2}{2d}$ and $d_2 = \frac{d^2-R_1^2+R_2^2}{2d}$.
As the position of the SU can be anywhere between $x_{min}$ and $x_{max}$ and assuming the SU are uniformly distributed in a circular area centered at the SAP, the expected value of the intersection area can be calculated as.

$$E\left(A\right) = \int_{x_{min}}^{x_{max}} \frac{2x}{R^2}\, A_{(x,R_1,R_2)}dx, \quad (5.5)$$

where $\frac{2x}{R^2}$ represent the PDF of the uniform distribution of SUs over the radial direction $r$ and $R$ is the network radius (see Appendix B for the proof). The probability of finding relay can be calculated as the percentage of the SUs number that lies in the intersection area to the total number of SUs in the coverage of the SAP.

$$P_{SU_R} = \frac{E\left(A\right)\ N_{nodes}}{A_{total}}, \quad (5.6)$$

Where $N_{nodes}$ is the total number of SUs and $A_{total}$ is the total area of the SAP coverage.

## 5.4 CO²MAC

This section presents the design details of CO²MAC. Recall that CO²MAC works in secondary infrastructure network where the bi-directional communication between SAP and any SU is guaranteed using at least the lowest supported data rate. CO²MAC uses a dedicated CCC to exchange control messages using the basic data rate $R_B$which enable all SUs to hear the from the SAP and build a topology map for the current status of the network and know about the ongoing and scheduled transmissions. It is assumed that SUs using CO²MAC utilize an efficient sensing mechanism to prevent interfering with the PUs transmissions.

### 5.4.1 CO²MAC Handshaking Process

CO²MAC handshaking process depends on exchanging RTS/CTS messages similar to that of IEEE 802.11 with some modifications to enable extra functions like relay(s), channel and transmission technique selection. The relays do not contribute in the selection process, but they know their future rules by listening to the exchanged messages. As CO²MAC utilizes CCC, CO²MAC can schedule future transmissions while all current data channels are still busy. As a result, the handshaking process will have a negligible effect on the throughput. Fig. 5.4 shows the control and data packet exchange time line for CO²MAC for two channels at the absence of the PUs.

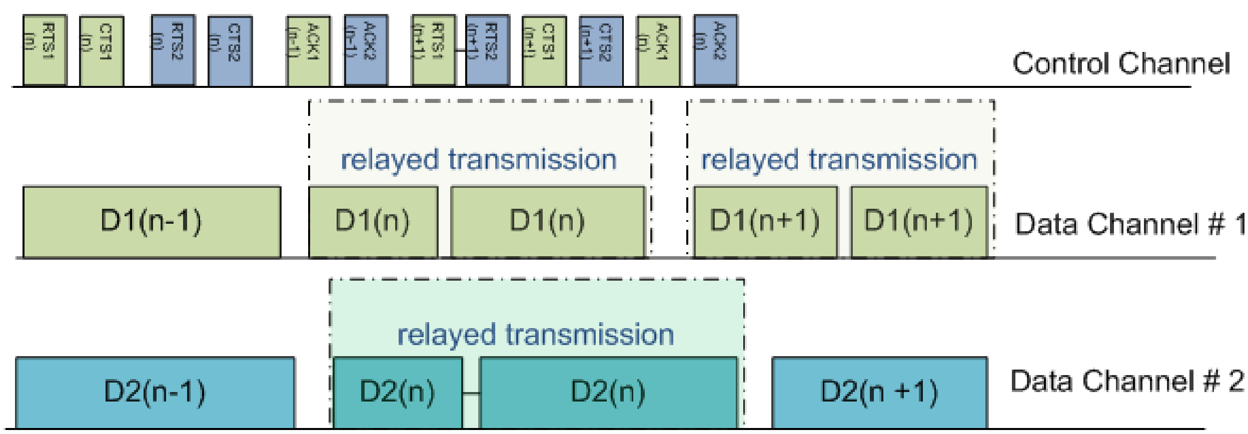



Figure 5.4: CO²MAC packet exchange time line over two channels.

The synchronization and timing pattern of CO²MAC is shown in Fig. 5.5 where $R_B$ is the basic rate that used to transmit all control packets over the CCC, $R_{DT}$ is the direct transmission range from source to the destination, $R_{SR}$ is the first hop rate from the source to the relay(s) when using relayed transmission. $R_{RD}$ is the transmission rate between the relay(s) and the destination in the second hop. For simplicity we ignore the presence of the PU in this time line.

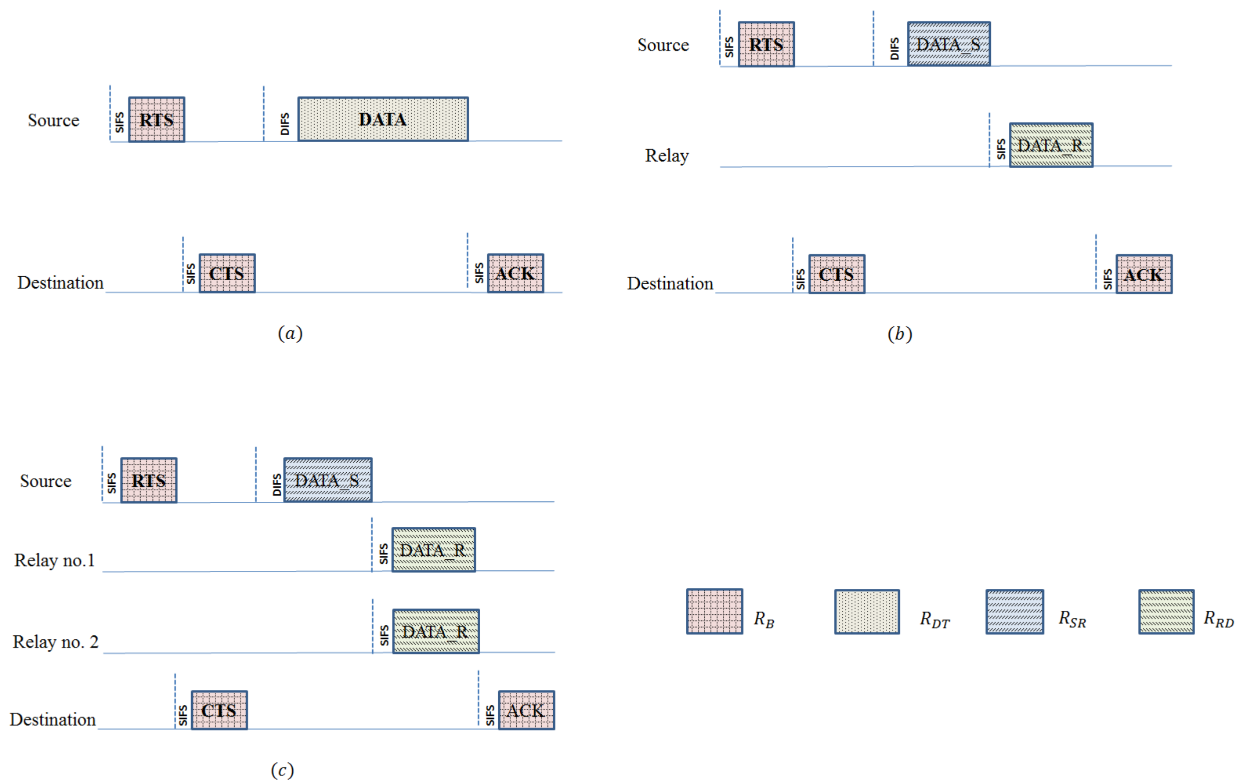



Figure 5.5: $CO^2$MAC rates and time line.

### 5.4.2 $CO^2$MAC Selection Process

The relay(s) and channel selection process depends on estimating the CSIs to find the best combination of free channel, available relay(s) and transmission techniques that leads to the highest throughput that meets the targeted BER at the receiver. Each SU overhears other neighbors data transmission and estimate the highest rate it can use to communicate with these SUs. Also, the SUs when exchange control messages with SAP they includes an ID for the highest supported DT modulation between each of them and the SAP. By this way, each SU knows the highest supported DT rate between the SAP and its neighborhood's SUs.

$CO^2$MAC starts the selection process by searching for the best two relays to forward the data and maximize the throughput over a free channel. If using two relays is not feasible, $CO^2$MAC will try to find the best single relay to use. As a last resort, $CO^2$MAC will use DT to forward the data. In all of the cases, the selection process is done at the SU except of multi-relays in the uplink direction where the decision is divided between the SU and the SAP.

In uplink or downlink DT, the SU can estimate the channel between itself and the SAP and decide what is the best modulation technique and consequently the highest data rate the channel can support. The SU will include this information in the RTS or CTS that it sends. In case of using a single relay, the SU knows the highest supported transmission between itself and every potential relay because it can overhear their transmissions. As the rest of SUs (potential relays) and SAP exchange the ID of the highest supported modulation in their handshaking, the SU knows the rate supported between every potential relay and the SAP. In this way, SU knows the two hops rates for every potential relay. The SU includes the address of chosen relay and the two hops rates in its handshaking with the SAP.

In case of using two relay to assist the transmission the selection process will be different in uplink and downlink directions.

In the case of using two relays in the downlink direction, the SU is still able to find the best combination of relays without the need of any extra information. The first hop from the SAP to the two relays are considered two separate DT to each of the relays and so the SU can know the highest common rate for every two relays the SAP can use in the first hop. The second hop is from the two relays to the SU and as SU knows the CSI between itself and every relays, it can decide what is the highest supported rate when a couple of relays use 2x1 STBC. The SU will search over all combinations of two relays to find the best couple and send their addresses in its control message to the SAP.

In the uplink direction, the SU knows what is the highest supported rate from itself to every relay and from every relay to the SAP. But, it cannot know if a couple of two relays send the data simultaneously to the SAP in 2x2 STBC mode, what will be the highest supported rate. That is because it cannot estimate the transmission channels between the relays and the SAP. To solve this problem, the SU has to *guess* what is the best two relays and sends its suggestion to the SAP in the RTS. The SAP examines the two relays and checks what is the highest rate both will support in 2x2 STBC mode and send this information back in the CTS. By other words, the relays selection is done by the SU but the rate selection is done by the SAP.

To estimate the potential relays, the SUs are pre-loaded with table called RANGE table that contains the average highest supported modulation for 2x2 STBC if the two relays lie within the mid-range of known DT range. For example, the table contains entries like, if node ($r_1$) DT modulation to the SAP is $XQAM$ and node ($r_2$) DT modulation to the SAP is $YQAM$, then, on the average, if both ($r_1$) and ($r_2$) use 2x2 STBC scheme to transmit to the SAP, they can use $ZQAM$. SUs use this table to guess the potential average 2x2 STBC range of any couples of relays.

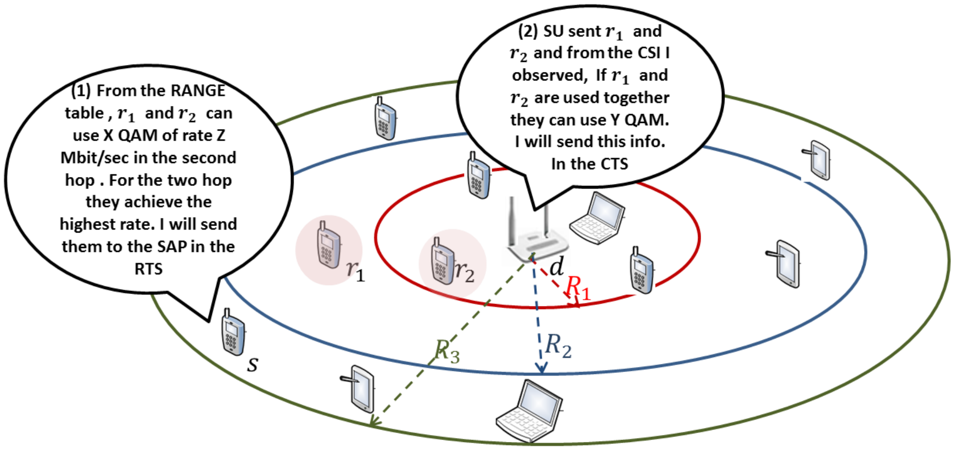



Figure 5.6: Two relay uplink transmission selection process.

The SU searches over all combinations of two relays for the highest achieved throughput over the two hops and sends the address of the best two relays with the first hop rate only if they achieve higher throughput than single relay and DT. The SAP checks the two relays and decides what it is the actual supported modulation in the second hop based on the CSI. The rate selection will be included in the SAP CTS to inform the chosen relay. The antenna index of every relay in the virtual MIMO system can be obtained by the order they mentioned in the control messages. Fig 5.6 illustrates the two step selection process in the uplink direction for two relays.

## 5.5 Performance Evaluation

In this section, the performance evaluation of using cooperative transmission on the secondary network throughput is evaluated analytically and by simulation. The simulation was carried out using the Riverbed OPNET Modeler network simulator [28] for a confiedence interval of 90%. All average BER performance curves over fading channel were simulated separately using Monte Carlo simulation. The secondary network consists of a number of stationary SUs uniformly distributed over a circle centered at the SAP. Table 5.1 shows the general network and simulation parameters.

### 5.5.1 DTMC Network Model Performance

This section shows the throughput performance of SAP in a simple network using the DTMC model and compare it with simulation results for the same network. For simplicity, the DTMC was modeled for downlink transmissions only. The SAP destinations are the SUs that lie in its BPSK DT range. Other SUs outside this range are assumed to act as

Table 5.1: $CO^2MAC$ Numerical simulation parameters.

| **Simulation Parameter** | **Value** |
|---|---|
| Number of channels | 2 |
| Modulation | BPSK, QPSK, (16,64,256)QAM |
| Data rate | 6,12,24,36,48 Mbit/sec |
| Path loss exponent | 3 |
| Symbol duration | 1/6 micro sec. |
| Packet size | 1K Byte |
| Max. Transmission Power per Antenna | 0.25 mW |
| Channel BW | 20 MHz |
| Successful reception BER threshold | $10^{-3}$ |

relays only. If the SAP finds feasible relays, it will prefer cooperative transmission over direct transmission. The feasible relay used in this model, is the one which can receive from the SAP with rate equals to 12 Mbit/sec using QPSK modulation, then forwards the data to the SU using 24 Mbit/sec using 16QAM modulation. This cooperative transmission give net throughput of 8 Mbit/sec. The DTMC for this transmission model is constructed for a given PU and SAP activities and number of SUs. The DTMC transition probabilities and relaying probability are calculated as in section 5.3. The same model was simulated by OPNET for validation.

Fig. 5.7 shows the performance of the DTMC model and the simulation for PU activity of 0% and 50%. In both cases, the throughput increases with the number of SUs as the probability of finding relay increases. In addition to the enhancement in the throughput, due to using the high data rate of cooperative transmission, the cooperation mechanism resulted in more successful transmissions than that of the DT. To show the last result, the performance of the previous DTMC which uses relay cooperation with probability $P_{SU_R}$ is compared with the one that uses only DT ($P_{SU_R} = 0$) at different PU activities. Fig. 5.8 shows the performance of DT and relay aided transmission against the PU activity at SAP activity of 95% and 280 SUs. The throughput was normalized by dividing the throughput by that of DT. As shown in the Figure, at low PU activity, the enhancement in the cooperative transmission throughput is mainly due to the fact that cooperative transmission net throughput is higher than that of the direct transmission. As the PU activity increases, the normalized throughput of cooperative transmission starts to increase until it reaches 80% at PU activity of 90%. This enhancement results because, as the PU activity increases, the chances to complete the transmission without being interrupted decreases. However, with the cooperative communication, the probability of successful transmission increases because

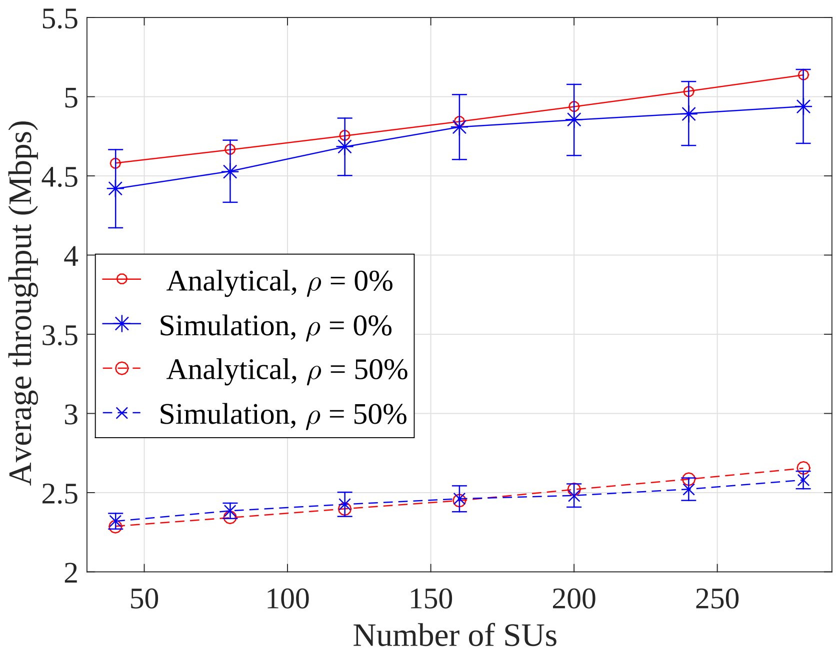



Figure 5.7: Average throughput performance with number of SUs at PU activities of 0% and 50%.

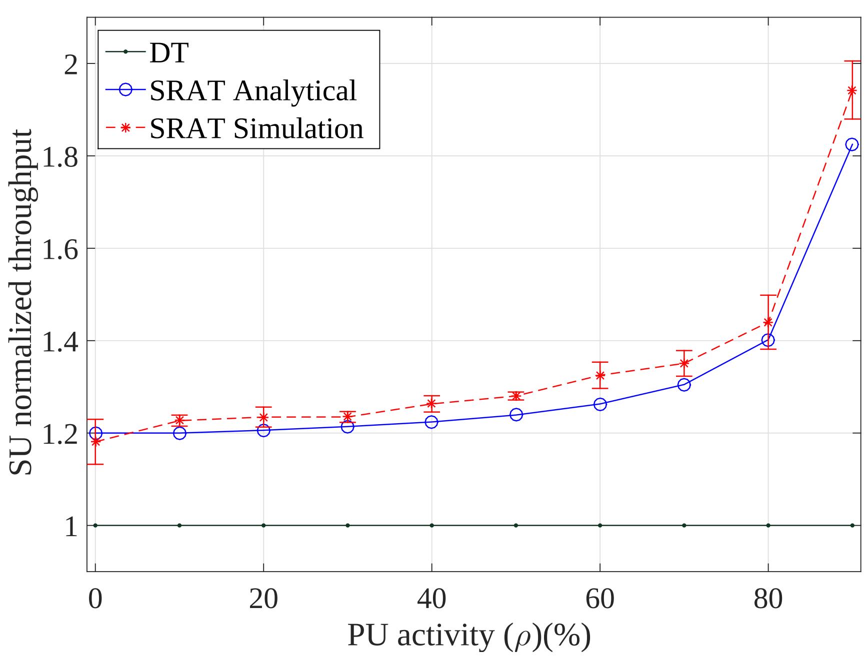



Figure 5.8: Simple scenario normalized throughput vs PU activity using DTMC model and by simulation.

the transmission uses better modulations and the distance between the transmitter and the receiver is traversed now over two transmissions rather than one.

### 5.5.2 CO$^2$MAC Performance

In this section, the performance of CO$^2$MAC protocol and the effect of cooperation on the average throughput are evaluated. Different versions of CO$^2$MAC with different capabilities were compared including:

- *Direct Transmission (DT):* CO$^2$MAC support only DT
- *Single Relay assisted Transmission (SRAT):* CO$^2$MAC can switch between single relay and DT according to the achieved data rate
- *Multi Relay Assisted transmission (MRAT):* CO$^2$MAC can switch between two-relay, single relay and DT

The PU is assumed to be transmitting 1 K Byte packets with rate of a 6 Mbit/sec. The PU activity is modeled by simulating a stand alone DTMC with $M = 10$ at the desired activity level. Fig. 5.9 shows the average throughput of CO$^2$MAC with different capabilities without PUs interaction over two data channels. For uplink MRAT, the performance of CO$^2$MAC relays selection process is compared to the optimum selection. The optimum two relays were found by a centralized brute force search and the relays addresses are presented to CO$^2$MAC. As shown in the figure, the throughput performance of CO$^2$MAC with different cooperation techniques outperforms DT. Also, CO$^2$MAC relay selection achieves a near optimum performance.

The throughput performance of CO$^2$MAC at different PU activities is evaluated in the uplink direction for slow SUs (SUs with a DT rate of 6 and 12 Mbit/sec that utilize cooperative transmission to increase the data rate). As shown in Fig. 5.10, cooperative transmission shows superior performance over DT at high PU activity as it reaches more than double the throughput of DT.

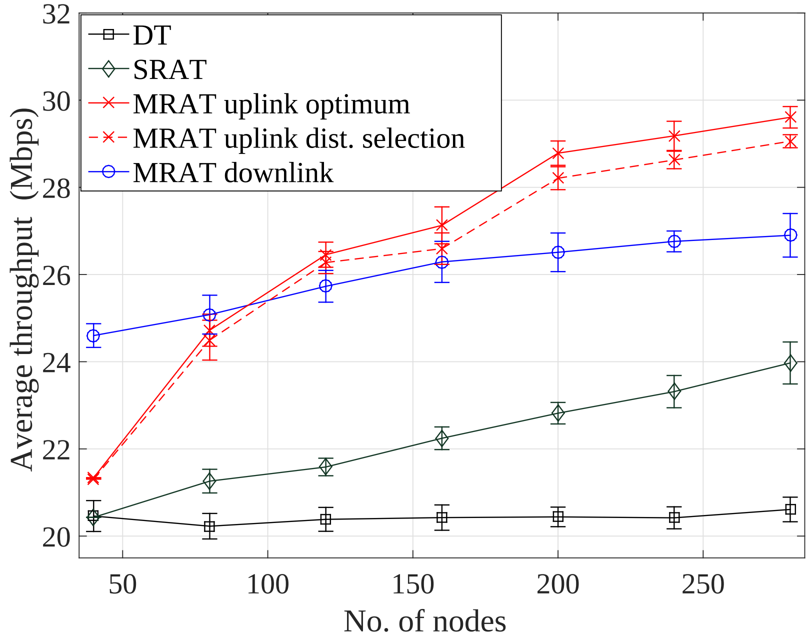



Figure 5.9: CO$^2$MAC average throughput vs number of SUs without PU presence.

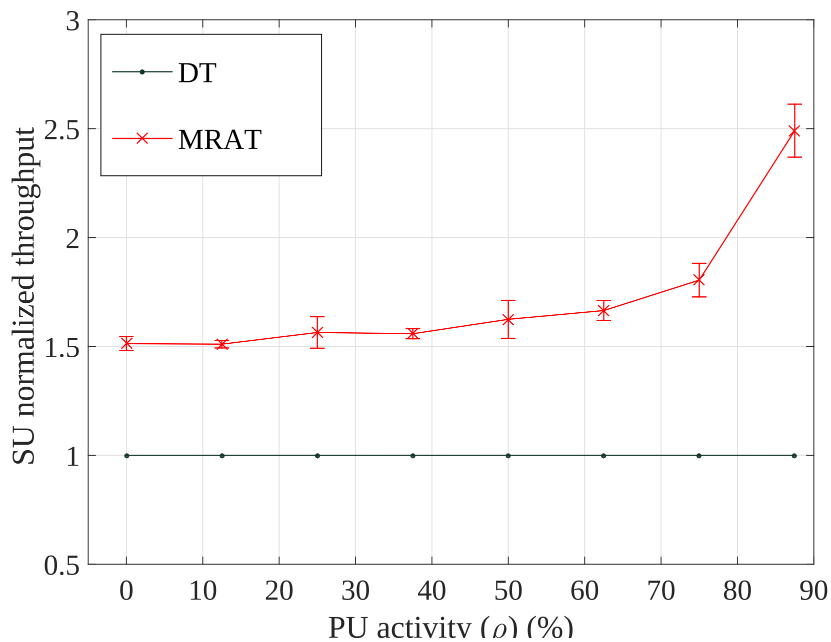



Figure 5.10: CO$^2$MAC normalized throughput vs PU activity ($\rho$).

