

Cooperative Spectrum Sharing in Cognitive Radio Networking

by

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Abstract

Driven by the massive growth in communications data traffic as well as flourishing users' demands, we need to fully utilize the existing scarce spectrum resource. However, there have been several studies and reports over the years showing that a large portion of licensed spectrum is actually underutilized in both temporal and spatial domains. Moreover, aiming at facing the dilemma among the fixed spectrum allocation, the ever enormous increasing traffic demand and the limited spectrum resource, cognitive radio (CR) was proposed by Mitola to alleviate the under usage of spectrum. Thus, cognitive radio networking (CRN) has emerged as a promising paradigm to improve the spectrum efficiency and utilization by allowing secondary users (SUs) to utilize the spectrum hole of primary users (PUs). By using spectrum sensing, SUs can opportunistically access spectrum holes for secondary transmission without interfering the transmissions of the PUs and efficient spectrum utilization by multiple PUs and SUs requires reliable detection of PUs. Nevertheless, sensing errors such as false alarm and misdetection are inevitable in practical networks. Hence, the assumption that SUs always obtain the exact channel availability information is unreasonable. In addition, spectrum sensing must be carried out continuously and the SU must terminate its transmission as soon as it senses the re-occupancy by a PU. As a better alternative of spectrum sensing, cooperation has been leveraged in CRN, which is referred as cooperative cognitive radio networking (CCRN). In CCRN, in order to obtain the transmission opportunities, SUs negotiate with the PUs for accessing the spectrum by providing tangible service for PUs.

In this thesis, we study cluster based spectrum sharing mechanism for CCRN, and investigate on exploiting the cooperative technique in heterogeneous network. First, we develop cooperation protocols for CRN. Simultaneous transmission can be realized through quadrature signalling method in our proposed cooperation protocol. The optimal power allocation has been analyzed and closed-form solution has been derived for amplify

and forward mode. Second, we study a cluster based spectrum sharing mechanism. The spectrum sharing is formulated as a combinatorial non-linear optimization problem which is NP-hard. Afterwards, we solve this problem by decomposing it into cluster allocation and time assignment, and we show that the result is close to the optimal solution. Third, we propose a macrocell-femtocell network cooperation scheme for heterogeneous networks under closed access mode. The cooperation between the femtocell network and macrocell network is investigated. By implementing the cooperation, not only the macrocell users' (MUEs') and femtocell users' (FUEs') utility can be improved compared with the non-cooperation case, but also the energy consumption as well as the interference from the femtocell network to the macrocell network can be reduced.

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Dedication

*To my dear parents,
Shuhai Tang & Junping Zhang*

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List of Abbreviations

4G	Fourth Generation
5G	Fifth Generation
AF	Amplify and Forward
AP	Access Point
AWGN	Additive White Gaussian Noise
BS	Base Station
CCRN	Cooperative Cognitive Radio Networking
CF	Compress and Forward
CFN	Cognitive Femtocell Network
CR	Cognitive Radio
CRN	Cognitive Radio Networking
CSI	Channel State Information
DF	Decode and Forward
FBS	Femtocell Base Station
FUE	Femtocell User
GP	Guard Period
ICNC	Inter-Cooperative Network Coding
IU	Intermediate User

KKT	Karush-Kuhn-Tucker
LEACH	Low Energy Adaptive Clustering Hierarchy
LTE	Long Term Evolution
LTE-A	LTE-Advanced
LICQ	Linear Independence Constraint Qualification
LS	Least Squares
MAC	Medium Access Control
MBS	Macrocell Base Station
MMSE	Minimum Mean-Square-Error
MPSK	M-ary Phase Shift Keying
MUE	Femtocell User
MWM	Maximum Weighted Matching
NICNC	Non-Inter-Cooperative Network Coding
OFDMA	Orthogonal Frequency Division Multiple Access
PCN	Primary Cooperative Networking
PU	Primary User
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
SCN	Secondary Cooperative Networking
SINR	Signal to Interference plus Noise Ratio
SU	Secondary User
SNR	Signal to Noise Ratio
TDMA	Time Division Multiple Access