## 5.6 Conclusion

This chapter studied the performance of secondary infrastructure networks when using a cooperative transmission technique with interweave spectrum sharing. The analytical model shows that using cooperative transmission outperforms direct transmission in terms of average throughput due to the efficient utilization of available white spaces. Using cooperative communications achieves up to 80% enhancement in the throughput over direct transmission at high PU activity. The superiority of using cooperative communication is also shown through the throughput performance of the $CO^2MAC$ protocol, especially with the crowded spectrum.

# Part III

# Bargaining-based Resource Allocation Framework in Secondary Cooperative Networks

# Chapter 6

# Cooperation Price in Cognitive Radio Network: A Resource Exchange Model

In this chapter [1], the cooperation price problem is modeled as a Resource Exchange (RE) process where the SU gives part of its free spectrum access time to the relay as a price of its energy. A suitable utility is designed that combines the throughput and energy for the cooperation pair and bargaining theory solutions are used to find the suitable price for the relay energy and the performance of the cooperation schemes is investigated at different non-cooperative access mechanisms and parameters.

## 6.1 Introduction

As mentioned in Chapter 1,cooperation in Dynamic Spectrum Networks networks can be categorized into cooperation between the primary users (PUs) and the secondary users (SUs) or between the SUs and themselves.

In the PU-SU cooperation schemes proposed in [13–20, 22–24], the PU is given a superiority role over the SU. For example, the PU acts as a monopolist in [13, 18–20],as a leader in the Stackelberg game in [17, 23, 24], and as a seller in auction based spectrum trading model [14][15]. These models cannot be used to study SUs cooperation, where no SU has a superiority role over the others. On the other hand, existing works on SUs cooperation focus only on studying the 'potential' performance gains brought by cooperation, without studying *how SUs agree on cooperating with each other* and *what are the conditions under which cooperation is beneficial for all cooperating SUs.*

[1]This chapter is based on work presented in [78].

In this Chapter, we aim to answer these questions by developing a framework for SUs cooperation. We aim to formulate the cooperation between secondary users in a way that is beneficial for all of them. The secondary users cooperation is modeled as a Resources Exchange (RE) between the slow secondary users and the relay where the slow secondary users pay to the relay a price for its transmission power in the form of giving part of its original spectrum occupancy (access time) to the relay. To emphasis the previous idea, we assume a simple illustrative scenario of a secondary network with four nodes and a Secondary Access Point (SAP). Nodes are categorized in two groups: slow Secondary Users SUs and fast Secondary Relays (SRs)[2]. The SR has a dual role, besides transmitting its own data, it can help other SUs to forward their data to the SAP. A simple network is depicted in Fig.6.1 where SR2 helps SU2 to forward its packet while the other nodes are not cooperating.

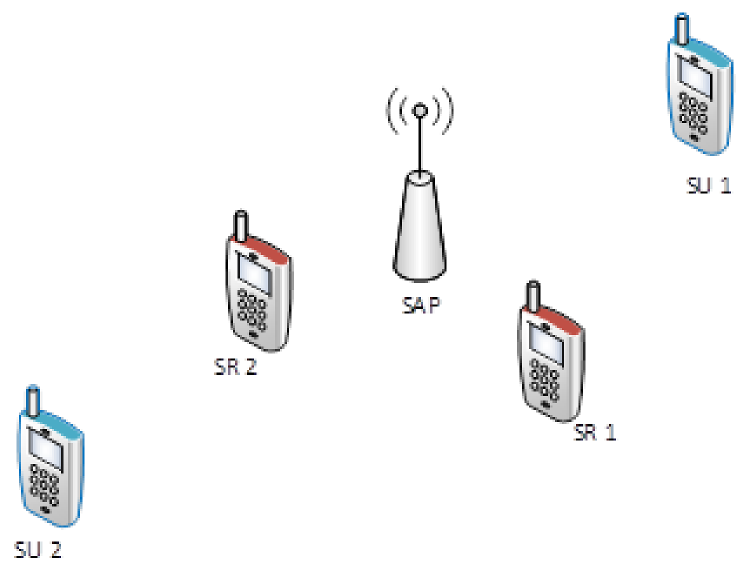



Figure 6.1: Simple secondary infrastructure network with cooperating and non-Cooperating nodes.

Assumes that the SAP gives equal access probability for all nodes so that, all nodes transmit equal amount of data regardless if the nodes are cooperating or not. The different nodes free spectrum time shares at different cases are depicted in Fig. 6.2

Fig.6.1 (a) represents the non-cooperative case with equal access probabilities for all secondary nodes. It is clear that the slow nodes (SU1 and SU2) occupy most of the available spectrum time and slow down the fast nodes. Also, as the PU activity ($\rho$)increases, the time the SU needs to complete its transmission will increase because of the frequent PU interruptions to the SUs transmission which means an increase in the SU occupancy distribution. In

[2]In this chapter, we will use the term SU to refer to the slow node (node with slow direct transmission data rate that may benefit from cooperation) and the term SR to refer to the fast node (node with a high direct transmission data rate that can act as a relay to the slow node).

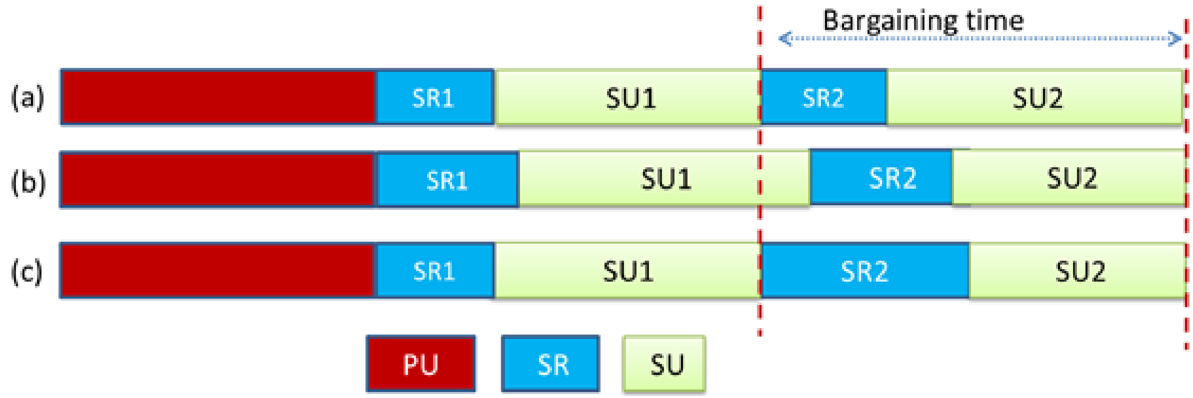



Figure 6.2: Different spectrum occupancy distributions.

Fig.6.1 (b) SR2 helps SU2 to forward its data packet at a higher speed and less transmission time. As a result, the occupancy distribution for SU2 will decrease and all occupancy distribution for other nodes will increase regardless of being involved in the cooperation with SU2 or not. This new spectrum occupancy reallocation may not be incentive for the SR to cooperate with the SU as the benefit of cooperation is divided equally between all nodes but, the SR is the only one involved in the SUs transmission. To provide an incentive reward for the relay to cooperation, the SU and SR goes through resource exchange process where the SU free part of its spectrum occupancy to the SR as a price for the power used by the relay in the SU second hop transmission( The leased spectrum occupancy from the SU should be incentive enough for the SR to involve in the cooperation). Spectrum access probabilities values for both the SU and SR are adjusted by the SAP to produce the new targeted spectrum occupancies. This scenario is depicted in Fig.6.1 (c) where, the total spectrum occupancy for both the SU2 and SR2 are redistributed between both of them without affecting other nodes share. The same method can be applied to any cooperative pair in the network. A utility functions that combines the throughput and the energy is designed and bargaining solutions are used to find a reasonable way to reallocate the spectrum occupancy between the SU and SR. The total spectrum occupancy of the SU and SR is available for bargaining where both SU and SR get spectrum occupancy according to each one utility and disagreement point.

## 6.2 System Model

The network model is a secondary infrastructure network with secondary nodes distributed at different direct transmission ranges from the SAP. The secondary network utilizes the white spaces of the licensed spectrum of a PU in interweave spectrum sharing access mechanism. The medium access scheme is assumed to be slotted access and the PU, SUs, and SRs are fully synchronized. The nodes can be categorized as slow and fast nodes where the slow nodes may ask for the fast nodes help in forwarding its data.

We assume the network nodes lie in three different transmission ranges from the SAP. The data rate of every SU depends on its distance to the SAP. We define three data rates named $R_1$,$R_2$, and $R_3$ with transmission time spans $4n$,$2n$, and $n$, respectively where $n$ is a factor reflects the time resolution of the transmission. Any node can transmit its packets directly to the destination, henceforth referred to as direct transmission (DT), or through another node who acts as a relay, henceforth referred to as cooperative communication. In the cooperation mode, the SU uses Decode and Forward (DF) cooperative communication. In DF, the SU transmits its data to an intermediate relay using rate $R_{sr}$ in transmission time $T_{srr}$ in the first hop. The relay decodes the data then forwards it to the destination using rate $R_{rd}$ in transmission time $T_{rd}$ in the second hop [3]. The overall transmission time and data rate are given by (4.1) and (4.2), respectively [40] as mentioned in Chapter 4 and repeated below:

$$T_{CC} = T_{sr} + T_{rd},$$
$$\frac{1}{R_{CC}} = \frac{1}{R_{sr}} + \frac{1}{R_{rd}}.$$

As a result of the cooperation between the SU and the SR, we define three cooperation levels according to the two hops rates and the net achieved rate. The cooperation level is determined by the number of time slots required to transmit the SU packet $M_{SU}$ over the two-hops from the SU to the SR $M_{(SU\rightarrow SR)}$ and from the SR to the SAP $M_{(SR\rightarrow SAP)}$. The four levels of cooperation between the SU and SR are defined as shown below.

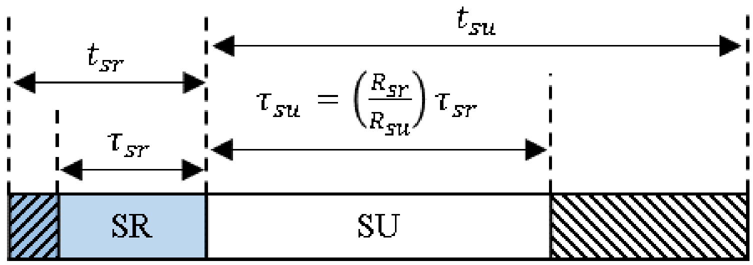
**Different Cooperation Levels:**

1. $L_0 : M_{SU} = 4n, M_{(SU\rightarrow SR)} = 2n, M_{(SR\rightarrow SAP)} = 2n$
2. $L_1 : M_{SU} = 3n$
   (a) $L_{(1a)} : M_{(SU\rightarrow SR)} = n, M_{(SR\rightarrow SAP)} = 2n$
   (b) $L_{(1b)} : M_{(SU\rightarrow SR)} = 2n, M_{(SR\rightarrow SAP)} = n$
3. $L_2 : M_{SU} = 2n, M_{(SU\rightarrow SR)} = n, M_{(SR\rightarrow SAP)} = n$

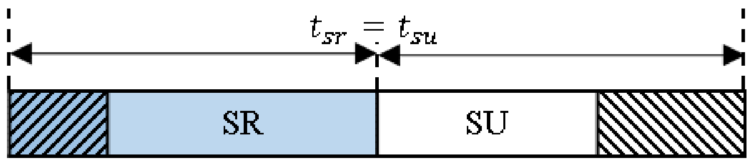
Levels $L_{(1a)}$ and $L_{(1b)}$ have the same throughput performance, but they differ in the rate of each hop which will be a concern in Section 6.5.

In this chapter, we propose three different spectrum access mechanism as follows:

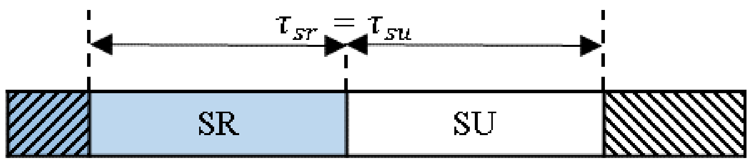
[3]In this chapter, we will refer to the uplink direction from the node to the access point in our analysis ,but the same procedures apply in the downlink direction.




(a) EAP




(b) ETT




(c) ESTT

Figure 6.3: Illustration of SU and SR free spectrum shares at different access mechanisms.

Different Secondary User Non-Cooperative Free Spectrum Access Mechanisms:

- *Equal Access Probability (EAP) media access mechanism:* In this mechanism, the SAP gives equal access for all nodes regardless of their data rates, cooperation level, or the primary user activity. In this method, if the different nodes have the same packet size, it will result in equal data transmission for all nodes.

- *Equal Transmission Time (ETT) media access mechanism:* In this method, the SAP controls the access probability such that, on the average, different nodes have equal access time to the free spectrum. This access method does not consider for the node data rate or the transmission efficiency.

- *Equal Successful Transmission Time (ESTT) media access mechanism:* In this mechanism, every node get an equal successful transmission time. This method compensates each node for its loss due to the PU interruption.

Fig. 6.3 shows the three different access mechanism where $t_{su}$ and $t_{sr}$ are the total transmission times of the SU and SR respectively and $\tau_{su}$ and $\tau_{sr}$ are the total *successful* transmission time of the SU and SR, respectively. The dashed portions represent the wasted times due to the PU interruptions.

As can be noticed form Fig. 6.3, EAP is the most beneficial access mechanism for the SU and the worst for the SR, as it allows every node to transmit the same number of packets regardless of its rate or transmission efficiency. On the other hand, ETT is the best for the SR and the worst for the SU as it does not compensate the slow node for its lower rate nor its lost packets. ESTT can be considered a moderate access mechanism between EAP and ETT as it gives equal successful time by compensating the nodes for their lost packets. The detail analysis of the different access mechanism performance is provided in Section 6.4.

The SU may ask for the SR's help to achieve higher throughput, however if SAP kept the access probability unchanged for the cooperating pair as before the cooperation, the SR may refuse to cooperate as the gain it will get in term of throughput will not compensate its energy loss due to forwarding the SU packets as described in Section 6.1 . As a solution, the SU will sacrifices by part of its free spectrum access time to the SR as a price for its dissipated energy. The cooperating nodes will try to reallocate the total time share they get among them self using bargaining solution. In this model, the cooperation is done in pair wise manner where other nodes are not affected positively nor negatively by the result of the cooperation. As the cooperation will not affect the other nodes share, the bargaining pair can be isolated and the isolated pair interaction with the PU can be modeled using discrete time Markov chain (DTMC). After finding the bargaining based spectrum shares for the SU and SR from the isolated model, the share can be normalized for the actual shares of the SU and the SR in the network model.

## 6.3 The PU, SU and SR Interaction DTMC Model

In this section, we present the PU,SU, SR interaction DTMC model in interweave spectrum access mechanism. The difference between this DTMC model and the previous one in Chapter 4 are 1) In this DTMC model, we explicitly model the active relay (SR) which transmits its own packets and help other SUs. 2) To simplify the DTMC model, we assumed that both the SU and the SR always have packets to transmit ($\zeta_{SU} = \zeta_{SR} = 100\%$). The transition diagrams show in Fig. 6.4 and 6.5represent examples of the PU/SU/SR non-cooperative and cooperative DTMC models [4], respectively for $M_{PU} = 2, M_{SU} = 3$ (non-cooperative mode) , $M_{SU} = 2$ ( cooperative mode) and $M_{SR} = 1$. Each state is labeled by three letters ($PSR$), where, $P$ represents the PU's status, $S$ represents the SU status, and $R$ represents the SR status. The letter ($A$) is used to indicate that the node is active transmitting or waiting for the PU to finish its transmission to start its own. The letter ($a$) indicates that this node (SU or SR) is waiting for its turn to start its transmission. The value of $P_{(X-Y)}$ is the probability that secondary node $Y$ starts a transmission after $X$ has finished its transmission.

The main difference between the non-cooperative and the cooperative model is that, in

[4] In our entire work, cooperative or non-cooperative mode refers to the relation between the secondary nodes

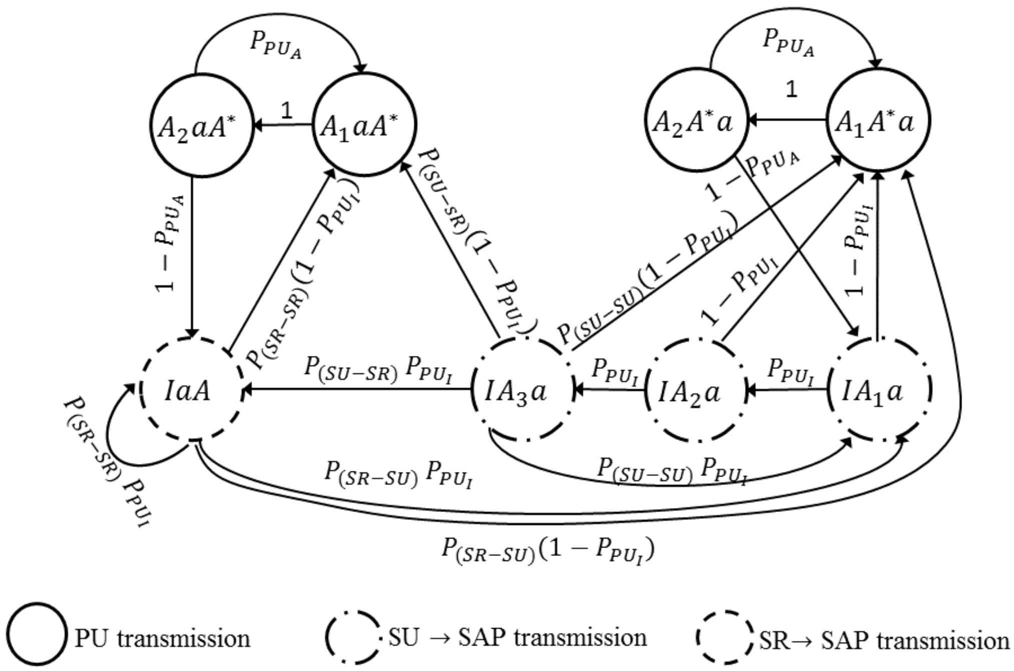



Figure 6.4: DTMC model for PU/SU interaction for non-cooperative secondary user with $M_{PU} = 2$, $M_{SU} = 3$, and $M_{SR} = 1$.

the cooperative model hence the first hop is finished successfully, the SR can buffer the SU's packet if the PU becomes active until the PU turn to the idle state again, then transmits the data without the need to repeat the first hop transmission. The successful active occupancy distribution for the SU and SR can be calculated by multiplying the occupancy distribution of the last active state by the number of time-slots per transmission as shown in equations (6.1) and (6.2) for the SU and the SR, respectively.

$$\pi_{(SU_A)} = M_{SU}\ \pi_{\left(IA_{(M_{SU})a}\right)}, \tag{6.1}$$

For the SR, the successful active state distribution has the same expression in the cooperative and non-cooperative models as:

$$\pi_{(SR_A)} = M_{SR}\ \pi_{\left(IaA_{(M_{SR})}\right)}. \tag{6.2}$$

The transmission efficiency of the SU and the SR can be calculated according to equations (6.3) and (6.4), respectively.

$$\eta_{SU} = \frac{M_{SU}\ \pi_{\left(IA_{(M_{SU})a}\right)}}{\sum_{i=1}^{M_{SU}} \pi_{(IA_i a)}}, \tag{6.3}$$

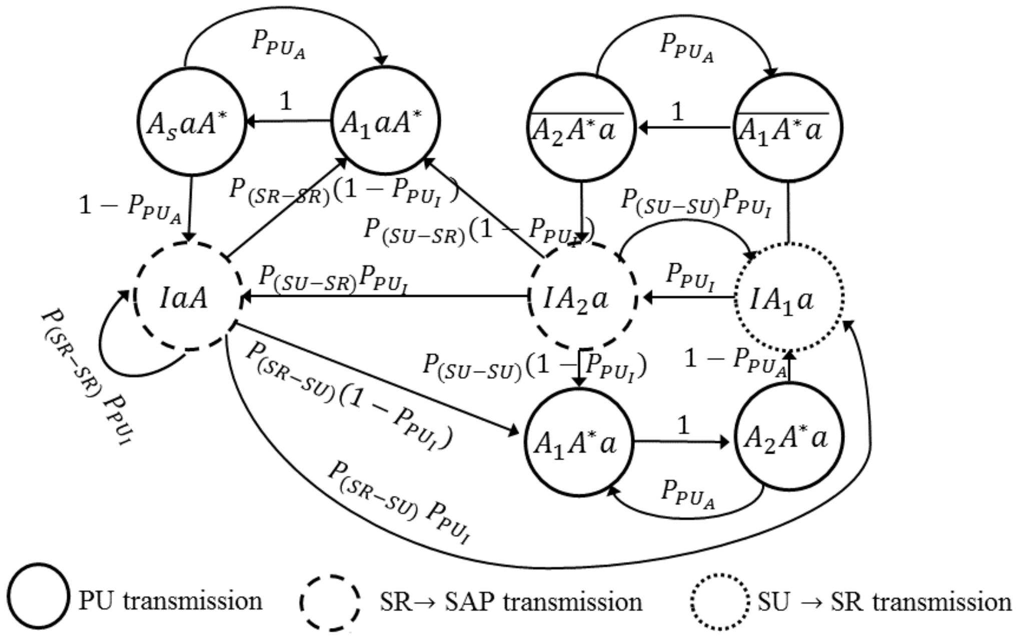



Figure 6.5: DTMC model for PU/SU interaction for cooperative secondary user with $M_{PU} = 2$, $M_{SU} = 2$, and $M_{SR} = 1$ .

$$\eta_{SR} = \frac{M_{SR}\ \pi_{\left(IaA_{(M_{SR})}\right)}}{\sum_{i=1}^{M_{SR}} \pi_{(IaA_i)}}. \tag{6.4}$$

In other words, $\eta_x$ is the ratio between the time (time slots) the node spends in transmitting successful packets to the total time it consumes in the transmission including the time-slots of the transmissions that were interrupted by the presence of the PU. The SU efficiency $\eta_{SU}$ depends only on the PU activity ($\rho$) and the cooperation level between nodes. As shown in Fig. 6.6 the transmission efficiency decreases with the increase of the PU activity due to the PU interruption and the decrease rate is more sever in the non-cooperative mode compared to the cooperative one with its different levels. Fig. 6.7 shows the free spectrum time shares of the SU and SR with different PU activity for at different rates for the SU and the SR if both the SU and SR have the same spectrum access probability. As the PU activity increases, the SU efficiency decreases with higher rate then the fast SR and so, it needs more time to achieve a higher throughput. As a result, with equal access probability, the SU time share will increases with the increase of the PU activity while the SR's spectrum time share will decrease. This figure emphasis the negative effect of the slow SU on the fast SR.

The SU throughput and the SR throughput can be calculated by (6.5) and (6.6), respectively.

$$T_{SU} = R_{SU}\ M_{SU}\ \pi_{\left(IA_{(M_{SU})}a\right)}, \tag{6.5}$$

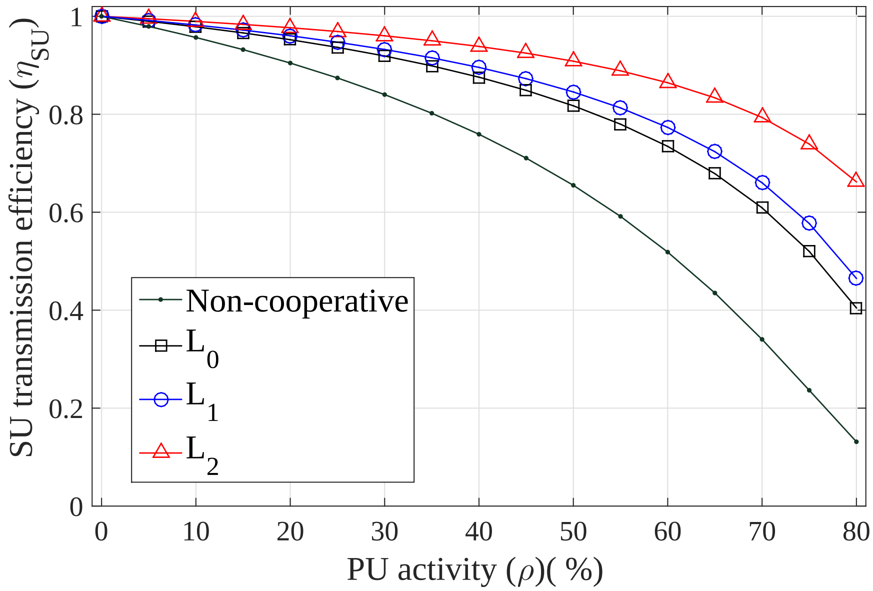



Figure 6.6: SU transmission Efficiency $\eta_{SU}$ vs. PU activity at different cooperation levels.

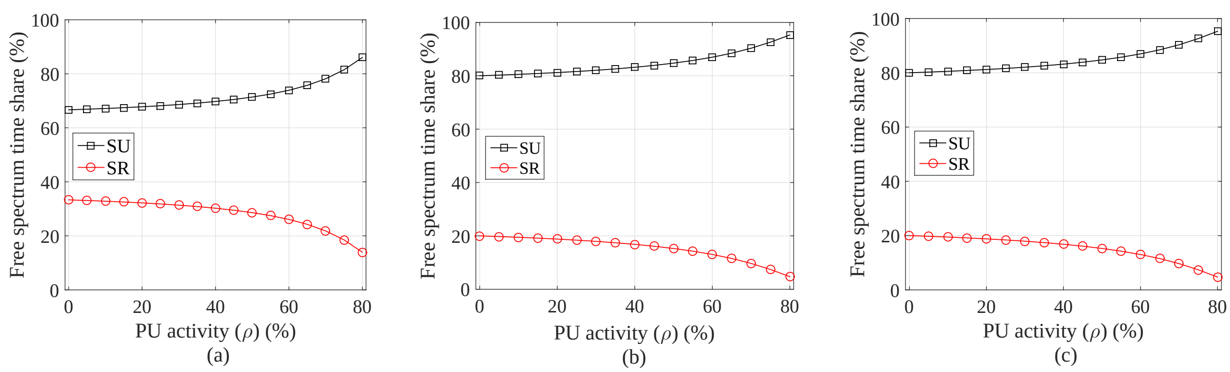



Figure 6.7: SU and SR Free Spectrum Time Shares at non-cooperaive EAP for the same data rates corresponding to (a) $L_{1a}$, (a) $L_{1b}$, and (c) $L_2$

$$T_{SR} = R_{SR}\, M_{SR}\, \pi_{\left(IaA_{(M_{SR})}\right)}. \tag{6.6}$$

where $R_{SU}$ and $R_{SR}$ are the data rate of the SU and the SR, respectively.

## 6.4 Analysis of Different Access Mechanisms

In this subsection, we analyze the three non-cooperative access mechanisms proposed in Section 6.2 using the DTMC models shown in Fig. 6.4 and Fig. 6.5. The goal is to calculate the SU and SR different transmission characteristics like the efficiency and the throughput for every one of the proposed access mechanisms. The efficiency and throughput can be calculated by finding the different state occupancy distributions then apply the set of relations described in the previous section.

### 6.4.1 Non-cooperative mode

**EAP**–To achieve equal spectrum access probabilities for both the SU and the SR, the values of the transition probabilities are set as follows:

$$P_{(SU-SU)} = P_{(SU-SR)} = P_{(SR-SR)} = P_{(SR-SU)} = 0.5 \tag{6.7}$$

and the value of $P_{PU_I}$ and $P_{PU_A}$ are calculated from the stand-alone DTMC model using equations (4.5) and (4.6). The probability matrix $P$ then can be constructed and the occupancy distributions of different states are calculated by solving equations (4.3) and (4.4). After finding the different state occupancy distributions, the transmission efficiency and throughput can be calculated using (6.3),(6.4), (6.5),and (6.6).

**ETT**– In ETT, Both the SU and the SR have equal access time which leads to equal summation of all the state occupancy distributions for the SU and the SR,

$$\sum_{i=1}^{M_{SR}} \pi_{(IaA_i)} = \sum_{i=1}^{M_{SU}} \pi_{(IAa_i)} = \frac{1-\rho}{2}, \tag{6.8}$$

where $\rho$ is the PU activity. From the DTMC model, the relation between two consecutive SU or SR state occupancy distribution $\pi_n$ and $\pi_{n-1}$ in the non-cooperative mode can be written as:

$$\pi_n = P_{PU_I}\, \pi_{(n-1)} \tag{6.9}$$

which can be generalized as,

$$\pi_n = P^i_{PU_I} \pi_{(n-i)}. \tag{6.10}$$

By expressing the different state occupancy distributions of the SU using the last state $\pi_{(IA_{(M_{SU})}a)}$ according to equation (6.10) and by substituting its value in (6.8), the the values of $\pi_{(IA_{(M_{SU})}a)}$ can be calculated and from it, the rest of SU state occupancy distributions can be calculated according to (6.10). The same procedure can be used for the SR.

**ESTT**–In ESTT, the SU and SR have the same *successful* transmission time, which may be translated to the relation between the state occupancy distributions for the SU and SR using the following two equations:

$$M_{SU}\, \pi_{\left(IA_{(M_{SU})}a\right)} = M_{SR}\, \pi_{\left(IaA_{(M_{SR})}\right)}, \tag{6.11}$$

$$\sum_{i=1}^{M_{SR}} \pi_{(IaA_i)} + \sum_{i=1}^{M_{SU}} \pi_{(IA_i a)} = 1 - \rho. \tag{6.12}$$

As in ETT, the different state occupancy distribution can be expressed using the last state occupancy distribution and by using equations (6.11) and (6.12) the different states occupancy distributions can be calculated.
For all the three mechanisms, by knowing the different states occupancy distributions the transmission efficiency and throughput can be calculated using the same procedure used for ETT.

The values of the access probability $P_{(SU-SU)}, P_{(SU-SR)}, P_{(SR-SU)}, P_{(SR-SR)}$, can be calculated by substituting the PU,SU and SR occupancy states distributions in (4.3). which will be reduced to the following two equations:

$$\pi_{\left(IAa_{M_{SU}}\right)} \; P_{(SU-SU)} \; P_{PU_I} + \pi_{\left(A_{(M_{PU})}Aa\right)} \; (1 - P_{PU_A}) + \pi_{\left(IaA_{(M_{SR})}\right)} \; P_{(SR-SU)} \; P_{PU_I} = \pi_{(IAa_1)} \tag{6.13}$$

and

$$\pi_{\left(IAa_{M_{SU}}\right)} \; P_{(SU-SR)} \; P_{PU_I} + \pi_{\left(A_{(M_{PU})}aA\right)} \; (1 - P_{PU_A}) + \pi_{\left(IaA_{(M_{SR})}\right)} \; P_{(SR-SR)} \; P_{PU_I} = \pi_{(IaA_1)} \tag{6.14}$$

The other equation resulted from (4.3) does not includes the targeted probabilities.
or give a dependent version of the equations 6.13 and 6.14 The other needed two equation are:

$$P_{(SU-SU)} + P_{(SU-SR)} = 1, \tag{6.15}$$

and

$$P_{(SR-SR)} + P_{(SR-SU)} = 1. \tag{6.16}$$

by solving these four equations, the different probabilities can be calculated.

### 6.4.2 Cooperative mode

If the SU and SR are cooperating and they adopt the same non-cooperative access method, the SU calculations will be different from the non-cooperative mode for ETT and ESTT.
For EAP, the transition probabilities will have the same values as the non-cooperative case and the different state occupancy distribution, efficiency and throughput are calculated using the same techniques used in the non-cooperative mode.

For ETT and ESTT, as the SU transmission is done over two hops, the calculations will be different from the non-cooperative case.

For the SU if the first hop transmission from the SU to the SR spans $l$ time slots, the relation between the last state occupancy distribution of the first hop transmission $\pi_{(IA_l a)}$ and the first state occupancy distribution of the second hop transmission from the SR to the SAP $\pi_{(IA_{(l+1)}a)}$ is given by the equation:

$$\pi_{(IA_l a)} = \pi_{(IA_{(l+1)}a)}. \tag{6.17}$$

By using equation (6.10), we can write the express any state occupancy distribution using $\pi_{(IA_l a)}$ using the following relation:

$$\pi_{(IA_l a)} = P^i_{PU_I} \cdot \pi_{(IA_{(l-i)}a)}. \tag{6.18}$$

The same can applied for the second hop by using $\pi_{(IA_{(l)}a)}$ as follows:

$$\pi_{(IA_{(l+i+1)}a)} = P^i_{PU_I} \cdot \pi_{(IA_{(l+1)}a)}. \tag{6.19}$$

by using the last two equations the relation between $\pi_{(IA_{(M_{SU})}a)}$ and $\pi_{(IA_{(l+i)}a)}$ can be found and so, as in the non cooperative case, we can express the different SU state occupancy distribution using $\pi_{(IA_{(M_{SU})}a)}$. Using the same procedure of the used in the non-cooperative mode for ETT and ESTT, the different state occupancy distribution, transmission efficiency and throughput can be calculated.

## 6.5 Utility Models

The utility function for the SU and SR is defined as the difference between the achieved *normalized* throughput and the *normalized* energy [18]. The utility for node $s$ is defined as follows:

$$U_s = \bar{T}_s - C_s \cdot \bar{E}_s, \tag{6.20}$$

where $\bar{T}_s$ is the network normalized throughput and $\bar{E}_s$ is the normalized energy. The factor $C_s$ is the energy evaluation factor. The normalized throughput and energy for SU $s$ can be defined using the following two equations:

$$\bar{T}_s = t_s \, \frac{R_s}{R_{min}} \, \eta_s, \tag{6.21}$$

$$\bar{E}_s = t_s, \tag{6.22}$$

where $t_s$ is the time share it get, $R_s$,is the data rate, $R_{min}$ is the lowest rate used in the model and the transmission power is set to be equals to one. The value of $C_s$ indicates the preference of the node between the energy and throughput. For example, When $C_s < 1$ it means that the node prefers to achieve higher throughput over to save its energy. Equation (6.22) is valid only in the non-cooperative case where the SR does not contribute in the SU's transmission.

For the cooperative case, we need to count for the energy consumed by the SR to relay the SU's packets including the power consumed in the transmission and in the reception of the packet. In the cooperative mode the definition of the normalized energy will be different for the SU and SR. For the SR, the normalized energy will be defined as:

$$\bar{E}_{(SR_{coo})} = t_{(SR_{coo})} + t_{(SU_{coo})}\, \varepsilon_{SR} + \gamma(1 - \varepsilon_{SR})\, t_{SU}, \tag{6.23}$$

where $\gamma$ is the ratio of the power consumed in the SU's packet reception by the SU to the power used in the transmission, $\varepsilon_{SR}$ is the ratio of the time of the second hop cooperative transmission to the total time of the two hops cooperative transmission. The value of $\varepsilon_{SR}$ depends of the cooperation level used. For example, $\varepsilon_{SR} = 2/3$ in $L_{1a}$, $1/3$ in $L_{1b}$, and $1/2$ in $L_2$. The values of $t_{(SU_{coo})}$ and $t_{(SR_{coo})}$ are the SU and SR's free spectrum time shares in the cooperative mode. For the SU, the normalized energy in the cooperative mode is defined as,

$$\bar{E}_{SU} = (1 - \varepsilon_{SR})\, t_{(SU_{coo})}. \tag{6.24}$$

For $t_{su}$ and $t_{sr}$ they must satisfies that

$$1 - \rho = t_{SU} + t_{SR}, \tag{6.25}$$

in both the cooperative or the non cooperative modes.

The utility function is chosen to be liner such that it combines both the throughput and the energy in one formulation. The linearity of throughput gain is not always valid, especially at high value of throughput where the gain may diminished. In our case the, linearity may be justified if we consider that the secondary users get just a fraction of free time of the primary user channel which may not reach a saturation region where extra throughput is not needed. To use other throughput functions that reflect diminishing marginal return of increasing the access time like the log function, some parameters should be taken into account such that the share of every node is translated to the actual access time. The throughput expression should include parameters to reflect how many secondary nodes sharing the same channel and what is the access mechanism used by the SAP to coordinate the access of the secondary nodes to the free channels. Also, the utility function expression should be able to combine the non-linear expression of the throughput (e.g., log) with the linear one of the energy expression.

## 6.6 Bargaining Model

To incentivise the SR to provide help to the SU, the SU offers part of its free spectrum time as a price for the SR energy in a resource exchange process. W use bargaining theory to determine the suitable amount of share the SU should give to the SR.ement point. From the bargaining result, the cooperative spectrum share is determined and so the throughput.

### 6.6.1 Nash Bargaining Solution (NBS)

The two player bargaining problem consists of a pair $(F, d)$ where F is called the feasible set of allocations and it is closed and convex and $d$ is the disagreement point. The utility of each player in the non-cooperative mode is used as a disagreement point if the nodes refused to cooperate. The NBS is unique and satisfies the following axioms:

**Nash Bargaining Solution Axioms:**

1. *Individual Rationality IR:* This axiom implies that the bargaining solution satisfies the following equation,

$$f_1(F,d) \geq d_1 \quad \text{and} \quad f_2(F,d) \geq d_2 \tag{6.26}$$

   where $(d_1, d_2)$ are the disagreement utilities (points).

2. *Pareto Optimality PO:* The bargaining solution is Pareto-optimal.
   For a feasible set F, the allocation $x = (x_1, x_2)$ is Pareto efficient if there exists no other point $y = (y_1, y_2)$ such that $y_1 \geq x_1$ and $y_2 \geq x_2$ where the strict inequality is satisfied for at least one player.

3. *Symmetry SYM:* The solution does not discriminate between players if they are indistinguishable.

4. *Scale Invariant SINV:* Transforming the bargaining problem by any linear scale transformation $\psi$ change the solution by the same transformation.

$$\psi(f(F,d)) = f(\psi(F), \psi(d)). \tag{6.27}$$

5. *Independence of Irrelevant Alternatives IIA:* The axiom states that for any closed and convex set Z,

$$G \subset F \text{ and } f(F,d) \in G \Rightarrow f(G,d) = f(F,d). \tag{6.28}$$

   the axiom implies that eliminating the not chosen feasible alternatives should not affect the solution

The unique NBS for two players is obtained by solving the following equation:

$$\begin{aligned} f(F,d) = \underset{(x_1,x_2)\in F}{\arg} \max \, (x_1 - d_1)(x_2 - d_2) \\ \text{subject to} \quad x_1 \geq d_1 \quad \text{and} \quad x_2 \geq d_2 \end{aligned} \tag{6.29}$$

where $d_1$ and $d_2$ are the disagreement points for players one and two, respectively.

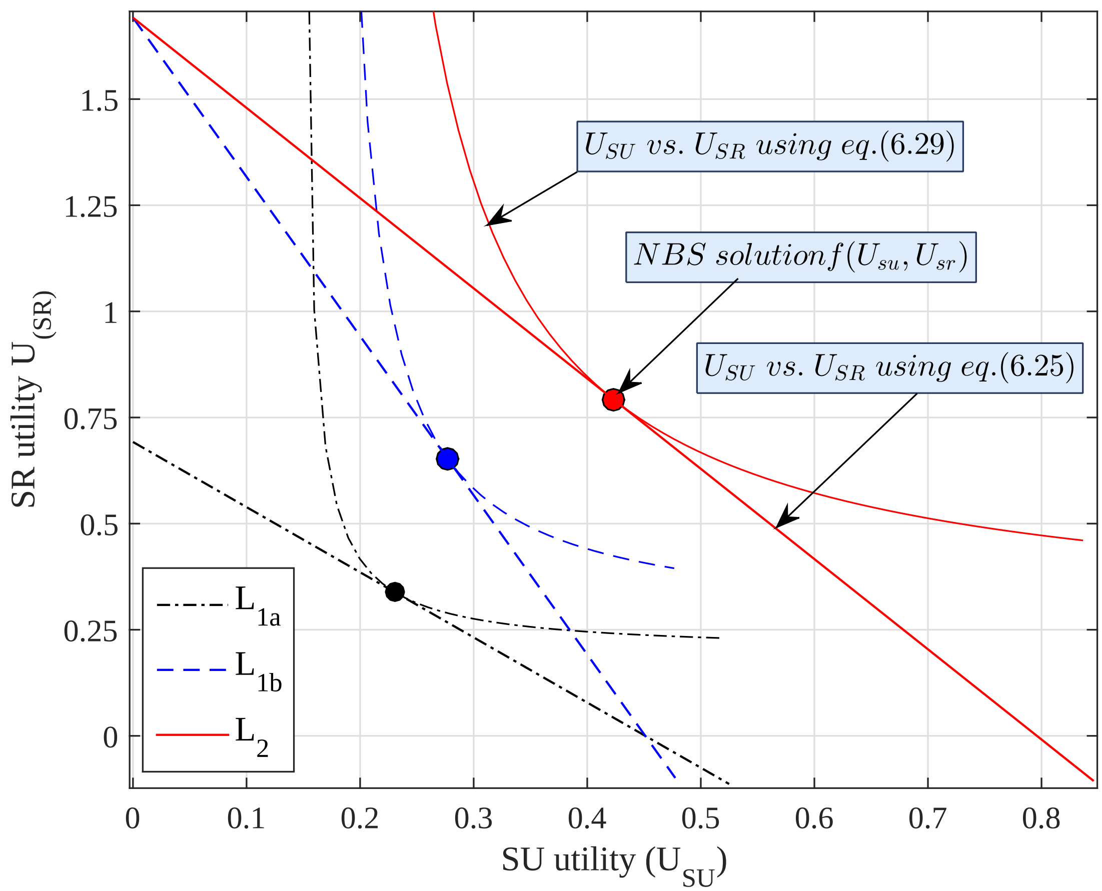



Figure 6.8: NBS graphical representation at different cooperation levels for $\rho = 50\%, C_{SU} = C_{SR} = 0.25,$ and$\gamma = 0.7$.

Fig. 6.8 shows the graphical representation for NBS as the intersection of the Pareto optimal boundary of the utility and the hyperbola of equation (6.29) for different cooperation levels between the SU and SR.

### 6.6.2 Egalitarian Bargaining Solution (EBS):

Egalitarian solution is the point in Weak Pareto set where the two players achieve equal utility increases relative to their disagreement points. The unique EBS can be expressed as the maximum point $(x_1, x_2) \in F$ such that

$$x_1 - d_1 = x_2 - d_2 \tag{6.30}$$

and satisfies the following condition:

$$x_1 \geq d_1 \quad \text{and} \quad x_2 \geq d_2.$$

Bargaining model will be used to determine the share of the SU and the SR after the cooperation. But also we investigated using NBS to allocate the non cooperative shares (as an alternative to the three access mechanisms) for the same utility function and for a disagreement point equals to Zero for both nodes. The SU and SR shares for this case are equal to those obtained by using ETT non-cooperative access mechanism. We carried out the experiment for two nodes (SU and SR) however the same result will be applied if the bargaining are applied over more than two nodes.

To determine the nodes shares after cooperation, we adopt pairwise bargaining between each cooperating pair of nodes. Using pairwise (two-players) bargaining is preferred as the cooperation between any two players should not affect other nodes.

The Multi-player bargaining can also be applied in the case of multi-relay where the shares of more than two players (SU and two or more SRs) are reallocated between the cooperation nodes.

## 6.7 Performance Evaluation

In this section, the performance of the bargaining based cooperation is investigated. In these experiments we will evaluate the resource exchange process between the SU and SR using two different bargaining solutions and three different media access mechanisms. In some the following experiments we use a normalized metric to show the performance of the cooperation. The normalization is done by dividing the cooperative metric over the non-cooperative one.

The numerical values of different parameters are listed Table 6.1 unless other clearly specified. The value of $C_K$ is chosen to be equal 0.25 so that the cooperation is beneficial in all cooperation levels and PU activity levels. The value of $\gamma$ is set to 0.7 as empirically shown in [79] and used in [46] .

Table 6.1: Parameters numerical values.

| **Parameter** | **Value** |
|---|---|
| Number of time slots per SU packet transmission $M_{SU}$ | 32 |
| Energy evaluation factor$C_{SU} = C_{SR}$ | 0.25 |
| Reception power to transmission power ration $\gamma$ | 7/10 |

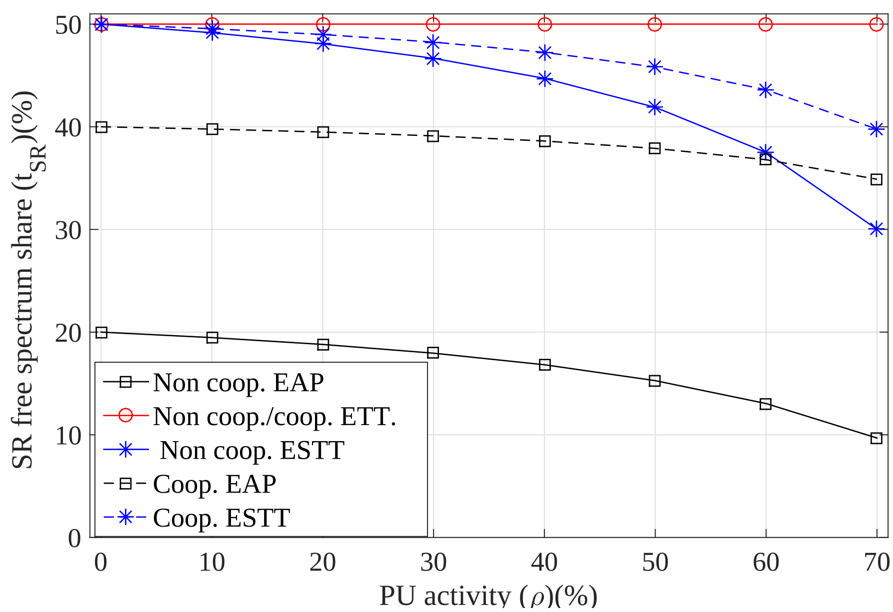



Figure 6.9: The SR shares vs. PU activity ($\rho$) for different access mechanisms for cooperation level $L_{1b}$

### 6.7.1 The Cooperation Performance with the non-cooperative Access mechanisms.

In this experiment, we investigate the performance of the cooperation between the SU and SR if the nodes has the same non-cooperative access probability. Under this condition, it is clear that for the SU, the cooperation is beneficial in terms of the throughput and utility. For the SR, the cooperation is beneficial in terms of throughput in EAP and ESTT as the SR gains more access time from the SU's time saved by cooperation,while in ETT the SR has the same throughput after and before cooperation. In terms of SR's utility, the increase in the throughput due to the cooperation may not compensate the energy consumed by SR in forwarding the SU's packets and so the SR may not be rewarded enough for its cooperation. Even if there is a utility gain received by the SR, it may not be a fair price for its power. Fig. 6.9 show the SR spectrum free time share as a function of the PU activity ($\rho$) for the three proposed access mechanism in cooperative and non-cooperative modes.

Fig.6.10 and .6.11 show the SR's beneficial cooperation PU activity threshold ($\rho_{th}$) as a function the energy evaluation factor $C_{SR} = C_{SR}$ for EAP and ESTT access mechanisms (for ETT it is always non-beneficial for the SR to cooperate), respectively. The area at the left of every curve indicates the value of $C_{SR} = C_{SR}$ and the PU activity threshold $\rho_c$ where the cooperation is beneficial to the SR in terms of the utility. For example, for $L_1b$ EAP shown in Fig. 6.10, before $C_{SR} = C_{SR} = 0.3$ the cooperation is beneficial at any PU activity.

For $0.3 < C_{SR} = C_{SR} \leq 0.52$ the cooperation is beneficial after a certain threshold value of PU activity $\rho_{th}$. In this interval, at low value of $\rho$ the cooperation may not beneficial for the SR as any throughput gain will not compensate its relaying power. When the PU activity increases, the SU negatively affects the SR performance as it reduce its access time share (as shown in Fig. 6.7) in a way SR finds that, if it cooperates with the SU, the gain it will get, in terms of throughput, will compensate its relaying power. After $C_{SR} = C_{SR} = 0.52$ the cooperation is not beneficial for the SR at any value of PU activity.

Form the figure, it is clear that the whether or not the SR benefits from the cooperation depends mainly on the level of cooperation (For the SR, the amount of energy it consumed in forwarding the SU's packets), the SR's energy evaluation factor, and the PU Activity level. As the cooperation level increases, it means the SR will dissipate less power in forwarding the SU's packet (level 2 and level 1b compared to level 1a) and there are more saved time to reallocate for the SR (level 2 compared to level 1a and 1b). The SR's energy evaluation factor effect is clearly shown in the figures where at low value of $C_{SR}$, the SR may benefit from the cooperation but this benefit may vanish for high $C_{SR}$ values.

Last note here is about the number of node in the network. In the previous example, we assumed that the amount saved from the SU's share due to cooperation will be redistributed between the SU and the SR only. If there are more nodes in the network and the amount of shares distributed among all of them and the cooperation will be beneficial only at lower value of $C_{SR}$.