List of Symbols

a_{ij}	Cooperation partner's state
C_i	Capacity of channel i
E_i	Energy consumption of PU $_i$
E_{ij}	Energy consumption of SU $_j$ who cooperates with PUs within cluster i
h_{ij}	Channel gain obtained from the source i to the destination j , when $j = 0$, BS is the destination
h_{iq}	Channel fading coefficients from the PU $_i$ to the IU $_q$
h_j	Channel gain of user j joins in a cluster
h_q	Channel gain of IU $_q$ transmitting to its own destination
K_i	Number of SUs assigned to each SCN cluster
L_x	the number of cluster heads in PCN cluster x
M	Number of PUs
N	Number of SUs
N_{P_i}	Transmission traffic demand of PU $_i$
N_0	One-sided power spectral density of the noise
n_{ij}	AWGNs with variance N_0W_i from source i to destination j
P_i	Transmission power of PU $_i$
P_{ij}	Transmission power of user j who joins in cluster i

P_{max}^j	Power limitation of IU _{<i>j</i>}
P_q	Transmission power of IU _{<i>q</i>}
Q	Number of IUs
R_{ij}	Transmission rate of user <i>j</i> on channel <i>i</i>
r_{ij}	Received signal at the destination <i>j</i> from the source <i>i</i> , when <i>j</i> = 0, BS is the destination
SNR_{ij}	Signal-to-noise ratio of user <i>j</i> on channel <i>i</i>
T	One time slot
T_1	Time allocated for the first phase cooperation
T_2	Time allocated for the second phase cooperation
t_{ij}	Time slot assigned to user <i>j</i> within cluster <i>i</i>
U_i	Utility of PU _{<i>i</i>} through cooperation
U_{ij}	Utility of user <i>j</i> on channel <i>i</i>
U_q	Utility of IU _{<i>q</i>} through cooperation
V_{min}^j	Minimum utility requirement for user <i>j</i>
V_{ij}	Utility of SU _{<i>j</i>} associates with SCN cluster <i>i</i>
W_i	Bandwidth allocated to PU _{<i>i</i>}
X	Number of clusters in PCN
x_i	Transmission signal of PU _{<i>i</i>}
Y	Number of clusters in SCN
β_i	Time allocation for the two-phase cooperation
γ_j	Amplification gain
ξ_i	Power fraction of P_q which is allocated for delivering PU _{<i>i</i>} 's traffic
η	Additive white Gaussian noise
$\mu_{i,j}$	Network connectivity coefficient

ω_{ij}

Weight of user j who associates with SCN cluster i

ω_{ij}^*

Weight obtained of IU $_j$ by cooperating with PCN cluster i

Chapter 1

Introduction

In wireless communication networks, spectrum is a limited and scarce resource that has been exclusively and statically allocated to various wireless applications through licensing by regulatory bodies, and there are more and more applications which are desiring for spectrum, such as e-health networks, vehicular ad hoc networks and smart grid. Specially, users will go through a level of call volume and high speed data transmission with the fifth generation (5G) wireless communications. However, the assigned spectrum is significantly underutilized [1].

Aiming at improving the spectrum efficiency and utilization, cognitive radio (CR) is, first proposed by Mitola in 1999 in [2], a generic term used to describe a radio that is aware of the environment around it and can adapt its transmissions parameters according to the interference it goes through [3]. In CR, secondary users (SUs) opportunistically access the idle spectrum which are not occupied by the primary users (PUs) at the current time. Nevertheless, whenever the PUs return to reoccupy the spectrum, the SUs need to vacate the spectrum in order not to disturb PUs' transmissions. Therefore, CR can provide spectrum bandwidth to mobile users via heterogeneous wireless architectures and dynamic spectrum access techniques.

The main functions for CR can be summarized as follows: spectrum sensing, spectrum management, spectrum mobility and spectrum sharing. Spectrum sensing is adopted by the SUs to detect unused spectrum and access the idle spectrum opportunistically without harmful interference with PUs [4–6]. With spectrum management, the SUs can capture the best available spectrum to meet their communication requirements [7–9]. Maintaining seamless communication requirements during the transition to better spectrum can be achieved through spectrum mobility [10, 11]. Spectrum sharing is used to provide a fair spectrum scheduling method among coexisting SUs.