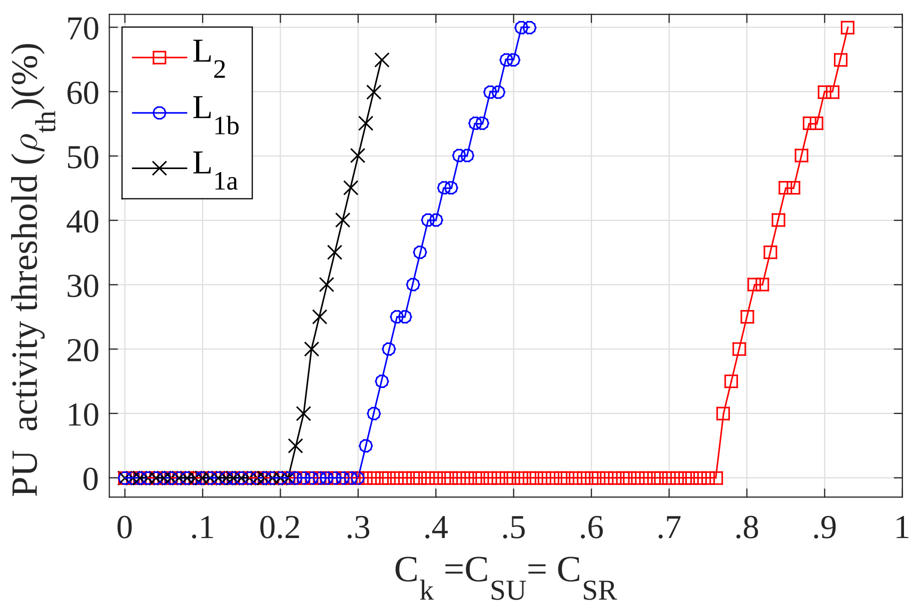



Figure 6.10: SR's beneficial PU activity threshold $(\rho_{th})(\%)$ vs. $C_K$ for EAP.

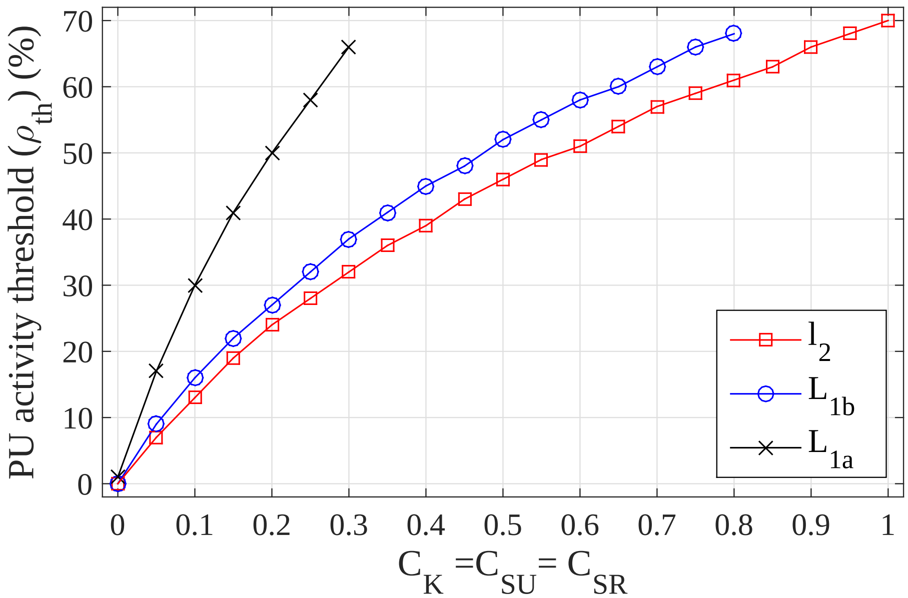



Figure 6.11: SR's beneficial PU activity threshold $(\rho_{th})(\%)$ vs. $C_K$ for ESTT.

### 6.7.2 The effect of the Bargaining Solution

This section evaluates the performance of different bargaining solution, namely NBS and EBS. The performance of the different bargaining solutions are evaluated for different access mechanism for $L_2$ of cooperation other levels show the same trend in the results.

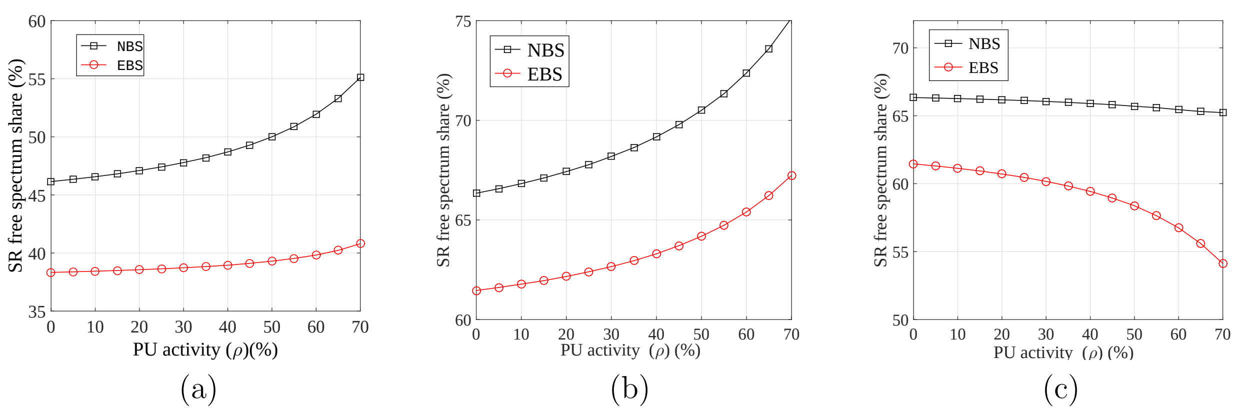



Figure 6.12: R spectrum share vs. PU activity ($\rho$) for different bargaining solution at (a) EAP, (b)ETT, and (c) ESTT non cooperative access mechanisms.

As shown in Fig. 6.12, the NBS gives more spectrum share to the SR than the EBS. That is because NBS tries to maximize the total gain of the players instead of finding a fair share as in the case of EBS.

The bargaining SR's spectrum share increases as the PU activity increases for EAP and ETT non-cooperative access mechanism and decreases for the ESTT. That can be justified by reconsidering the SR's utility defined as in equation 6.20. The bargaining solution assigns a cooperation utilities that proportional to the disagreement point (the non cooperative utility) and from this utility the shares can be calculated.

For EAP, the SR has a small share in the non-cooperative mode and so that will negatively effect its bargaining power resulting in a smaller share. The SR has to relay the SU's packets and as the SU's share is large the amount of energy the SR dissipate is also high. As the PU activity increases, the SR has to dissipate more energy to help the SU and the compensation it receives in terms of increasing the throughput compared to the non-cooperative case is not enough and so to achieve a beneficial bargaining agreement, the SR has to get more spectrum share as the PU activity increases.

In the ETT, in the non-cooperative mode, the SR is not affected by the performance of the SU and so it is disagreement utility. As a result, the SR will ask for a price that is proportional to its energy consumption as it receive no compensation in terms of throughput.

In ESTT, in contrast of ETT case, the SR performance in non-cooperative mode is affected by the SU ones and so, if the SR cooperated with the SU it may receive a throughput enhancement that overcomes its energy dissipation and achieve the targeted utility at lower SR shares. For example, moving from a value of PU activity to a higher one will result in increase of the energy consumption of the SR due to cooperation, however the relative increase in the throughput is higher and the SR needs lower share to achieve its bargaining utility.

Fig. 6.13 (a) and (b) shows the normalized utility for the SU and SR, respectively for EAP as the non-cooperative access mechanism. As shown in Fig. 6.13 (a),the utility the SR gets from NBS is higher than that from EBS as the EBS tries to give more to the SU as shown in (b). The achieved throughput also follows the same trends as shown in Fig. 6.13 (a) and (b) for the SR and SU, respectively.

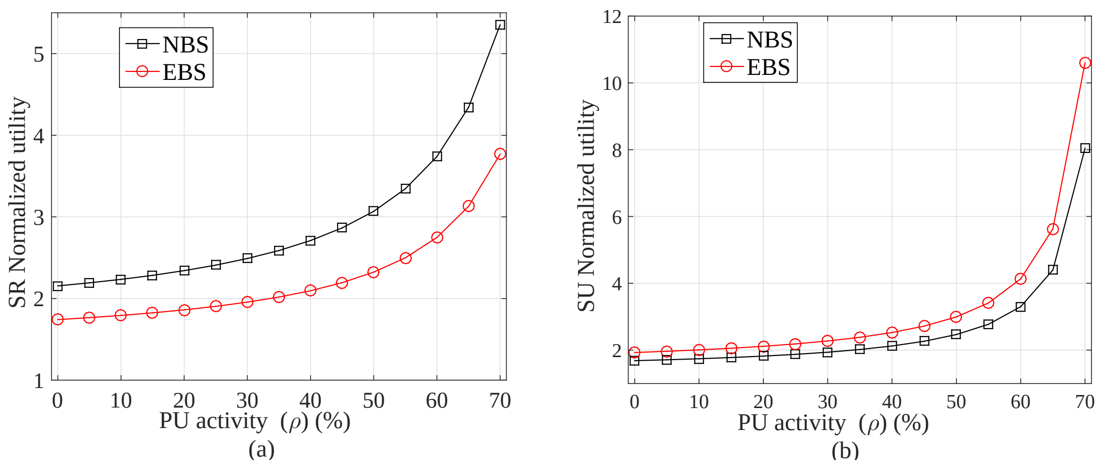



Figure 6.13: Normalized utility for (a) the SR, (b) the SU.

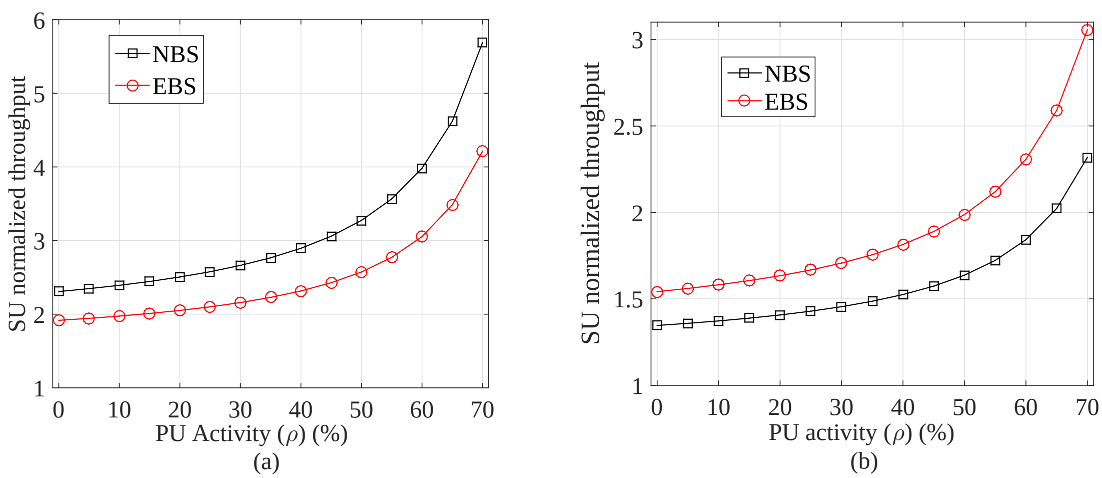



Figure 6.14: Normalized throughput for (a) the SR, (b) the SU.

The overall achieved utility is shown in Fig.6.15. As shown in the figure, the NBS achieves a higher total utility than the EBS.

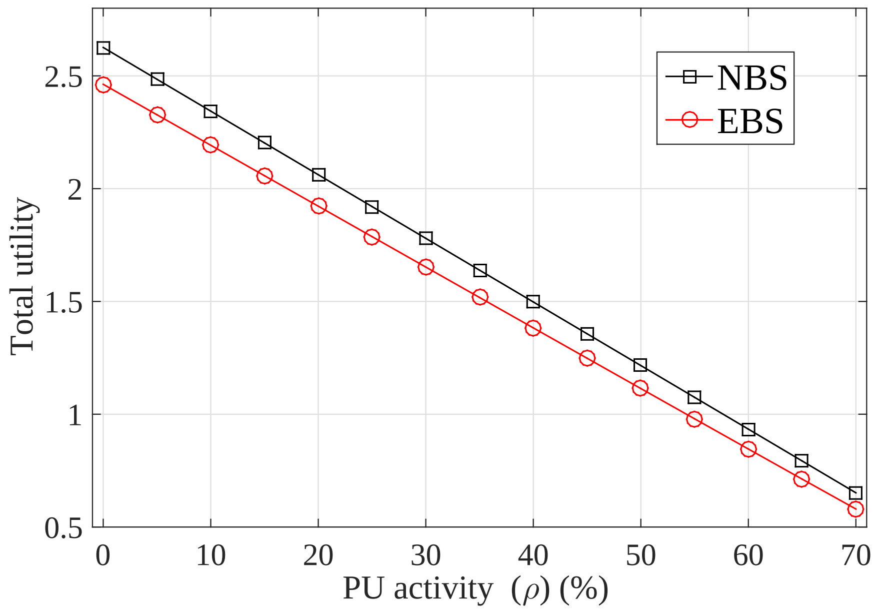



Figure 6.15: Total achieved utility for EAP using different bargaining solutions.

### 6.7.3 The Effect of the Non-Cooperative Access Mechanism ( Bargaining Disagreement Utility )

In this subsection, the effect of the non-cooperative access mechanism (the bargaining disagreement point) on the cooperation performance is investigated. The NBS is used to find the nodes shares at different cooperation levels[5].

Fig.6.16 shows the SR's spectrum shares of the non cooperative case at different access mechanism and different cooperation levels. For all cooperation levels, EAP is the best mechanism for the SU and the worst for the SR as it gives both equal access probability to the media regardless to the data rate used or the efficiency. On the other hand, ETT is the best mechanism for the SR and the worst for the SU as it does not compensate the SU and the SR for the packet loss due to the PU interruption which for the SU is more sever due to its low transmission rate. As shown in Fig. 6.16, in EAT, the SR (and consequently the SU) has fixed shares of the available free spectrum, however in terms of successful access time, the SU will have a lower successful share because it has a lower transmission efficiency. ESTT provides a more fair share between the SU and the SR as it compensate for the unsuccessful transmission attempts. Because the SU suffers from a higher retransmission rate, ESTT compensate it more than the SR especially, as the value of PU activity increases. As a result, the SR share will decrease as the PU Activity increases, but it will be higher than

[5]From this point, NBS will be used in the rest of experiments.

that of the EAP.

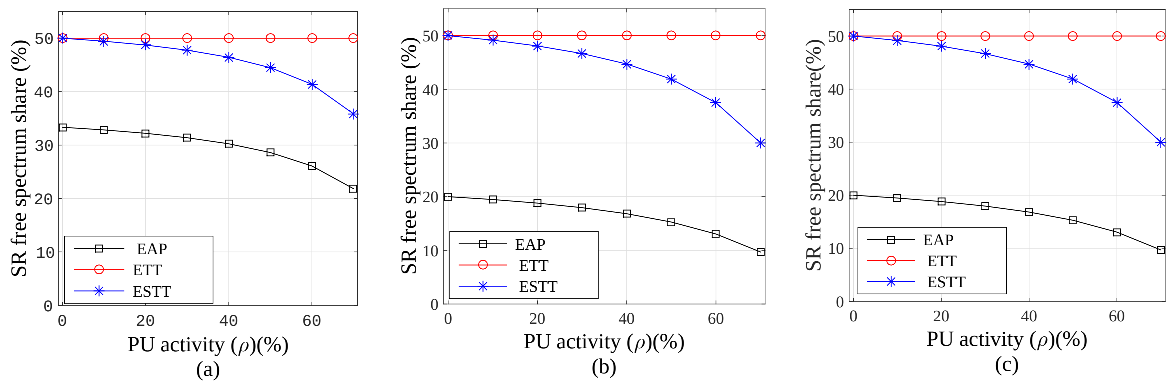



Figure 6.16: The non-cooperative SR shares for different access mechanism (a) EAP, (b) ETT and (c) ESTT.

Fig 6.17 shows the SR spectrum shares of the NBS based cooperation at different access mechanism and different cooperation levels. As shown in the figure, the SR shares mainly increases with the increase of the PU activity as it gain more access time as a price for its cooperation power. For NBS cooperation with EAP as a non cooperative mechanism, the SU achieves a higher shares compares to the non-cooperative case, and the share increases as the PU activity increase, however it is still less than the other two cases with ETT and ESTT non-cooperative mechanism, this show the effect of the disagreement point that when the SR has a small disagreement utility it accept a lower bargaining share compared to the other cases where the SR has a higher utility in the non-cooperative case. the same scenario is applied when comparing ETT and ESTT.

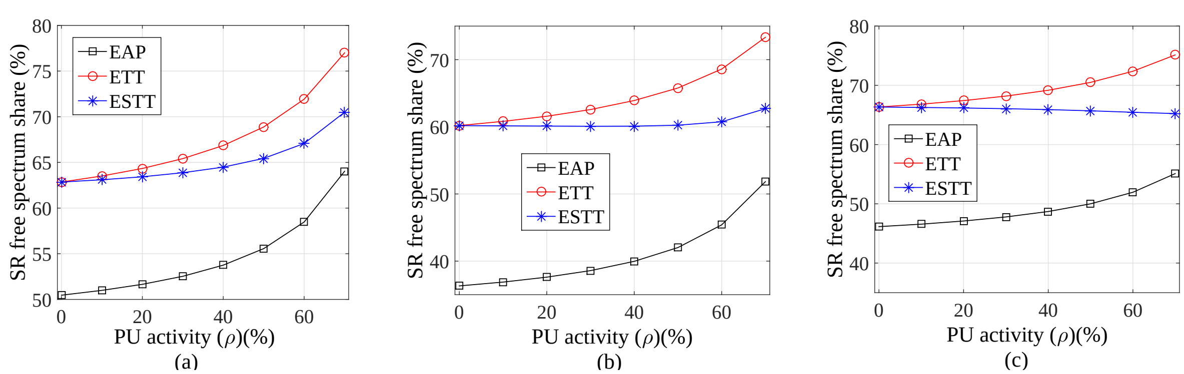



Figure 6.17: The SR NBS based cooperative share for different non-cooperative access mechanism at for different access mechanism at (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$.

Fig.6.18 shows the SR's utility for different cooperation scenarios and levels. As shown, the SR's utility achieved for cooperation when ETT is the non-cooperative access mechanism is the highest over the other two methods for all cooperation levels.

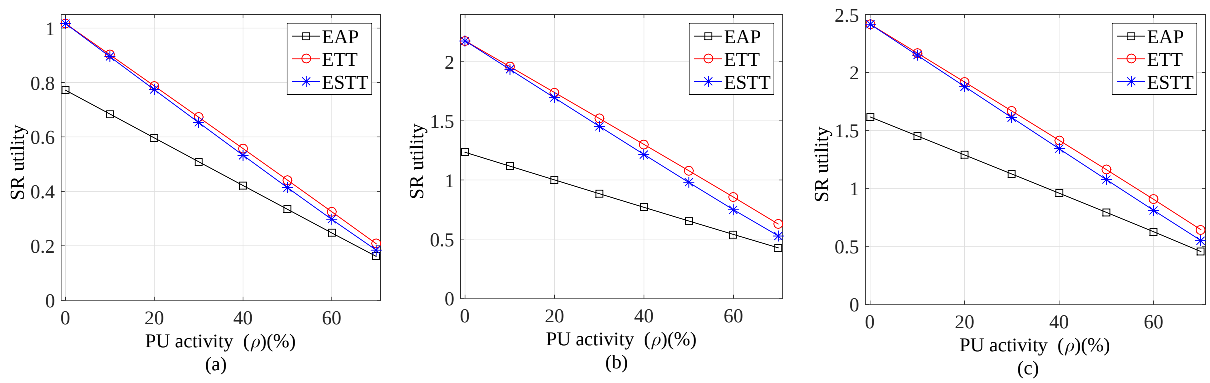



Figure 6.18: The SR NBS based cooperative utility for different non-cooperative access mechanism at for different access mechanism at (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$.

Fig.6.19 shows an alternative view for the SR's utility, by plotting the normalized utility. The results show that, the normalized utility for NBS cooperation with EAP non-cooperative access mechanism is the highest compared to the other two methods. That means, the SR benefits more from the NBS based cooperation when the non cooperative access mechanism is EAP than for ETT or ESTT.

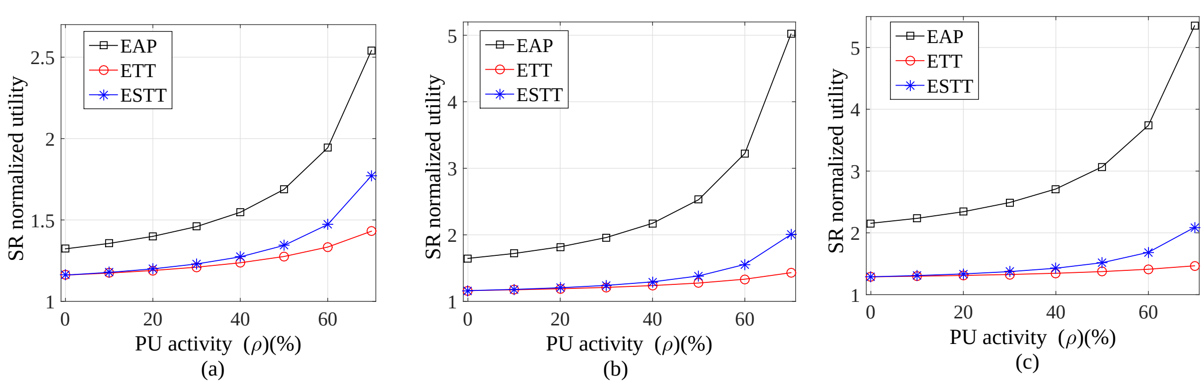



Figure 6.19: The SR NBS based cooperative normalized utility for different non-cooperative access mechanism at for different access mechanism at (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$.

Fig.6.20 shows the utility of the SU at different non-cooperative access mechanisms and cooperation levels. The SU utility for the EAP case is the highest due to the better bargaining power (highest disagreement utility) and its the lowest for ETT. The normalized utility performance shown in Fig. 6.21 shows that the SU's utility increases with the same rate for all non-cooperative starting points.

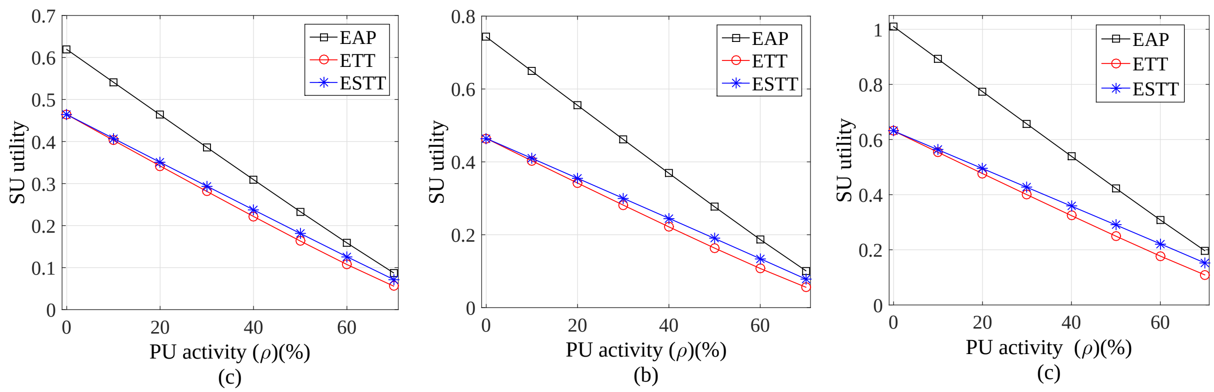



Figure 6.20: The SU NBS based cooperative utility for different non-cooperative access mechanism at (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$.

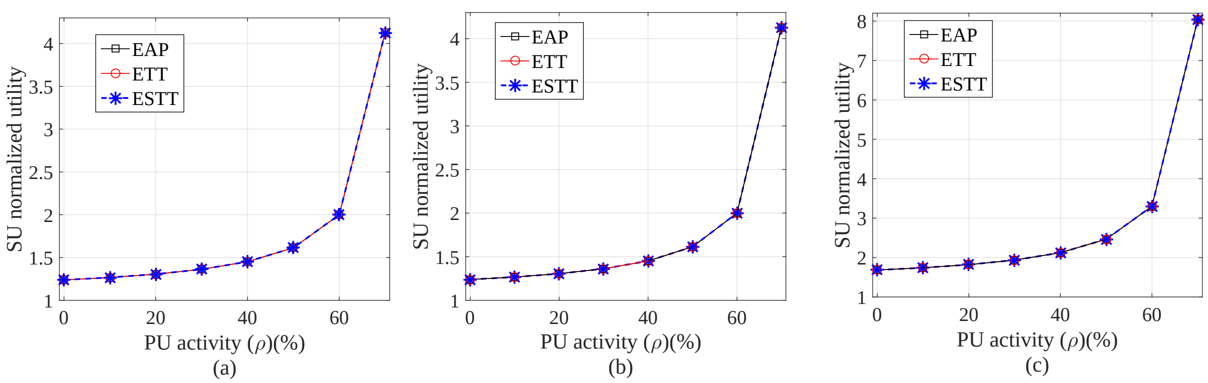



Figure 6.21: The SU NBS based cooperative normalized utility for different non-cooperative access mechanism at (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$.

The throughput performance fo the SR in the cooperative mode is shown in Fig. 6.22 and Fig. 6.23 for the achieved throughput and normalized one, respectively. The results follow the same trends as the utility curves (Fig.6.18 and Fig.6.19 ), where when the SR has EAP utility as a disagreement point it achieve the lowest throughput, however, it achieves the highest increase compared to its non-cooperative throughput.

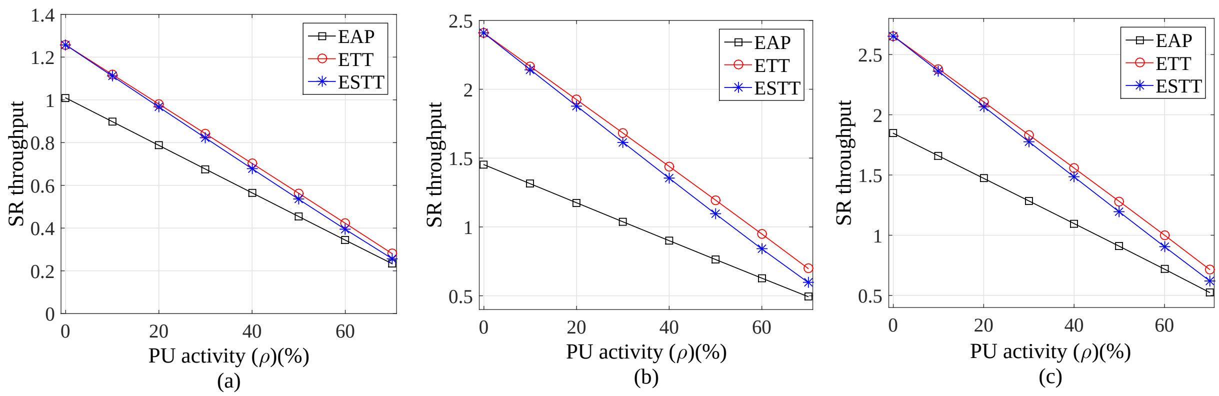



Figure 6.22: The SR NBS based cooperative throughput for different non-cooperative access mechanism at (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$.

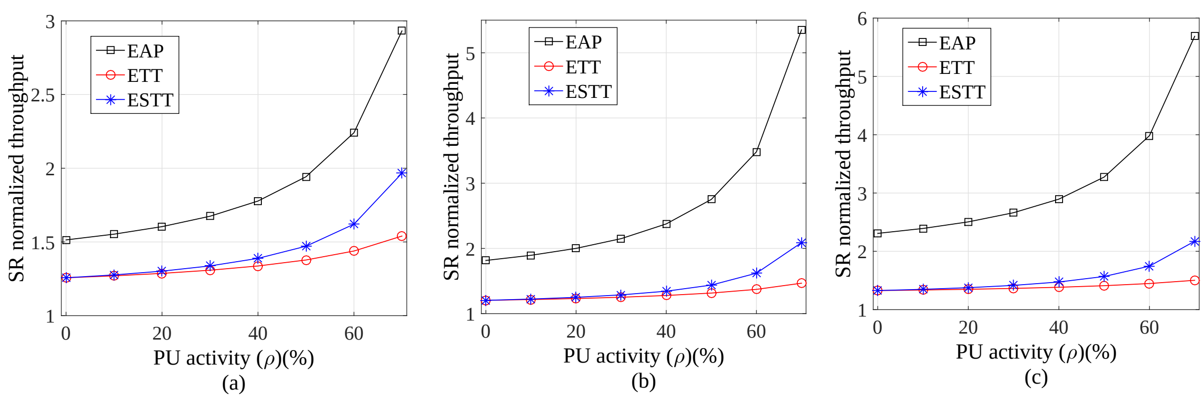



Figure 6.23: The SR NBS based cooperative normalized throughput for different non-cooperative access mechanism at (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$.

The SU throughput performance shows the same trends as its utility as shown in Fig. 6.24 and Fig. 6.25 for the SU achieved throughput and normalized throughput, respectively.

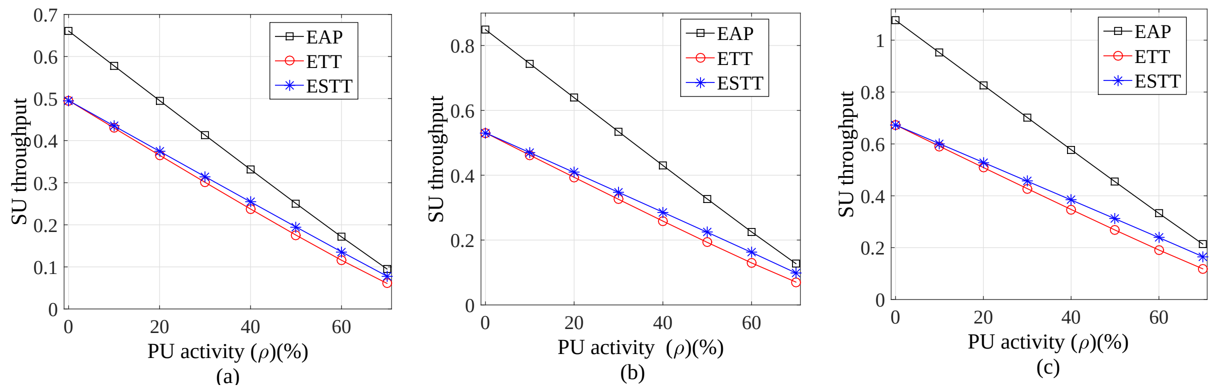



Figure 6.24: The SU NBS based cooperative throughput for different non-cooperative access mechanism at (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$

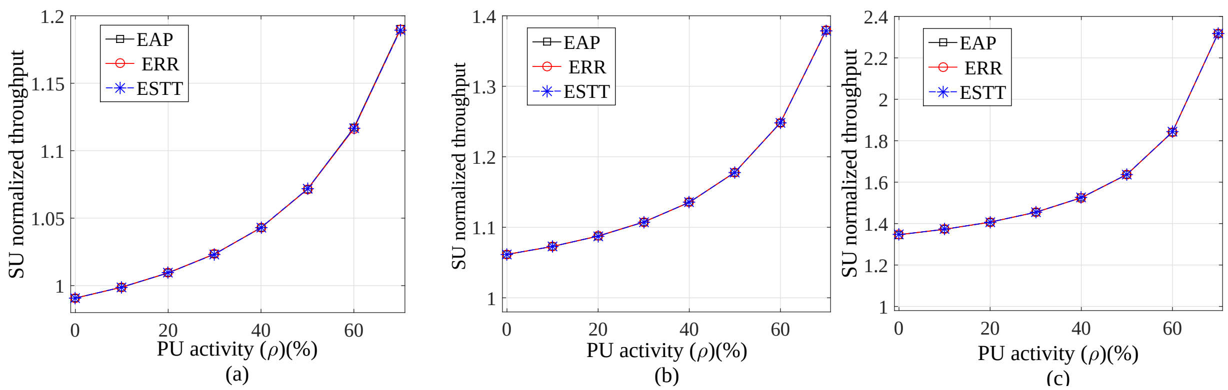



Figure 6.25: The SU NBS based cooperative normalized throughput for different non-cooperative access mechanism at (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$.

### 6.7.4 The effect of $C_k$

In this experiment, the effect of the energy evaluation factors $C_{SU}$ and $C_{SR}$ are evaluated.

As the bargaining process divide the shares based on the players' utilities, the bargaining may give a share for one of the player that results in lowering its throughput. That cannot happen to the SR as its rewarded in term of extra time, however the bargaining share of the SU may be small such that its achieved throughput is lower than the non-cooperative case. By other words the SU transmit less number of packets but with higher efficiency than the non-cooperative case and achieve a higher utility. That may not be the main target of the SU as it may prefer to achieve a higher throughput rather than achieve a higher utility.

Fig.6.26 shows the PU activity threshold for which the SU can achieve a throughput higher than the non cooperative case.

As shown in the figure, up to PU activity level equals 20% the three levels of cooperation are beneficial in terms of SU throughput. After that, for level $l1_a$ the SU can achieve a higher throughput than the non cooperative case but at PU Activity higher than zero and after $C_{SU} = C_{sk} = 0.3$ the cooperation cannot give a higher throughput for the SU than the non cooperative mode.

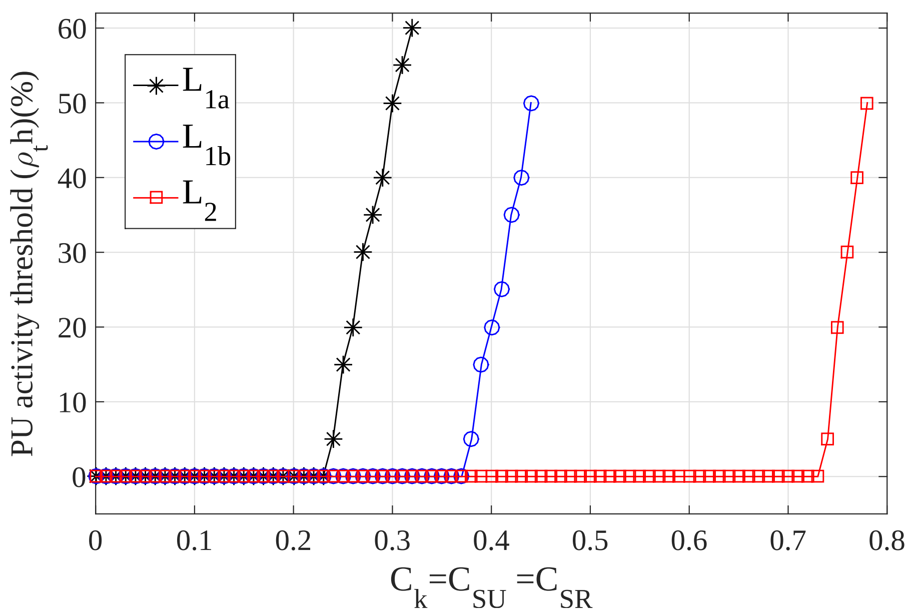



Figure 6.26: The PU threshold VS the value of $C_{SU} = C_{SR}$

Next we evaluate the performance of cooperation if the nodes (SU and SR) evaluation of the energy is not fixed but change with the environment. Fig. 6.27 shows the performance the SU's throughput when $C_{SU} = C_{su} = 1 - \rho$ for the different cooperation level using EAP for non cooperative mode. Fig. 6.28 show the same performance but when the SU and SR have a different evaluations for the energy. In this case, each node will evaluate its own energy according to its transmission efficiency $C_{SU} = \eta_{su_{non}}$ and $C_{SU} = \eta_{sr_{non}}$. when the nodes has a evaluation of the energy equals to every node transmission efficiency, as the PU activity increases the efficiency of the slow SU falls down with a higher rate compared to the fast SR and so its energy evaluation. The effect of that can be emphasized by comparing the SU performance in Fig.6.27 and Fig.6.28 where, when each node has energy evaluation equal to its own transmission efficiency the SU will get a lower share than when $C_k = 1 - \rho$ that also shown by comparing the value of $1 - \rho$ and the efficiency of the different node.

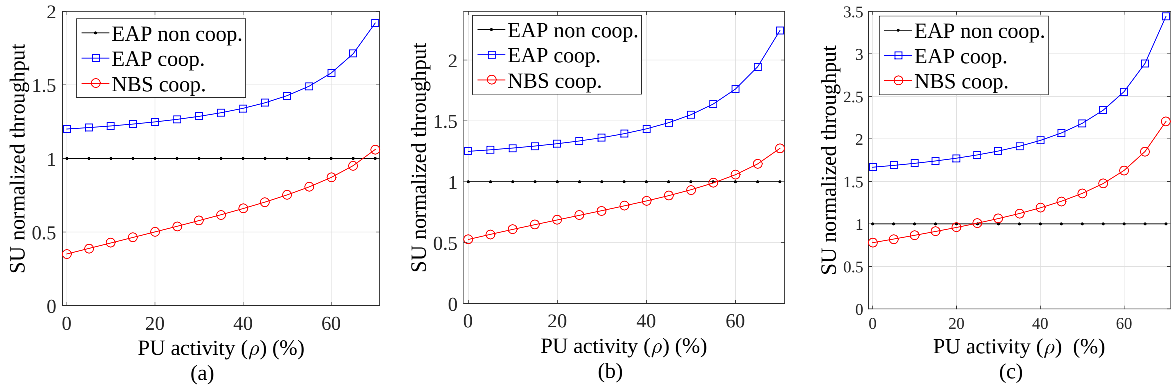



Figure 6.27: SU Normalized throughput with non cooperative EAP disagreement point when $C_{SU} = C_{SU} = 1 - \rho$ for (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$

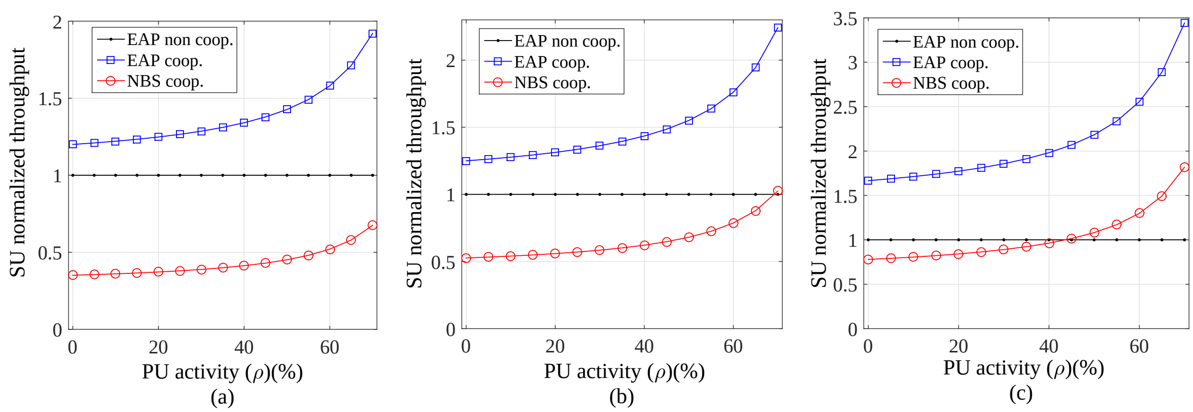



Figure 6.28: SU Normalized throughput with non cooperative EAP disagreement point when $C_{SU} = \eta_{SU_{non}}, C_{SR} = \eta_{SR_{non}}$ for (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$

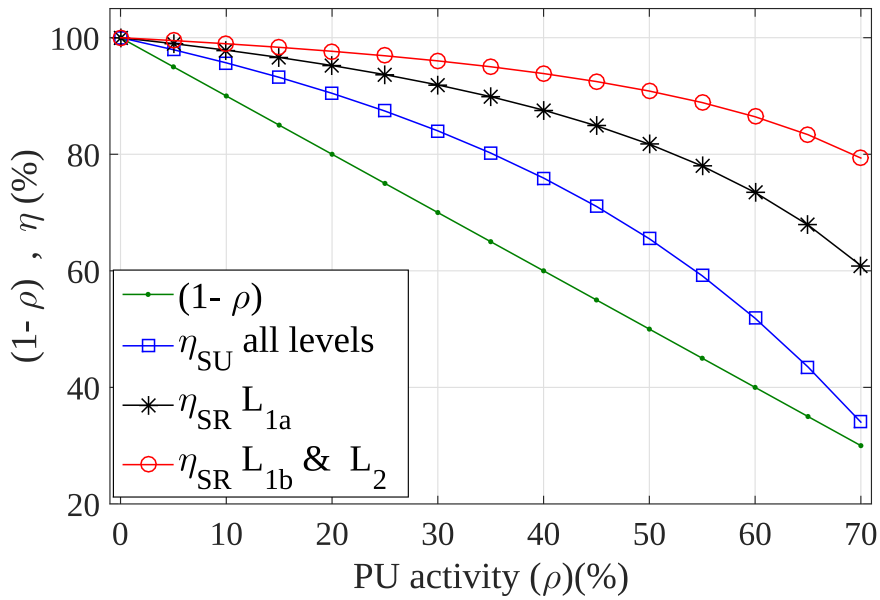



Figure 6.29: $(1-\rho)$ and the transmission efficiency of the SU and SR at different cooperation levels data rates.

A special case is when $C_{SU} = C_{SR} = 0$, in which the different node do not care about the power dissipation, for example, the nodes are connected to power supplies. In this case, the bargaining nodes will divide the additional time that will be saved from the transmission of the SU. as shown in Fig. 6.30 both the SU and SR achieve a higher throughput than the non cooperative case in all cooperation level.

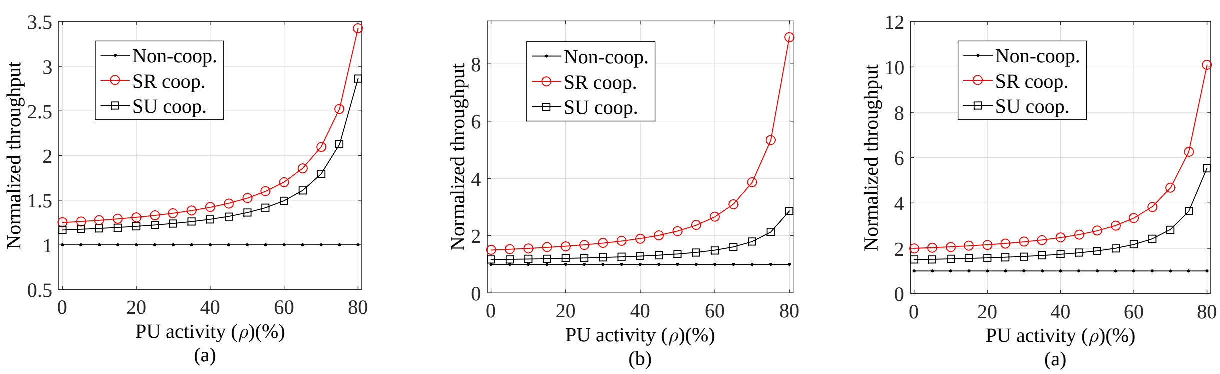



Figure 6.30: The SR and SU normalized throughput when $C_{SU} = C_{SR} = 0$ for (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$

### 6.7.5 Energy Analysis of Cooperation Schemes

In this experiment we investigate the energy performance of the cooperation scheme between the SU and SR. We use the normalized throughput to the the normalized energy ratio as a performance metric. Fig.6.31 shows the energy performance for NBS based cooperation for different cooperation levels when using EAP as a disagreement (non-cooperative) access scheme. As noticed from the figure, the cooperation enhance the energy performance higher than the non-cooperative case. Also, as the level of cooperation increases the energy performance enhances as the nodes transmit more packets for less power.

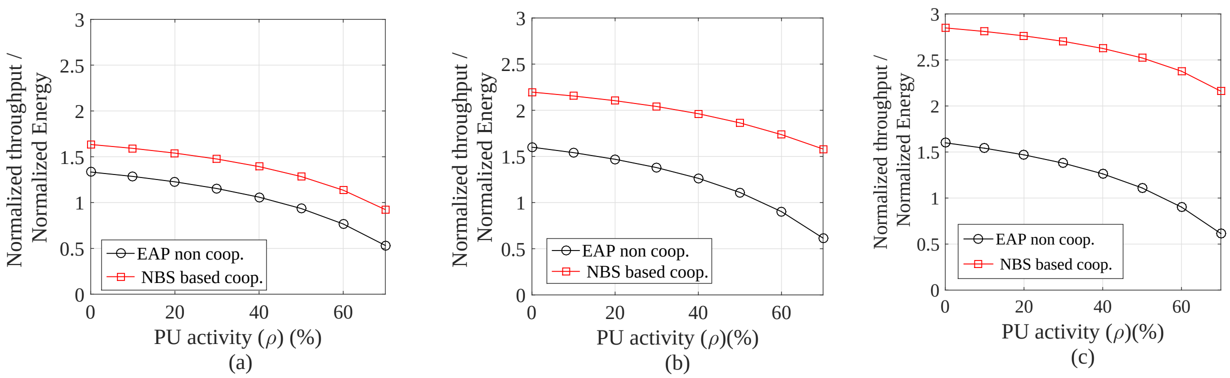



Figure 6.31: The energy performance at different cooperation levels for NBS based cooperation and EAP non cooperative access mechanisms for (a) $l_{1a}$ (b)$l_{1b}$ (c)$l_2$.

Fig.6.32 shows the energy performance for $L_2$ NBS based cooperation for different non-cooperative access schemes. ETT has the best performance as it gives more share for the SR more than ESTT and EAP and as the SR has a better energy performance the whole scheme has a better performance then the ESTT and EAP where the later has the lowest performance.

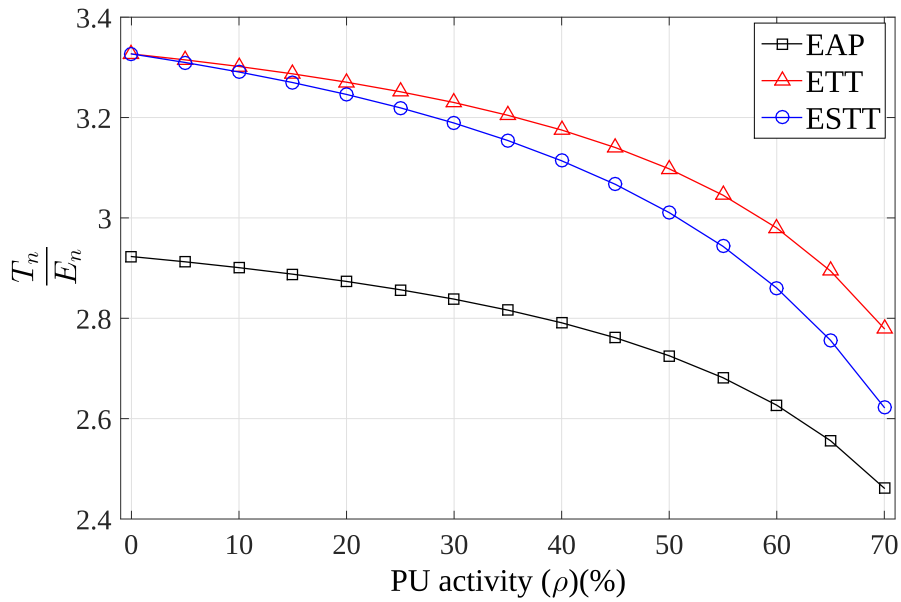



Figure 6.32: The energy performance at different for NBS based cooperation and EAP non cooperative access mechanisms.

## 6.8 Conclusion

In this chapter, we studied the performance of the cooperation between the secondary user (SU) and secondary relay (SR). To incentivise the relay to involve in the cooperation, the cooperation is modeled as a resource exchange process where the SU pays the price of the SR power by giving the SR part of its dedicated access time to the spectrum. The after cooperation shares are determined using Nash and egalitarian bargaining solutions based on a utility function that combines the throughput and the energy. The analysis was done for three different non-cooperative access mechanisms namely, equal access probability, equal transmission time, and equal successful transmission time. According to the different nodes data rates, we define three levels of cooperation based on each hop rate and the net achieved cooperative rate.

The performance of the cooperation between the SU and SR is evaluated first without changing the access probability before and after cooperation. The results show that the cooperations in such cases will not be beneficial for the SR especially at low cooperation level or at high energy evaluation factor.

The performance of the two bargaining solution is evaluated considering the three non-cooperative access method as a disagreement point and the three different level of cooperations. The NBS gives a high spectrum share to the SR compared to the EBS which tries to find a fair distribution between the SU and SR by giving more to the SU at different scenarios. In terms of the overall achieved utility, as expected, the NBS achieves higher overall utility compared to EBS for different PU activity and access scenarios.