1.1 Cooperative Cognitive Radio Networking

1.1.1 Spectrum Sharing Paradigms in Cognitive Radio

There are three paradigms in cognitive radio networking (CRN): underlay paradigm, overlay paradigm and interweave paradigm. In underlay paradigm, the SUs access the spectrum only when the interference they cause to the PUs is below a given threshold or meets a given bound on PUs' performance degradation. In overlay paradigm, the SUs are overlaid with PUs which means the SUs transmit simultaneously at the same spectrum as the PUs. In interweave paradigm, the SUs sense the absence of PUs' signals in space, time, or frequency, and access the spectrum opportunistically.

Underlay Paradigm

In underlay paradigm, when exploiting spectrum holes, the SUs can be anywhere in the primary network, provided that the interference caused to the PUs does not degrade their receiving performance. Moreover, the SUs can be beyond the coverage area which is secured by a given guard distance of the primary network, under the constraint on

the SUs' transmission power. Therefore, as shown in underlay paradigm is utilizing the whole spectrum.

The underlay model has the advantage that the SUs can directly occupy the spectrum without considering the PUs' traffic patterns. However, a key issue in underlay paradigm is that the SUs may suffer from bad performance due to the interference from the PUs and power constraints imposed at the SUs.

Overlay Paradigm

Compared with the underlay paradigm, overlay paradigm does not require strict transmission power constraints at the SUs due to interference caused to the PUs. Cooperative relaying has emerged as a powerful technique for the overlay paradigm, since it can exploit spacial diversity and provide higher capacity and reliability in CRN. With the help of cooperative relaying technique, SUs trustfully negotiate with PUs for transmission opportunities by providing tangible services that the SUs relay the PUs' transmission by cooperative relaying techniques or advanced coding in overlay paradigm.

Interweave Paradigm

The interweave paradigm is based on the idea of opportunistic communication, and was the original motivation for cognitive radio. In interweave paradigm, the SUs first sense the availability of spectrum holes which are the spectrum bands that are not occupied by the PUs. In other words, the SUs estimate the presence and absence of spectrum holes without help from the PUs. Moreover, the SUs access the spectrum opportunistically since once the PUs reoccupy the spectrum bands the SUs need to vacate the spectrum as soon as possible. However, this model is highly sensitive to PU traffic patterns and sensing errors, since PUs activities change over time and also depend on geographical locations.

Underlay, overlay and interweave paradigms are shown as Fig. 1.1.

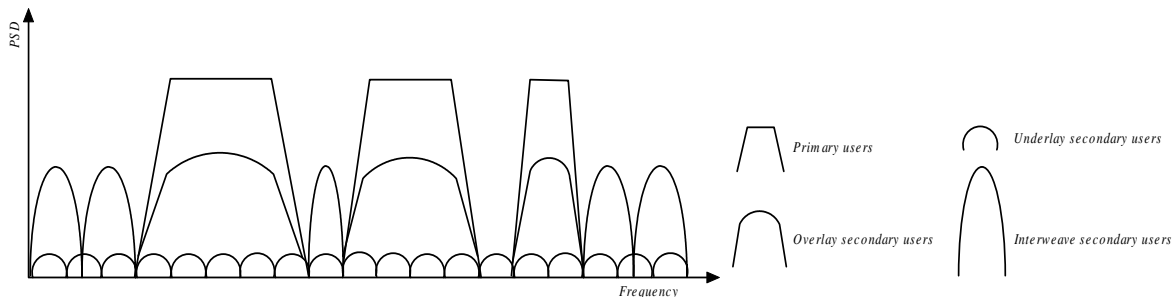


Figure 1.1: Underlay, overlay and interweave spectrum sharing paradigms.