The affect of the non-cooperative access scenario (disagreement point) on the cooperation performance was investigated. In this experiments, the utility and the throughput achieved by the SR is higher than the non cooperative case for all scenarios (EAP, ETT, and ESTT non cooperative access) at different a cooperation levels. For EAP, the NBS based cooperation utility and throughput are lower than the other two access methods , however compared to its non-cooperative counter-part it achieve the highest increase. For the SU, the EAP gives it the highest utility after cooperation as it initially give it a high bargaining power by giving it a larger non cooperative time share compared to the SR.

The effect of the energy evaluation factor $C_K = C_{SU} = C_{SR}$ on the cooperation performance is evaluated. As stated before, the cooperation with the same non-cooperative access mechanism may not be beneficial to the SR in terms of the utility, the bargaining based cooperation may decrease the throughput of the SU compared to the non cooperative case That depends mainly on how much the nodes evaluate its energy compared to the throughput.

The effect of $C_k$ clearly shows that after a certain value of $C_{SU} = C_{SR}$ the SU throughput will be lower than the non cooperative counterpart and the SU may not accept the cooperation offer for all values of PU activities. It also shows that at a certain range of $C_k$ the cooperation may turn to be beneficial if the PU activity increased.

The results show also that as the cooperation level between the SU and SR increases, the cooperation will be beneficial for the SU up to a higher values of $C_k$.

The effect when $C_k$ is dynamic is also investigated. First, we considered the case when both $C_{SU} = C_{SR} = 1 - \rho$, where $\rho$ is the PU activity, then the case where each node has a different evaluation for its own energy and equals to its transmission efficiency. For both methods, the PU threshold in which the cooperation turned to be throughput beneficial for the SU was found.

The final case is a special case when the SU and SR have $C_{SU}, C_{SR} = 0$ in which the nodes do not care about the consumed energy and the result is that the cooperation is always beneficial and the nodes divide the extra access time saved due to cooperation.

In terms of the energy efficiency, cooperation show a better performance than the direct transmission especially at higher cooperation levels.

# Chapter 7

# Bargaining-based Node Pairing and Channel Allocation in Secondary Infrastructure Networks

In this chapter [1], we investigate the optimal ways to pair the secondary nodes and allocate channels to them in a secondary infrastructure networks. The objective is to achieve maximum network throughput or to minimize the maximum difference between any node demand and its achieved throughput.

## 7.1 Introduction

In the previous chapter we introduce our framework to enable the cooperation between secondary users based on the idea of resource exchange. The bargaining based shares will be used to determine the optimal way to allocate the resources [2] in secondary infrastructure network.

The resource allocation problem in cooperative and cognitive networks was studied in prior research such as[49, 56–58]. However, none of this prior work fits in our problems for the three reasons listed below, all of which our proposed work aims to address.

- We consider the channels' primary users activity levels as a main characteristic of the channels.
- We consider the cooperation agreement conditions between a secondary users and its relay.

[1] This chapter is based on work to be presented in [80].
[2] Resources in this chapter refer to free access time, channels and relays

- We consider the spectrum free time as the shared resource between the secondary users to trade.

In our research, we take into consideration the above mentioned points We will start by formulating the pairing and channel allocation problem when the free spectrum shares of every node is determined according to Nash Bargaining Solution (NBS), with different non-cooperative access mechanisms.The problems are formulated in a linear integer programming (ILP) form. Then, we will consider two other approaches. In the first one, the shares of the cooperating nodes are jointly optimized but within the limits of the total non-cooperative shares of the two cooperating nodes. The second approach is to optimize the shares of all nodes using the same channel regardless of the cooperation relation between different node.

## 7.2 Network Model

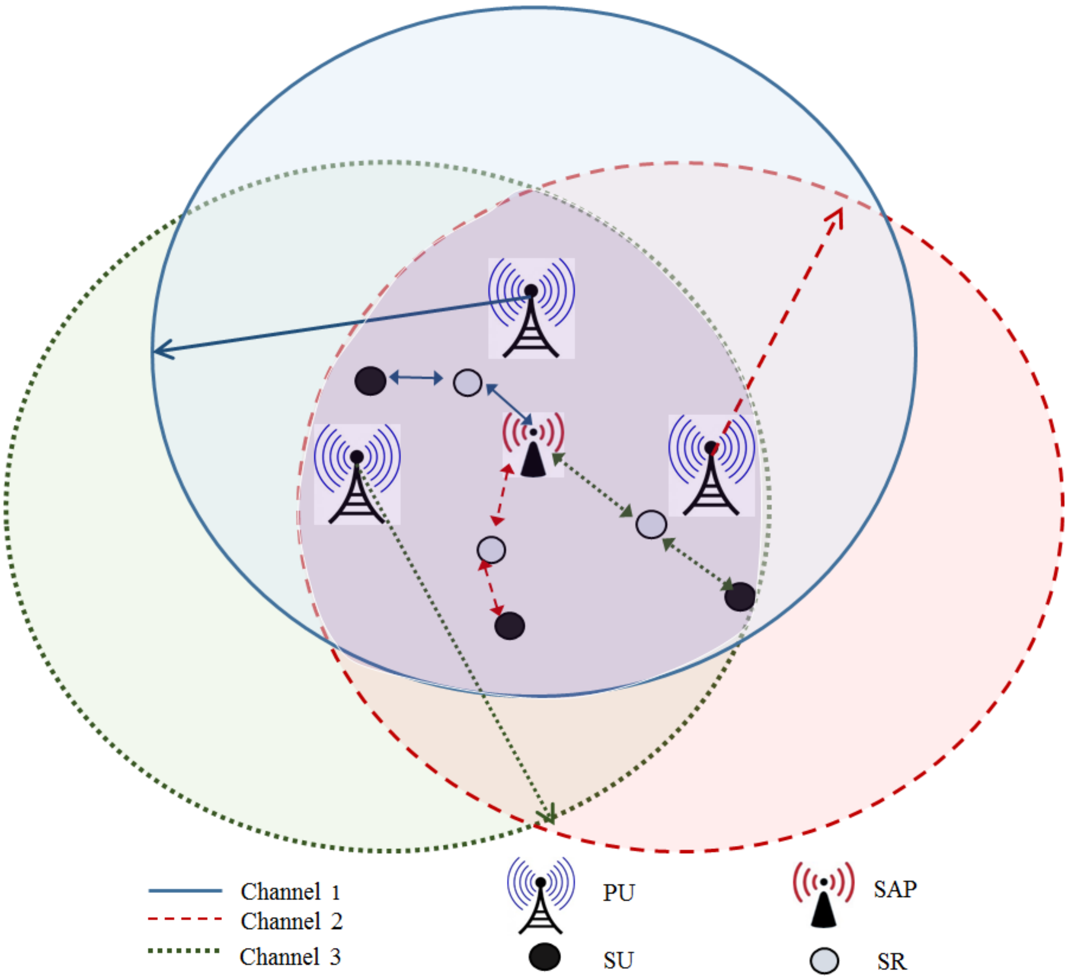



Figure 7.1: Cooperative multi-channel secondary network.

We consider an infrastructure network as shown in Figure 7.1 with a $\in \mathcal{N} \stackrel{def}{=} \{1, 2, ...N\}$ of SUs uniformly distributed within an area that is divided into a number of regions characterized by the direct transmission rate $R \in \mathcal{R}_{\mathcal{D}} \stackrel{def}{=} \{R_1, R_2, ...R_l\}$ between each region's SUs and the SAP. Every SU $n$ can transmit/receive packets from the SAP with a rate $R_n \in \mathcal{R}$, in addition, each SU is able to transmit to other SU $r$ using direct transmission rate $R_{nr} \in \{0, R_1, R_2, ...R_l\}$ where $R_{nr} = 0$ means that these two SUs are out of the transmission range of each other. There a set of transmission channels $\mathcal{C} \stackrel{def}{=} \{1, 2, ...C\}$, each one is characterized by its primary user activity $\rho_c$. The initial access time share $I_n$ for nodes $n$ defines how much free spectrum access time share the node will get without using cooperation. The value of $I_n$ depends on the non-cooperative access mechanism used, the node data rate and the transmission efficiency. The initial share value for the different access mechanisms are determined for every non-cooperative access mechanism as follows:

1. *Equal Access Probability (EAP) Initial Shares:* In EAP nodes get equal access to the spectrum. In the case that all node has the same packet size, the initial share vector for $N$ nodes sharing the same channel should be as follows:

$$I_{EAP} = \left[ \left( \frac{R_{max}}{\eta_1 \cdot R_1} \right), \left( \frac{R_{max}}{\eta_2 \cdot R_2} \right), \ldots, \left( \frac{R_{max}}{\eta_N \cdot R_N} \right) \right], \tag{7.1}$$

   where $\eta_n$ is the transmission efficiency of node $n$ and $R_{\max}$ is the maximum rate in the network.

2. *Equal Transmission Time (ETT) Initial Shares:* In ETT, nodes get equal access time shares regardless of their transmission rate or efficiency, which leads to initial shares vector to be as follows:

$$I_{ETT} = [1, 1, \ldots, 1]. \tag{7.2}$$

3. *Equal Successful Transmission Time (ESTT) Initial Shares:* In ESTT, nodes get equal successful access time shares as they are compensated for their loss due to PU interruptions. The ESTT initial share vector can be expressed as follows:

$$I_{ESTT} = \left[ \left( \frac{1}{\eta_1} \right), \left( \frac{1}{\eta_2} \right), \ldots, \left( \frac{1}{\eta_N} \right) \right]. \tag{7.3}$$

For every pair of SUs if they agreed to cooperate, they will redivide their initial shares among themselves according to their utilities using NBS, the share division ratios between of node $n$ when cooperating with node $r$ over channel $c$ is defined as $S_{cnr}$ where $S_{cnr} = (1 - S_{crn})$ and $S_{cnn} = 0.5 \quad \forall n, r \in \mathcal{N}, \forall c \in \mathcal{C}$ where$S_{cnn}$ represents the direct transmission share of node $n$ .
The transmission rate $R_{cnr}$ is the net achieved rate for node $n$ if it cooperates with node $r$ over channel $c$, and $R_{cnn}$ represents the direct transmission rate of node $n$ over channel $c$. The values of $S$ and $\eta$ are pre-calculated as mentioned in the previous chapter.

## 7.3 Node Pairing and Channel Allocation Problem

In this section, we provide the mathematical formulation for the two optimization problems of nodes pairing and channel allocation in secondary infrastructure networks.

Let $x_{cn}, c \in \mathcal{C}, n \in \mathcal{N}$, be a binary variable that represent the channels allocation such that:

$$x_{cn} = \begin{cases} 1, & \text{if SU } n \text{ will operate over channel } c \\ 0, & \text{otherwise} \end{cases}$$

and $y_{nr}$, $n, r \in \mathcal{N}$ , be a binary variable that indicates the cooperation relation between secondary nodes such that:

$$y_{nr} = \begin{cases} 1, & \text{if nodes } n \text{ and } r \text{ will cooperate} \\ 0, & \text{otherwise.} \end{cases}$$

Two notes to be taken into consideration. First, if $y_{nn} = 1$ that means the SU $n$ will use direct transmission. Second, the cooperation rule between two SUs is not reversible, that means if node $r$ will help node $n$, node $n$ cannot help node $r$.
The achieved throughput $\hat{T}$ of node $n$ is defined as follows:

$$\hat{T}_n = \sum_{c \in \mathcal{C}} \sum_{r \in \mathcal{N}} \left\{ x_{cn}\, y_{nr}\, B_{cnr}\, R_{nr}\, \eta_{cnr} \left( \frac{1 - \rho_c}{\sum_{l \in \mathcal{N}} x_{cl}\, I_l} \right) \right\}, \tag{7.4}$$

where $B_{cnr}$ is the bargaining based spectrum time share for node $n$ that cooperates with node $r$ over channel $c$ and equals to,

$$B_{cnr} = (I_n + I_r) \cdot S_{cnr} - \left( \frac{\sum_{i \in \mathcal{N}} y_{ni} - 1}{\sum_{i \in \mathcal{N}} y_{ni}} \right) I_n. \tag{7.5}$$

The second term in (7.5) is subtracted to ensure that, in the case that the SR helps more than one SU, the share of the SR is not counted more than one time. Node $n$ demand $d_n$ is set to be proportional to its data rate capability and equals to $\frac{R_n}{R_{min}}$ where $R_{min}$ is the minimum rate in the network. The SAP tries to achieve $\beta \times 100\%$ of each node's demand where $0 \leq \beta \leq 1$ .

## 7.3.1 Bargaining-based shares resource allocations problem

We define two optimization problems that depend on calculating the cooperating nodes spectrum access shares using Nash bargaining solution with two different objectives. The first optimization problem named BBS-MXNT and aims to maximize the network throughput where the shares of every node is based on the Nash bargaining solution as discussed in the previous chapter. The solution must satisfy a fixed percentage of all nodes demands.

**Problem 1 (BBS-MXNT):**

$$\underset{\{x_{cn}, y_{nr}\}}{\text{maximize}} \left\{ \sum_{n \in \mathcal{N}} T_n \right\} \tag{7.6}$$

subject to:

$$\sum_{c \in \mathcal{C}} x_{cn} = 1, \forall n \in \mathcal{N} \tag{7.7}$$

$$y_{nr} = y_{rn}, \forall n, r \in \mathcal{N} \tag{7.8}$$

$$\sum_{r \in \mathcal{N}_s} y_{zr} = 1, \forall z \in \mathcal{N}_s \tag{7.9}$$

$$x_{cr} \geq x_{cn}\, y_{nr}, \forall c \in \mathcal{C}, \forall n, r \in \mathcal{N} \tag{7.10}$$

$$\sum_{r \in \mathcal{N}} y_{nn}\, y_{nr} \leq 1, \forall n \in \mathcal{N} \tag{7.11}$$

$$T_n \geq \beta\, d_n \tag{7.12}$$

$$x_{cn} \in \{0, 1\}, \forall c \in \mathcal{C}, \forall n \in \mathcal{N} \tag{7.13}$$

$$y_{nr} \in \{0, 1\}, \forall n, r \in \mathcal{N}. \tag{7.14}$$

Constraint (7.7) ensures that every SU will operate only over one channel. Constraint (7.8) ensures that the cooperation matrix is symmetric. Constraint (7.9) ensures that every slow node $s \in \mathcal{N}_{\mathcal{S}}$ (Nodes with low direct transmission data rate that asks for a relay help ) receives help by, at maximum, one relay. To ensure that every cooperating pair's nodes belong to the same channel, constraint (7.10) is used. If the SR $r$ is helping one SU or more it should not have its $y_{rr} = 0$ and that ensured by using constraint (7.11).

Constraint (7.12) ensures that every node gets $\beta \times 100\%$ of its demand. The previous formulation gives the slow nodes the minimum demand while allocating the rest of resources to the other nodes with high rate. The problem will fail to achieve a solution, if for any node constraint (7.12) is not satisfied.

Another problem named BBS-MNMXD is defined with an objective to ensure fairness among different nodes. The new objective is to minimize the maximum difference between $\beta \times 100\%$ of any node's demand and its achieved throughput. As in BBS-MXNT, the cooperating nodes shares are determined using Nash bargaining solution. For this objective, constraint (7.12) is relaxed so the problem will always find a solution.

**Problem 2 (BBS-MNMXD):**

$$\underset{\substack{x_{cn}, y_{nr}, \\ c \in \mathcal{C}, n, r, \in \mathcal{N}}}{\text{minimize}} \ \underset{n \in \mathcal{N}}{\text{maximum}} \left\{ \frac{\beta \ d_n - T_n}{\beta \ d_n} \right\} \tag{7.15}$$

Subject to:

(7.7)-(7.11),(7.13), and (7.14).

### 7.3.2 Joint Shares Resource Allocation Problem

In this formulation, the shares of node $n$ cooperating with node $r$ over channel $c$ ($S_{cnr}$) is not pre-determined according to the bargaining process like in BBS-MXNT and BBS-MNMXD, but they are jointly optimized to achieve the optimization objective. In this problem, the share of any of the cooperating nodes is limited by the total share of itself and its cooperation partner so it cannot affect other nodes in the network. The first problem named JOS-MXNT and aims to maximize the total network throughput and satisfies all nodes' demand with a certain percentage.

**Problem 3 (JOS-MXNT):**

$$\underset{\{x_{cn}, y_{nr}\}}{\text{maximize}} \left\{ \sum_{n \in \mathcal{N}} T_n \right\} \tag{7.16}$$

subject to:

$$0 \leq S_{cnr} \leq 1, \forall c \in \mathcal{C}, \forall n, r \in \mathcal{N} \tag{7.17}$$

$$S_{cnr}\, y_{nr}\, x_{cn} + S_{crn}\, y_{rn}\, x_{cr} = y_{nr}\, x_{cn}, \forall c \in \mathcal{C}, \forall n, r \in \mathcal{N} \tag{7.18}$$

$$S_{cnn}\, y_{nn}\, x_{cn} = 0.5\, y_{nn}\, x_{cn}, \forall c \in \mathcal{C}, \forall n \in \mathcal{N} \tag{7.19}$$

$$S_{cnr}\, (1 - y_{nr})\, x_{cn} \leq\ y_{nr}\, x_{cn}, \forall c \in \mathcal{C}, \forall n, r \in \mathcal{N} \tag{7.20}$$

$$S_{cnr}\, S_{knr} \leq 0\ \forall c, k \in \mathcal{C}, \forall n, r \in \mathcal{N}, c \neq k, \mathcal{N} \tag{7.21}$$

In addition to the following constrains:

(7.7),(7.8),(7.9),(7.10),(7.11),(7.12),(7.13),(7.14).

Constraint (7.17) ensures that the share value is between $[0, 1]$. To ensures that the sum of shares of the two cooperating SU equals to 1, constraint (7.18) is used. Constraint (7.19) ensures that for direct transmission the shares equal to 0.5. Constraints (7.20) and (7.21) ensure that all the values of $S_{cnr}$ of the non cooperating nodes equal to zero.

As in the predetermined shares, the other problem named JOS-MNMXD and aims to minimize the maximum unsatisfied demand.

**Problem 4 (JOS-MNMXD):**

$$\underset{\left\{ \substack{x_{cn}, y_{nr}, \\ c \in \mathcal{C}, n, r, \in \mathcal{N}} \right\}}{\text{minimize}}\ \underset{n \in \mathcal{N}}{\text{maximum}} \left\{ \frac{\beta\, d_n - T_n}{\beta\, d_n} \right\} \tag{7.22}$$

subject to:

(7.7),(7.8),(7.9),(7.10),(7.11),(7.13),(7.14),(7.17),(7.18),(7.19),(7.20),(7.21).

### 7.3.3 Unlimited Shares Resource Allocation Problem

In this section we formulate the problem such that the nodes can get any shares without being limited by the initial shares of itself or its partner. In this formulation, the allocation of the resources may affect the shares of other nodes not involved in cooperation.

In this problem the achieved throughput of node $n$ when cooperating with node $r$ over channel $c$ has a different form than previous one, and defined as follows:

$$\hat{T}_n = \sum_{c=1}^{C} \sum_{r=1}^{N} \left\{ x_{cn}\, y_{nr}\, U_{cnr}\, R_{nr}\, \eta_{cnr}\, (1-\rho_c) \right\}, \tag{7.23}$$

The first problem named ULS-MXNT aim sto maximize the total network throughput and satisfies all nodes' demand with certain probability.

**Problem 5 (ULS-MXNT):**

$$\underset{\{x_{cn}, y_{nr}\}}{\text{maximize}} \left\{ \sum_{n=1}^{N} T_n \right\} \tag{7.24}$$

subject to:

$$0 \leq U_{cnr} \leq 1, \forall c \in \mathcal{C}, \forall n, r \in \mathcal{N} \tag{7.25}$$

$$0 \leq \sum_{r \in \mathcal{N}} U_{cnr} = (1-\rho_c) \leq 1, \forall c \in \mathcal{C}, \forall n \in \mathcal{N} \tag{7.26}$$

In addition to the following constrains:

(7.7),(7.8),(7.9),(7.10),(7.11),(7.12),(7.13),(7.14).

The other problem named ULS-MNMXD and aims to minimize the maximum unsatisfied demand.

**Problem 6 (ULS-MNMXD):**

$$\underset{\left\{\substack{x_{cn}, y_{nr}, \\ c \in \mathcal{C}, n, r, \in \mathcal{N}}\right\}}{\text{minimize}}\ \underset{n \in \mathcal{N}}{\text{maximum}} \left\{ \frac{\beta\, d_n - T_n}{\beta\, d_n} \right\} \tag{7.27}$$

Subject to:

(7.7),(7.8),(7.9),(7.10),(7.11),(7.13),(7.14),(7.25),(7.26).

### 7.3.4 Resource Allocation in Multiple Secondary Access Points Network

The previous problem investigates resource allocation when all SU are served by only one SAP. In this section, we extend the problem to a more general case when there are more than one SAP under the cover of the same PUs. The new problem includes ,in additional to relay pairing and channel allocation for SUs as before, assigning SUs to different SAPs bearing in mind that SUs utilize a certain channels must all belong to the same SAP. In other words, one channel cannot be accessed by more than one SAP's SUs.

The problem is reformulated by introducing two new binary decision variable $w$ and $v$.

Let $w_{an}$ $\forall s \in \mathcal{A}, n \in \mathcal{N}$, be a binary variable that represent the SAPs allocation for the SUs such that:

$$w_{an} = \begin{cases} 1, & \text{if SU } n \text{ is assigned to SAP } a \\ 0, & \text{otherwise} \end{cases}$$

where $\mathcal{A}$ represent the set of the available SAPs.

And $v_{ac}$ $\forall a \in \mathcal{A}, c \in \mathcal{C}$ , be a binary variable that indicates the relation between the channels and the SAPs

$$v_{ac} = \begin{cases} 1, & \text{if channel } c \text{ is assigned to SAP } a \\ 0, & \text{otherwise.} \end{cases}$$

The throughput of SU n is redefined as:

$$T_n = \sum_{a=1}^{A} \sum_{c=1}^{C} \sum_{r=1}^{N} \left\{ w_{an}\, x_{cn}\, y_{nr}\, B_{cnr}\, R_{nr}\, \eta_{cnr}\, \frac{1-\rho_c}{\sum_{l=1}^{N_{SU}} x_{cl}\, I_l} \right\} \tag{7.28}$$

As before we define two problem, the first one named MSAP-BBS-MXNT tries to maximize the total network throughput and satisfies a fixed percentage of every node demand

The problem can be formulated as:

**Problem 7 (MSAP-BBS-MXNT):**

$$\underset{\{x_{cn}, y_{nr}, w_{an}, v_{ac}\}}{\text{maximize}} \left\{ \sum_{n \in \mathcal{N}} T_n \right\} \tag{7.29}$$

subject to:

$$x_{cn}\, v_{ac} \leq w_{an}\ \forall c \in \mathcal{C},\ \forall n \in \mathcal{N}, \forall a \in \mathcal{A}, \tag{7.30}$$

$$\sum_{a=1}^{A} v_{ac} = 1, \qquad \forall c \in \mathcal{C}, \quad \forall a \in \mathcal{A}, \tag{7.31}$$

In addition to the following constrains:

(7.7),(7.8),(7.9),(7.10),(7.11),(7.12),(7.13),(7.14).

Constraints (7.30) and (7.31), ensure that every channel is operated by a single SAP.

The second problem named MSAP-BBS-MNMXD aims to minimize the maximum unsatisfied demand among all nodes as follows

**Problem 8 (MSAP-BBS-MNMXD):**

$$\underset{\{x_{cn}, y_{nr}\}}{\text{minimize}}\ \text{maximum} \left\{ \frac{\beta\, d_n - T_n}{\beta\, d_n} \right\},\ \forall n \in \mathcal{N}. \tag{7.32}$$

Subject to:

(7.7)-(7.11),(7.13)-(7.14), (7.30), and (7.31)

## 7.4 Performance Evaluation

In this section, we evaluate the proposed nodes pairing and channels allocation schemes. All schemes are implemented in CPLEX [81] for a confidence interval of 90%. The numerical values of various parameters are listed in Table 7.1 unless otherwise specified. Some metrics are normalized by dividing its value to the non-cooperative counterparts. The optimization problems abbreviations and their meaning are listed in Table 7.2. The number of time slots per transmission is chosen such that it does not affect the performance as discussed in Chapter 4. The initial value of $C_k = 0.25$ is chosen such that the cooperation is beneficial for both SU and SR at all levels. A separate experiment is carried out to investigate the effect of $C_k$. The set of modulation techniques and data rates combined with the transmission power, ensure the availability of different cooperation levels. The Number of channels with their PU activities are chosen such that they span different network scenarios. The different

PU and channel parameters are investigated separately.

Table 7.1: Numerical values of various parameters.

| **Parameter** | **Value** |
|---|---|
| SU # of time slots per packet ($M_{su}$) | 32 |
| Energy evaluation factor $C_{SU} = C_{SR}$ | 0.25 |
| $\gamma$ | 0.7 (see[46]) |
| Modulation | BPSK, QPSK, 16QAM |
| Data rate | 6, 12, 24 Mbps |
| Demand ($d$) | 1, 2, 4 Mbps |
| Path loss exponent | 3.5 |
| Transmission power | 0.5 mW |
| Successful reception BER threshold | $10^{-3}$ |
| Number of nodes $N$ | 10 |
| Number of channels $C$ | 3 |
| PU activity $\rho$ | 0.4 ,0.6, 0.8 |

Table 7.2: Optimization problems abbreviations.

| **Abbreviation** | **Nodes Shares Selection** | **Objective** |
|---|---|---|
| BBS-MXNT | Bargaining-based Shares | Maximize Total Network Rate |
| BBS-MNMXD | Bargaining-based Shares | Minimize Maximum Difference between any node demand and its achieved throughput |
| JOS-MXNT | Jointly Optimizes Shares | Maximize Total Network Rate |
| JOS-MNMXD | Jointly Optimizes Shares | Minimize Maximum Difference between any node demand and its achieved throughput |
| ULS-MXNT | Unlimited Shares | Maximize Total Network Rate |
| ULS-MNMXD | Unlimited Shares | Minimize Maximum Difference between any node demand and its achieved throughput |
| MSAP-BBS-MXNT | Bargaining-based Shares | Multi-SAP Maximize Total Network |
| MSAP-BBS-MNMXD | Bargaining-based Shares | Multi-SAP Minimize Maximum Difference between any node demand and its throughput |

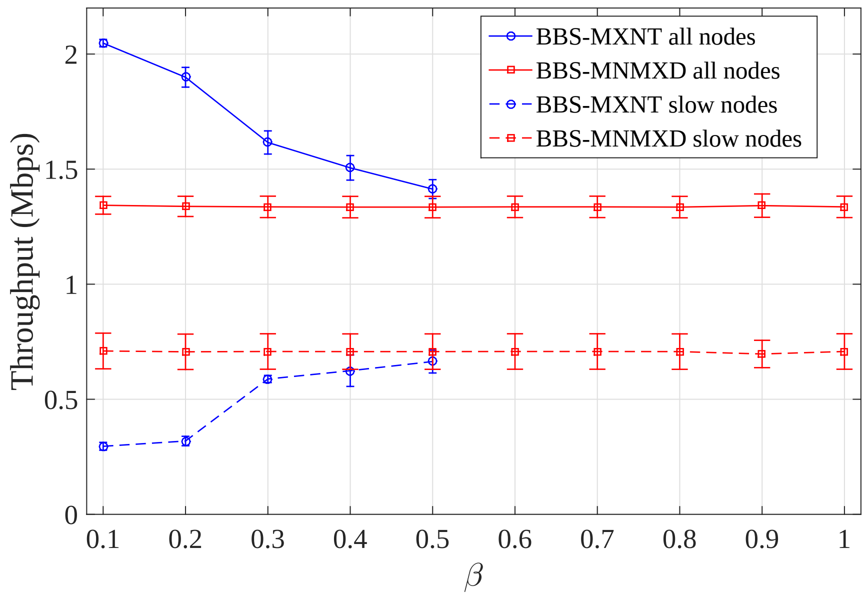



Figure 7.2: Average throughput vs. $\beta$.

**Effect of $\beta$**

Fig. 7.2 compares the performance of BBS-MXNT and BBS-MNMXD in terms of the average throughput for all nodes and for slow nodes[3] only. At low demand (low value of $\beta$) BBS-MXNT barely satisfies the demand of the slow nodes and gives the rest of resources to the nodes with high data rate. This allocation contains grouping slow nodes in a separate channels from the fast nodes so slow node do not slow down the fast ones as long as all demands are satisfied. As $\beta$ increases, the resource allocation is changed to satisfies the slow nodes demand. At this point, fast node and slow node share the same channels and cooperation is enforced to satisfy all nodes demand. That may result in lowering the fast nodes rate and the total network rate compares to low values of $\beta$. As a result, the slow nodes average rate increases and the average rate of all nodes decreases. The same trend continues until a certain value of $\beta$ (0.5 in this experiment) where after that, there is no solution for the problem. For BBS-MNMXD, the achieved throughput is mainly constant for different values of $\beta$ which means that BBS-MNMXD allocates the channels and pair nodes in a fair way that will not change as $\beta$ increases.

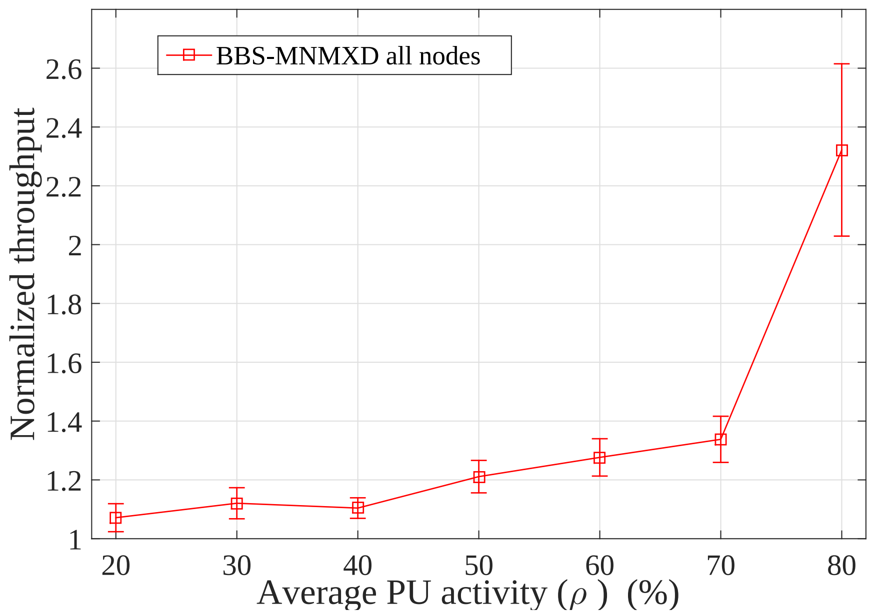



Figure 7.3: Normalized throughput vs. average PU activity ($\rho$) (%).

### Effect of PU activity $\rho$

In this experiment, we study the effect of the PU activity ($\rho$)on the achieved throughput for BBS-MNMXD. To show the effect of nodes cooperation on the throughput for different $\rho$, we compare the throughput when nodes are allowed to cooperate with that when nodes are only allowed to use direct transmission (direct transmission can be enforced by setting the value of $y_{nn} = 1, \forall n \in \mathcal{N}$). Fig. 7.3 shows the normalized throughput as a function of $\rho$. As can be inferred from the figure, the cooperative-enabled throughput is higher than that of the direct transmission and the enhancement increases as the PU activity increases because the cooperation can reduce the PU interruption effect compared to the direct transmission.

[3] As defined before, slow node is the SU that has low direct transmission data rate and benefit from the help of other SUs as relays.

**Effect of the number of secondary nodes**

As shown in Fig. 7.4, for the slow nodes, the average normalized throughput increases as the node density increases because the availability of potential relays increases. The average normalized throughput for the entire network increases even with a higher rate than that of the slow nodes. That can be understood by referring to the previous chapter SU and SR normalized throughput performance (Fig.6.23 and Fig. 6.25) where, as a result of cooperation, the relay (fast node) get much higher increase in the throughput compared to the nodes it helped. Fig. 7.5 depicts the percentage of slow nodes that utilize direct and cooperative transmission. As shown in the figure, as the node density increases the number of slow node that utilize cooperative transmission increases and so the rate of both nodes and thus the rates of both nodes increase.

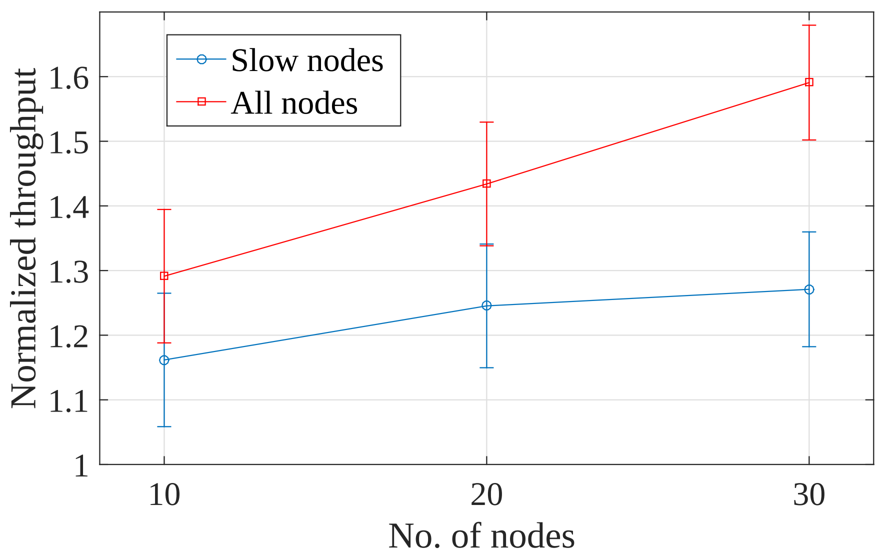



Figure 7.4: Normalized throughput vs. number of nodes, for $c = 2$ and $\rho = [0.6\ 0.8]$.

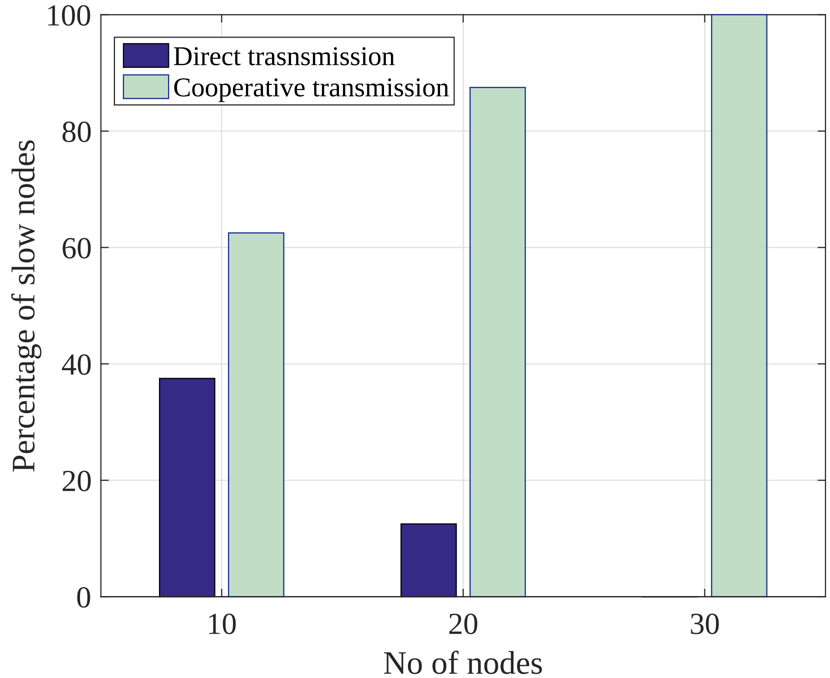



Figure 7.5: Percentage of slow nodes that utilize direct or cooperative transmission for $c = 2$ and $\rho = [0.6\ 0.8]$.

#### Effect of non-cooperative access mechanisms

In this experiment we investigate the effect of the non-cooperative access mechanisms on the performance of BBS-MXNT and BBS-MNMXD.

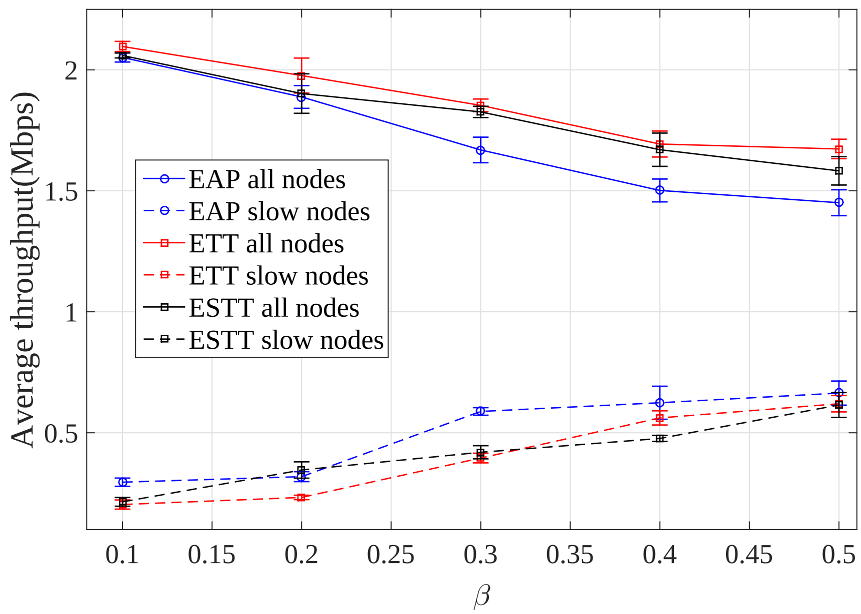



Figure 7.6: Average cooperative throughput vs. $\beta$ for different non-cooperative access mechanism in BBS-MXNT problem

Fig. 7.6 shows the average throughput for problem BBS-MXNT at different non-cooperative access mechanisms (different disagreement utilities). The average throughput achieved when EAP is the non-cooperative mechanism, is the lowest one and that for EET is the highest among the three access mechanisms. This result agreed with the previous chapter finding. When EET is used the bargaining share for the SR is higher than that if EAP is used and so the fast nodes get more access to the free spectrum, which resulted in increasing the overall throughput of the network. Even for non-cooperating nodes, there equal share used by ETT gives them larger shares compared to EAP.

For BBS-MNMXD problem, as in the EAP case, all the other non-cooperative access mechanisms has a mainly constant throughput performance regardless of the value $\beta$ with the same observation that ETT achieves the highest average throughput for all nodes, while EAP achieves the highest average throughput for the slow nodes. Fig. 7.8 shows the success rate of BBS-MXNT for different non-cooperative access mechanism, again as a result that EET gives the smallest share for the slow nodes, BBS-MXNT probability to find no solution is higher than in ESTT and EAP.

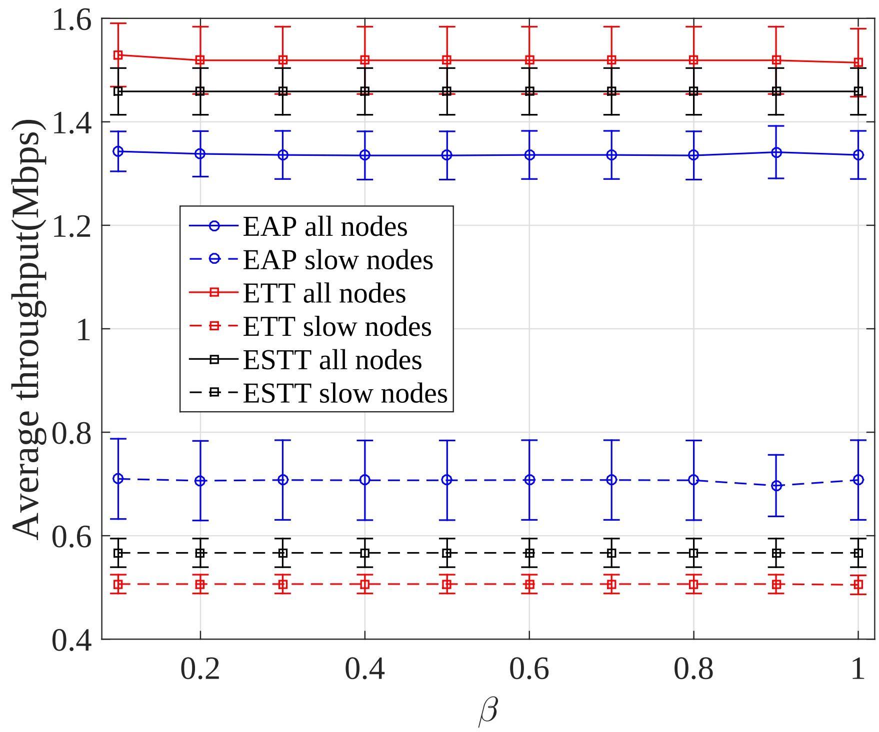



Figure 7.7: Average cooperative throughput vs. $\beta$ for different non-cooperative access mechanism in BBS-MNMXD problem

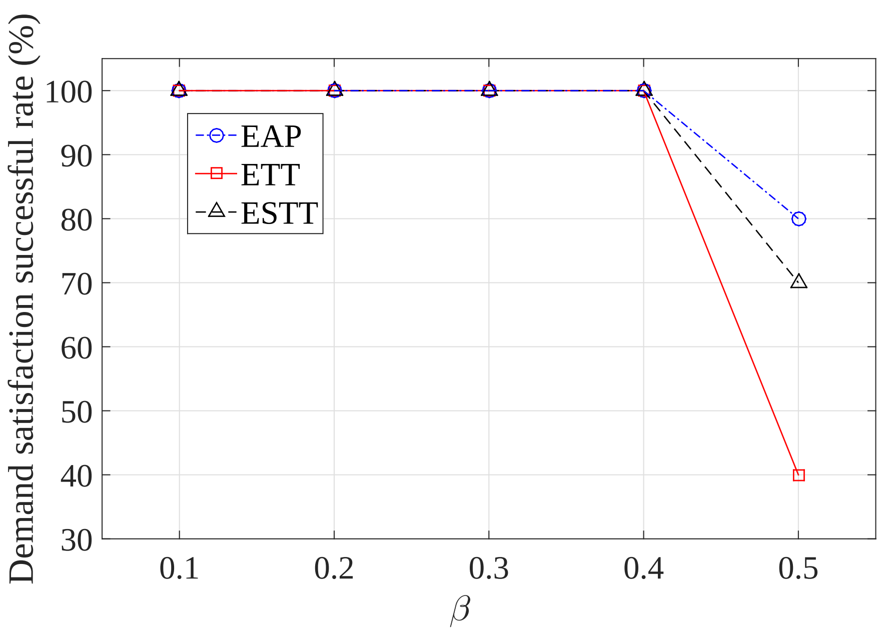



Figure 7.8: Success rate of BBS-MXNT for different non-cooperative access mechanisms

For BBS-MNMXD we evaluate the rational amount of excess capacity for every node (when node's demand is not satisfied by $\beta \times 100\%$ it means the demand shortage ratio ), which can be defined as the amount of excess capacity above the demand divided by the node demand as shown in equation (7.33).

$$EC_n = \left( \frac{\hat{T}_n - \beta \, d_n}{\beta \, d_n} \right). \tag{7.33}$$

While all the three methods achieve nearly the same average excess capacity as shown in Fig. 7.9, ESTT resulted in a bargaining shares that has the highest minimum excess demand among all access mechanisms. That can be justified because the bargaining shares resulted when ESTT is used have moderate values between ETT and EAP or by other words, in ESTT no one of the two categorize (slow node and fast node) get as extreme share as in ETT and EAP.

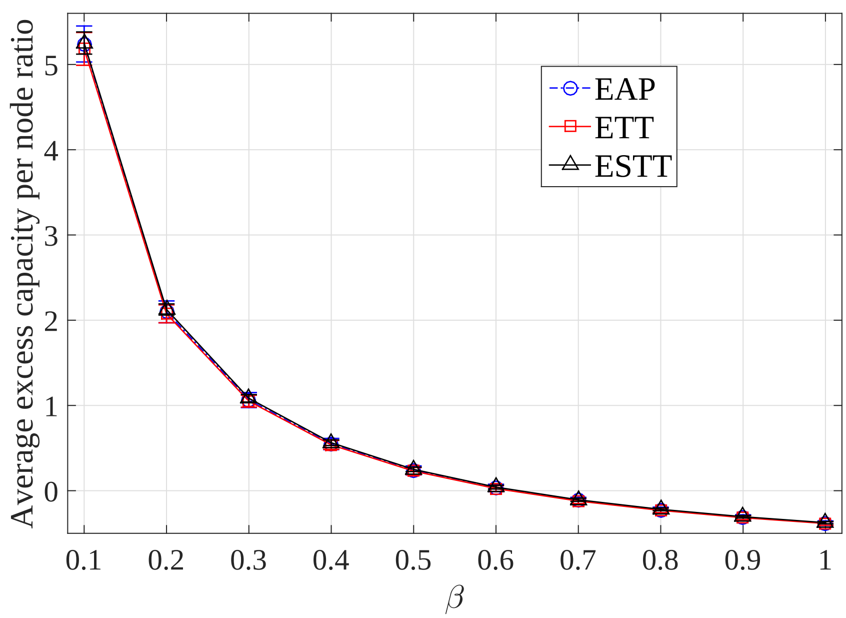



Figure 7.9: Average excess capacity for all nodes at different non-cooperative access mechanisms.

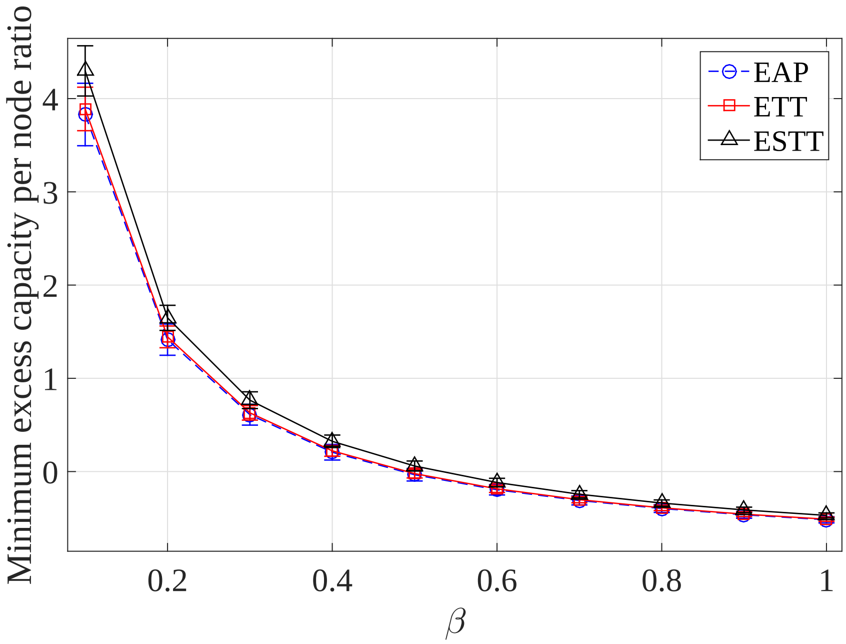



Figure 7.10: Minimum excess capacity for all nodes at different non-cooperative access mechanisms.

### 7.4.1 The non-bargaining based resource allocation problems

In this experiments we investigate the performance of the non-bargaining based resource allocations problems and compare their performance with that of BBS-MXNT and BBS-MNMXD. Fig. 7.11 shows the average achieved throughput for all and slow nodes for BBS-MXNT, JOS-MXNT, and ULS-MXNT. As shown in the figure, ULS-MXNT achieve the highest throughput among all schemes as it tries to allocate most of the resources to the nodes with fast data rate without being bounded by the initial shares of the different node, also it can satisfy all nodes minimum demand at higher value of $\beta$ compared to the two other schemes. BBS-MXNT achieve the lowest average demand, but it has the highest one for the slow nodes. JOS-MXNT achieves a moderate performance between ULS-MXNT and BBS-MXNT. On the average ULS-MXNT average throughput is around only 15% higher than BBS-MXNT. However, BBS-MXNT preserves the rights of slow node to achieve a throughput that is probational to their utility and non-cooperative performance.