1.1.2 Cooperation in Cognitive Radio Networking

Normally, there are two ways for spectrum access in CRN: spectrum sensing and cooperation. The aim of spectrum sensing is to detect a spectrum hole precisely in order to share the spectrum without harmful interference to other users. The term “spectrum hole” refers to a band of frequencies that are not being occupied at a particular point of time and specific geographic location by a PU [12]. SUs sense the spectrum holes to probe for spectrum access opportunities and prevent harmful interference on the ongoing transmissions of PUs [13–17]. The other way for spectrum access is cooperation. Leveraging cooperation in CRN is referred as cooperative cognitive radio networking (CCRN), which is proposed as an alternative since sensing errors are inevitable in practical network operations. In CCRN, SUs negotiate with PUs for transmission opportunities by relaying PUs’ traffic through cooperative communication techniques. SUs cooperate with PUs to improve the PUs’ performance in terms of transmission rate, reliability, energy efficiency and so on, and in return gain transmission opportunities. When the channel conditions of the primary links become poor, PUs are obliged to find an appropriate cooperator to relay their traffic against performance degradation. Moreover, the surrounding SUs with

better channel conditions are seeking for spectrum access opportunities at the same time. Therefore, the cooperation between PUs and SUs are feasible in wireless networks and beneficial to both user parties.

There is an increasing member of research works focus on the second spectrum access method: leveraging cooperation in CRN. Many issues are needed to be considered in CCRN, such as who to cooperate, when to cooperate and how to cooperate.

1.2 Motivations, Objectives and Contributions

1.2.1 Motivations and Objectives

Due to the ever increasing users' requirements, improving the spectrum efficiency has always been a fundamental issue in wireless networks. Spectrum sharing is an efficient and effective method to improve the spectrum efficiency by overcoming the scarce and limited availability of spectrum. Traditionally, spectrum sharing has been studied broadly in various wireless networks to improve the utilization of existing spectrum. CR is emerged as an useful technology for spectrum sharing. However, considering the unique features of CRN, spectrum sharing in future-generation networks faces new challenges which should be tackled.

- In CRN, spectrum sensing plays the first and most important role in CR. The aim of spectrum sensing is to detect the spectrum hole and to share the spectrum without harmful interference to other users. However, sensing error is inevitable in practical network operations, which has negative effect on the network performance, e.g., causing harmful interference to the PUs. Moreover, once the PU returns to its channel, it is very challenging for the SUs to make the mobility plan of moving from one channel to another seamlessly. In addition, it is possible that when the

SU starts to access the previous detected spectrum hole, it is reoccupied by the PU again. Cooperation adopted in CRN can address the aforementioned problems.

- To fulfill ideal cooperation for CRN, upgraded physical-layer and MAC-layer designs are indispensable. Synchronization between cooperators, coordination of the cooperation, energy consumption and interference management during multi-user multi-channel spectrum sharing need to be revisited.
- Since there are considerable wireless users desiring for diverse wireless applications and services with more spectrum bands and higher transmission rate, there will be more SUs who do not have their own communication bands searching for spectrum hole to access. Therefore, competition among the SUs becomes more intense than before.

These fundamental challenges pose great difficulties for future-generation network designers, which motivates us to propose novel spectrum sharing mechanisms. Therefore, the objective of this dissertation is to incorporate the physical layer cooperative relaying technique in the CRN and design spectrum sharing protocols to reduce interference and improve spectrum efficiency, energy efficiency as well as network fairness.

1.2.2 Contributions

The first part of this dissertation studies the cooperation protocol design for uplink CRN. In a traditional three-phase time division multiple access (TDMA) based cooperation protocol, the PU yields a fraction of time slot for the SUs to access the spectrum in exchange for cooperation in the form of relaying the primary traffic. In the first phase, the PU transmits the data to the relaying SUs. The second phase is used for one or multiple SUs relaying the PU's data to the primary receiver, aiming at improving the throughput of the primary link. As a reward, the SUs transmit their own traffic in the third

phase. However, in this dissertation, we combine the former two phases of the traditional three-phase framework together using the two degrees of freedom in a 2-dimensional modulation. Specifically, both the PU and the selected relaying SU use quadrature phase shift keying (QPSK) which is equivalent to quadrature amplitude modulation (QAM). But the PU only uses the in-phase component to transmit its data while at the same time, the SU only uses the quadrature component to relay the PU's data. In this way, the transmissions by the PU and the SU together form quadrature signaling. Thus, there will be no interference and the SU will have more time for its own transmissions. An extensive analysis on cooperation between the PU and the SU is presented, and we also optimize the performance of the PU while satisfying the cooperative SU's QoS requirement.