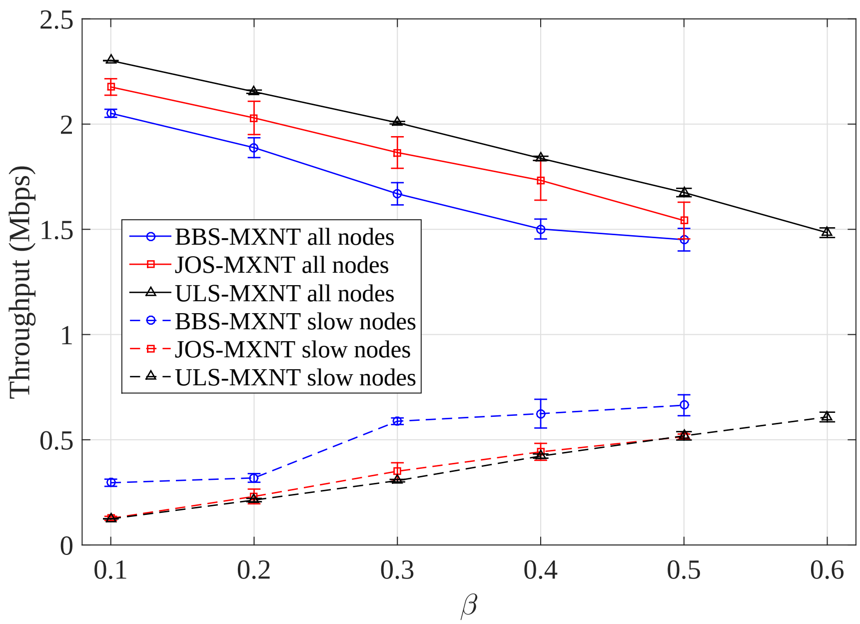



Figure 7.11: Average throughput performance for BBS-MXNT, JOS-MXNT, and ULS-MXNT.

Fig. 7.12 and Fig. 7.13 show the average and minimum excess capacity ratio for the different problems. As shown in Fig. 7.12 all the three schemes have almost the same performance. However, ULS-MXNT has a slightly higher minimum excess capacity as shown in Fig. 7.13

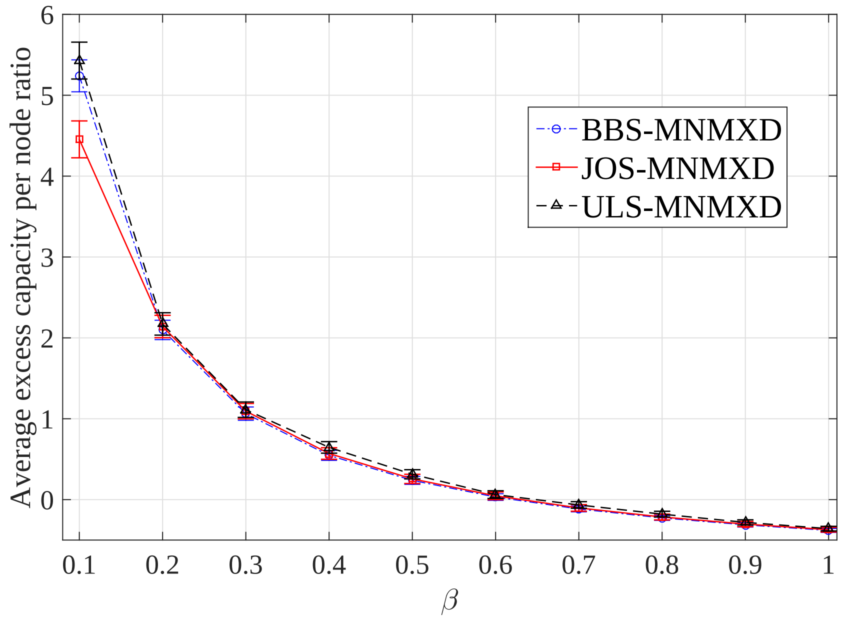



Figure 7.12: Average excess capacity ratio performance for BBS-MXNT, JOS-MXNT, and ULS-MXNT.

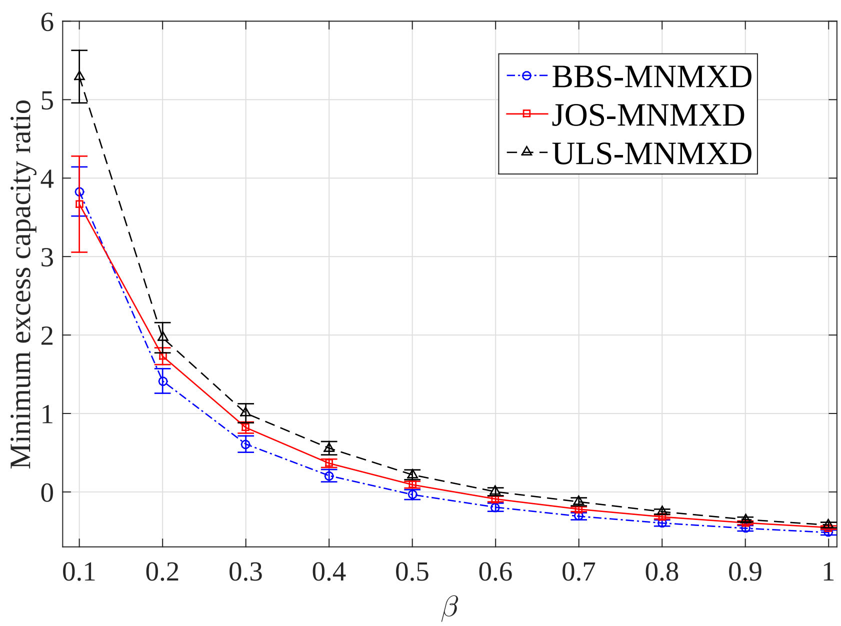



Figure 7.13: Minimum excess capacity ratio performance for BBS-MXNT, JOS-MXNT, and ULS-MXNT.

### 7.4.2 Multi-SAP Secondary Network

In this experiment we compare the performance of secondary network with single SAP with that of two SAP. To achieve a fair comparison we doubled the number of nodes and the number of resource (channels).

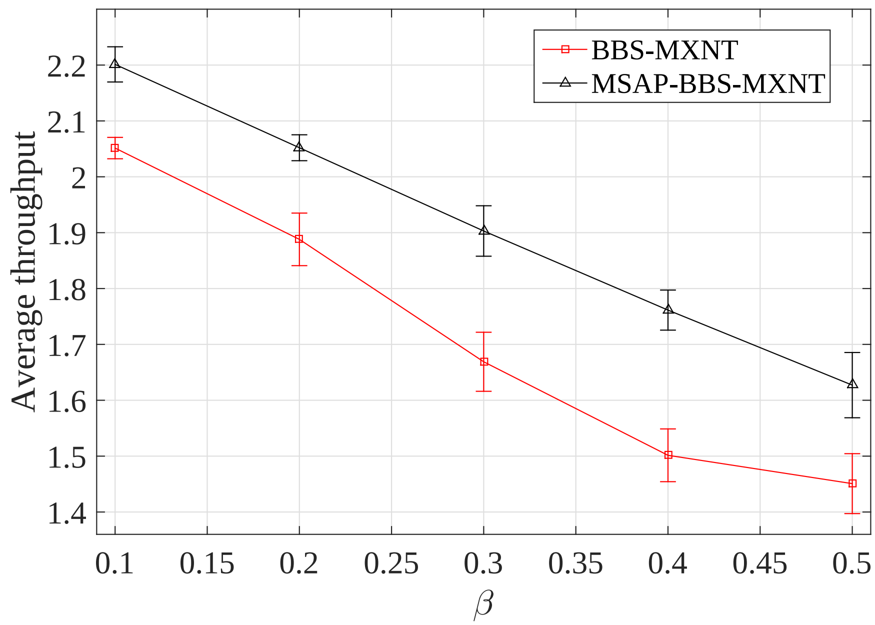



Figure 7.14: Average secondary user throughput for single SAP (BBS-MXNT) and two SAPs (MSAP-BBS-MXNT) .

Fig. 7.14 show the average SU's throughput for single SAP network (BBS-MXNT) and for two SAP network(MSAP-BBS-MXNT). For MSAP-BBS-MXNT $c = 6$ and $\rho = [0.4, 0.6, 0.8, 0.4, 0.6, 0.8]$. As shown in the figure, the MSAP-BBS-MXNT achieve a higher average throughput at different values of $\beta$ due to the flexibility of some nodes to join one of the two available SAP.

Fig. 7.15 7.16 show the average and minimum excess capacity for both BBS-MXNT and MSAP-BBS-MXNT for two SAP, respectively. As shown in the figures, MSAP-BBS-MXNT achieves a better performance in both cases. Figure

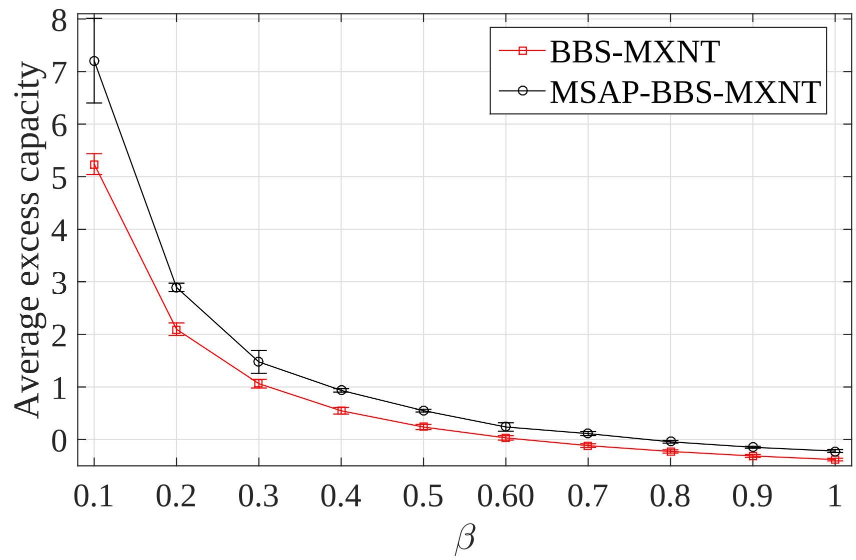



Figure 7.15: Average excess capacity fot single SAP (BBS-MXNT) and two SAPs (MSAP-BBS-MXNT) .

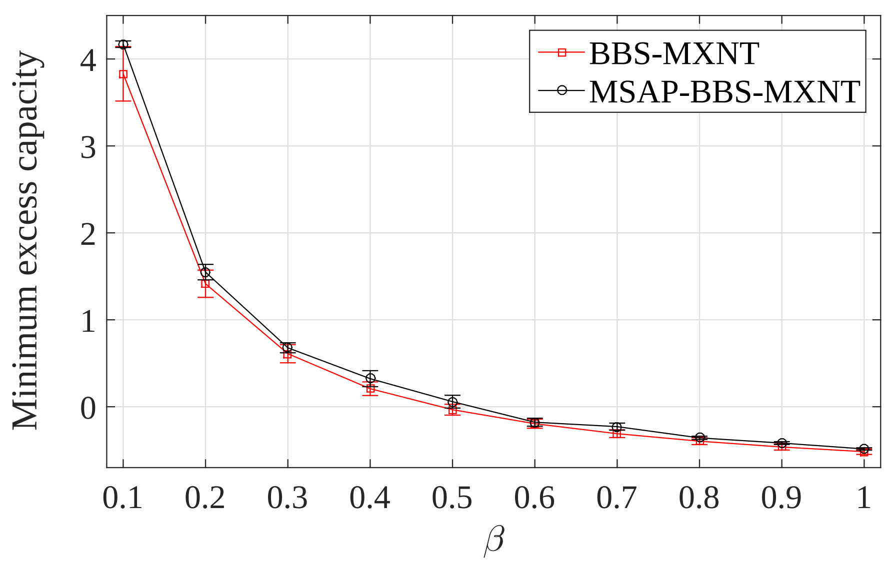



Figure 7.16: Minimum excess capacityfor single SAP (BBS-MXNT) and two SAPs (MSAP-BBS-MXNT) .

## 7.5 Conclusion

In this chapter, we investigated the nodes pairing and channels allocation problems in infrastructure secondary networks. We formulated two optimization problems based on the bargaining based cooperation shares developed in the previous chapter. The first problem named BBS-MXNT aims to maximize the total network rate and satisfies the certain percentage of all nodes' demand. The other problem named BBS-MNMXD and aims to achieve fairness among nodes by minimizing the maximum difference between the $\beta \times 100\%$ of the node's demand and achieved throughput. The results show that, when the value of $\beta$ is low, the BBS-MXNT assigns most of the resource to the nodes with high data rate, that changes as the value of $\beta$ increases to accommodate low data rate nodes' demands. For BBS-MNMXD, the allocation of resource is mainly constant regardless of the value of $\beta$. We also studied the effect of the channels primary users activity and secondary nodes density on the throughput performance. For the previous two parameters, we compared the performance of the secondary cooperative transmission throughput with that of the direct transmission. The results show a significant enhancement in the cooperative transmission throughput compared to that of the direct transmission, especially at high primary users activity and at high nodes density. Also, we investigated the effect of the non-cooperative access mechanism on the performance of the two proposed optimization problems. The results agreed with that of the previous chapter where the non-cooperative access mechanism affects the bargaining shares. If EAP is used, it gives more shares to the slow nodes than the other two schemes so, the average throughput of slow nodes will be higher than the other mechanisms, but the average throughput of all nodes, will be the lowest and vice versa for ETT where the throughput of slow nodes will be the lowest and the average throughput of all nodes will be the highest. ESTT achieve a moderate performance between ETT and EAP.

We extended our study to compare our bargaining based share allocation with two other problem formulation. The first one, jointly optimizes the cooperating nodes shares within the limits of non-cooperative initial shares and the other jointly optimizes the shares of all nodes utilizing the same channel without being limited by the non-cooperative shares. The results show that the bargaining based resource allocation achieves a comparable performance with the other two schemes and ,at the same time, achieves enhancement utility of all participating nodes compared to the non-cooperative case. We also introduced a more general case of multi secondary access points. The access points redistribute the channels and the users among themselves in an optimum way to achieve the desired objective. The result show that utilizing more than one access point gives more flexibility in allocation and pairing and achieves better results in terms of average throughput or demand shortage.

# Chapter 8

# Conclusion and Future Directions

In this chapter we conclude the work presented in this dissertation and list the publication resulted from this work. Finally, we present some future work directions.

## 8.1 Dissertation Conclusion

In this dissertation we have explored the benefits of utilizing cooperative communication to enhance the performance of secondary infrastructure based networks. The main idea is to utilize a two-hop cooperative transmission through intermediate relay to mitigate the interruptions occurred by the presence of the primary user and force the secondary user to retransmit the data again. In the cooperative mode the two-hop transmission is carried out at a higher data rate and less transmission time and so less vulnerable to the primary user interruption. In addition to the ability to buffer the data at the relay in case the primary user appeared after the first hop transmission is performed successfully.

We performed a series of experiments to measure the throughput enhancement in ordinary infrastructure network due to using cooperative Multi-Input-Multi-Output (MIMO) technique where relays shares their antennas to mimic MIMO techniques. That includes the ability to utilize one or two relay to forward the source packets. The performance of these techniques are used later in our research.

To quantify the enhancement in the secondary transmission characteristic like efficiency and throughput, we modeled the interaction between a primary user and a secondary user in interweave spectrum sharing mechanism using discrete-time Markov chain (DTMC) in secondary cooperative and non-cooperative mode. The analysis of the model shows that utilizing cooperative communication in the secondary transmission enhance the efficiency of the transmission significantly compared to the direct transmission case, especially at high levels of primary user activity.

We take a further step by studying the performance of secondary infrastructure network that utilizes cooperative transmission with cooperative MIMO techniques. We start by modeling a simple scenario of a single-relay assisted transmission analytically using DTMC that take into consideration the node density and the probability to find a relay or not. The same scenario was simulated using discrete-event network simulator where the results confined with the analytical one. We introduce a cooperative and cognitive Media Access Control (MAC) to facilitate cooperative transmission in secondary infrastructure network. The proposed MAC carry out all traditional MAC functionality like handshaking and media access coordination in addition to transmission technique and relay(s) selection. The performance evaluation shows that cooperative transmission outperform the direct transmission especially at crowded spectrum and at high secondary user density.

Up to this point we showed the benefit of using cooperative communication in the secondary network, but we did not show how the source node and the relay agreed to cooperate and if this cooperation is beneficial for both of them or not. We introduce a cooperation framework in secondary network in which cooperation is modeled as a resource exchange process between the cooperating pair. The secondary user vacate part of the free spectrum time dedicated ot its transmission to the relay in return of the relay energy consumed in forwarding its packet. We modeled the interaction between primary user, secondary user and secondary relay using a DTMC for three different non-cooperative secondary access mechanisms that coordinate the secondary user and relay access to the free spectrum. The three mechanisms give the secondary user and the secondary relay an equal access probability, or equal access time, or equal successful transmission time to the free spectrum. From the DTMC we calculate the transmission efficiency and throughput. These statistics used to determine the disagreement utility if nodes do not agree to cooperate. We defined the node utility such that it combines the achieved throughput and the consumed energy. Then we apply Nash bargaining solution (NBS) and egalitarian solution (ES) to find the new shares for the secondary user and the secondary relay with the non-cooperative utility as a disagreement point. We studied the the performance of the cooperation framework fir both NBS and EBS. The result show that NBS gives more share for the relay than the EBS and vice versa for the secondary user. Also, the total achieved utility for the cooperation pair is higher in NBS compared to that of EBS. We showed also that both the secondary user and the secondary relay can achieve utility and throughput enhancements under certain conditions that depends on the primary user activity, level of cooperation, and each node evaluation for the value of its energy. We evaluated the energy efficiency of the proposed framework. Compared to the direct transmission case, cooperation show a better energy performance, especially at high cooperation levels.

Finally we used the bargaining based node shares to solve the node pairing and channel allocation problem in infrastructure based secondary network. We formulated a two optimization problems with objective to maximize the total network throughput or to minimize the difference between any node demand and achieved throughput. We compared our bargaining based pairing and allocation technique with two other techniques that jointly optimize cooperating nodes shares with the pairing and allocation steps. One of these technique optimize the shares of the each the two cooperating nodes within the limits of their total original share and the other optimize the shares of all nodes sharing the same channel. Our proposed technique shows a comparable performance to the two other techniques an at the same time provide a fair method that incentivize every node to cooperate.

## 8.2 Publication

The following list summarizes the publivations resulting from the dissertation:

- Journal Articles:

  1. **M. AbdelRaheem**, M. Abdel-Rahman, M. El-Nainay, and S. F. Midkiff "Spectrum-efficient Resource Allocation Framework for Cooperative Opportunistic Wireless Networks" submitted to IEEE Transaction on Cognitive Communication and Networking.
  2. **M. AbdelRaheem**, M. Abdel-Rahman, M. El-Nainay, and S. F. Midkiff bargaining-based Node Pairing and Channel Allocation for Secondary Cooperative Infrastructure Networks " Under preparation.

- Conference Papers:

  1. **M. AbdelRaheem**, M. El-Nainay, and S. F. Midkiff, Spectrum occupancy analysis of cooperative relaying technique for cognitive radio networks," in Proceedings of the IEEE International Conference on Computing, Networking and Communication (ICNC), February 2015, pp. 237-241.
  2. **M. AbdelRaheem**, M. El-Nainay, and S. F. Midkiff, "Analytical and simulation study of the effect of secondary user cooperation on cognitive radio networks," in Proceedings of the IEEE WCNC conference, 2015, pp. 949-954.
  3. **M. AbdelRaheem**, M. El-Nainay, and S. F. Midkiff, "An Experimental Study of Data Rate Enhancement Using Cooperative and Multi-Antenna Communications in Infrastructure Networks," submitted to the IEEE WCNC 2016 conference

## 8.3 Future Directions

### 8.3.1 Hybrid underlay-interweave spectrum access mechanism with cooperative communication and self interference cancellation capabilities

In our research, we investigated the cooperation in interweave spectrum sharing mechanism where the secondary user cannot coexist with the primary user at the same time in the same channel. One promising direction is to use the same idea in a underlay or hybrid interweave-underlay spectrum sharing mechanism. In underlay spectrum sharing, the secondary user can transmit at the same time and channel with the primary users as long as the interference caused by the secondary user does not exceed an interference temperature threshold. based on physical layer sensing data and geographical locations information, the unlicensed transmission can be done over two high speed hops to mitigate interfering with the primary user. A simple scenario is when both the primary and the secondary receiver are located in nearby, so any secondary transmission will cause an unaccepted interference at the primary receiver. To mitigate this point, a hybrid underlay-interweave spectrum sharing can be used by utilizing cooperative transmission. The first hop from the secondary source to the relay can be performed with the help of power control such that the interference at the primary receiver is at an accepted limits. The secondary relay buffer the packet(s) until the primary user is absent then it start to forward the buffered packets at high speed.

New technologies like self interference cancellation (SIC) can boost the performance of the cooperative secondary transmission by allowing the relay to receive a new packets form the source at the same time that it forward the previous ones.

### 8.3.2 CO$^2$MAC for Dynamic Networks

Our proposed MAC protocol was benchmarked through a stationary network where there is no mobility challenge. One feasible extension is to modify the mechanism of CO$^2$MAC to include node discovery like keep alive messages. Also, the proposed version of CO$^2$MAC utilizes common control channel (CCC) to exchange the required control messages. Utilizing CCC remove the overhead on throughput. A future direction is to study the effect of the overhead caused by transmitting the control messages on the same data channels including the challenge of primary user interruption to the control messages.

### 8.3.3 Node Pairing and Channel Allocation Heuristic Algorithm

Instead of solving the resource allocation problem via optimization technique which many not be adequate for implementation in real life network, a heuristic algorithm with suboptimal performance is a future direction to discover.

# Appendices

# Appendix A

# Proof of Equations (4.5) and (4.6)

By referring to Fig. 4.1, for a stand-alone DTMC of $M+1$ states, equation (4.3) can be written as:

$$[\pi_1 \cdots \pi_M \pi_I] = [\pi_1 \cdots \pi_M \pi_I] \cdot \begin{pmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \vdots \\ P_A & \cdots & \cdots & \cdots & (1-P_A) \\ (1-P_I) & \cdots & \cdots & \cdots & P_I \end{pmatrix} \tag{A.1}$$

By solving the first or the last equation we obtain the following equation

$$\pi_{A_M} \cdot (1-P_A) = \pi_I \cdot (1-P_I) \tag{A.2}$$

And as the transition probabilities between different active states equal to 1 we have equal state occupancy for all active states such that $\pi_{A_M} = \frac{\pi_A}{M}$. and given that $\pi_A = 1 - \pi_I$, $P_I$ can be written as,

$$P_I = 1 - \frac{\pi_A(1-P_A)}{M(1-\pi_A)} \tag{A.3}$$

To ensure that both $P_I$ and $P_A$ values are in the range from 0 to 1, We set $P_A$ in the following range,

$$1 \geq P_A \geq 1 - \frac{M(1-\pi_A)}{\pi_A}. \tag{A.4}$$

# Appendix B

# Probability Density Function of Uniform Distributed Nodes in Polar Coordinates

For uniformly distributed nodes in a circle of radius $R_c$, the joint PDF over the Cartesian coordinates (X,Y) can be expressed as:

$$f_{X,Y}(x,y) = \begin{cases} \dfrac{1}{\pi R_c^2}, & \text{if } x^2 + y^2 \leq R_C^2 \\ 0, & \text{otherwise} \end{cases} \tag{B.1}$$

The joint PDF of $R$ and $\Theta$ can be calculated using the joint PDF of $X$ and $Y$ [82] as:

$$f_{R,\Theta}(r,\theta) = \frac{f_{X,Y}(h_1(r,\theta), h_2(r,\theta))}{|J(x,y)|} \tag{B.2}$$

Where $x = h_1(r,\theta) = r\cos\theta$, $y = h_2(r,\theta) = r\sin\theta$ and $|J(x,y)|$ is the Jacobian of the transformation whic is equal to:

$$J(x,y) = det \begin{vmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \theta} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial \theta} \end{vmatrix}$$

finally

$$f_{R,\Theta}(r,\theta) = \begin{cases} \dfrac{r}{\pi R_c^2}, & \text{if } 0 \leq \theta \leq 2\pi, 0 \leq r \leq R_c \\ 0, & \text{otherwise} \end{cases} \tag{B.3}$$

For non zero part within the Circle radius,

$$f_{R,\Theta}(r,\theta) = f_R(r) f_\Theta(\theta) = \frac{2r}{R_C^2} \frac{1}{2\pi} \tag{B.4}$$

So,

$$f_R(r) = \frac{2r}{R_c^2} \tag{B.5}$$

and

$$f_\Theta(\theta) = \frac{1}{2\pi} \tag{B.6}$$

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