The second part investigates a spectrum sharing framework for primary cooperative networking (PCN)/secondary cooperative networking (SCN) cognitive radio networking which is performed not only between the PUs in the PCN and the selected cooperating SUs, but also among the cooperating SU and the remaining SUs within a cluster of SCN. First, the PUs form clusters of PCN. Each PU has an equal chance to serve as the cluster head. The cluster heads of SCN, whom we call intermediate users (IUs), acquire some spectrum after relaying PUs' traffic. Afterwards, the IUs aggregate the acquired spectrum, and share them with other cluster members. Since the relaying capabilities of the SUs will vary from slot to slot due to their locations, power levels, or channel conditions, the SUs can not always be selected as IUs. Specially, we design a cooperative spectrum sharing mechanism, in which,

- an IU selection scheme is operated by the maximum weighted matching (MWM) algorithm with the objective of maximizing the ratio of integrated utility to total energy consumption. Hence, energy efficiency is taken into consideration;
- a cluster based spectrum sharing framework is proposed to improve the network utility and reliability as well as network fairness by introducing a group of IUs. The

IU, who is the head of SCN, can benefit more SUs, so that the network fairness can be improved. Network coding is implemented during the spectrum sharing process within the cluster of SCN to increase communication utility and reliability;

- the spectrum sharing problem within the clusters of SCN is formulated. Since this problem is NP-hard, we decompose it into two sub-problems: bandwidth allocation (i.e., cluster formation) and time allocation, and we derive the bandwidth allocation by exploiting the two-sided stable matching algorithm, which is a basic and classical approach in matching theory to solve the matching problems. A stable matching result can be obtained through using the above mentioned approach, which can not only take both parties' (IUs' and SUs') interests into consideration, but also enhance the network robustness.

In the third part, we consider a cooperation scheme in heterogeneous macrocell-femtocell networks. By adopting CR technology, femtocell networks can efficiently cope with spectrum scarcity as well as exploit spectrum management in small areas to obtain high transmission rate for indoor communications. Usually, the cooperation in macrocell-femtocell networks is performed between the femtocell users (FUEs) and macrocell users (MUEs). However, femtocell base stations (FBSs) have more powerful relay capability than the FUEs, and can transmit multiple traffic simultaneously. To this end, we design a framework for cooperation between one or multiple MUEs and one FBS in closed access mode, and the benefit is quantified in terms of utility. MUEs who suffer with a bad transmission situation are allowed to access an FBS after the cooperation relationship between the FBS and the MUEs is established, and the FBS acts as a relay for these MUEs. In return, the cooperative FBS acquires a fraction of spectrum for its serving FUEs as a reward. The FBSs are equipped with dual modes: relay mode and traditional base station mode. FBSs relay MUEs' traffic with relay mode, and serve their FUEs with traditional base station mode. Cooperating with more MUEs will enable the FBSs

to acquire more spectrum access opportunities for their serving FUEs. Moreover, such kind of cooperation framework can benefit the scenario that when the MUE is located at the cell boundary, suffering from a bad performance at its serving macrocell base station. Unlike existing macrocell-femtocell architecture, we propose a cooperation model in which MUEs are granted to communicate with the FBS after the cooperation relationship between MUEs and FBS has been established, wherein

- we formulate the cooperation as a many-to-one stable matching problem, and the matching pairs represent the cooperation pairs of the FBS and multiple MUEs. In the matching process, the interests of both FBSs and MUEs are taken into consideration, and each FBS and each MUE can have their own preference lists based on their specific requirements, such as utility, geographical location, energy efficiency, and delay tolerance. The matching result is a stable matching;
- FBSs are equipped with dual modes: relaying mode and traditional mode with different power levels. By adopting dual modes, the FBSs can save their energy and mitigate interference to the macrocell network. FBSs act as relays since they have more relaying capability than the FUEs as they have higher power limitations and they can perform concurrent transmissions.

1.3 Outline of the Thesis

This thesis is organized as follows: we model the CCRN based on orthogonal signaling in Chapter 2, and study the cooperation protocols for cognitive radio networking with the design of spectrum-energy efficiency. The spectrum sharing mechanism for PCN/SCN cognitive radio networking is investigated in Chapter 3. In Chapter 4, we focus on heterogenous cognitive femtocell networks in which the FBSs cooperate with the MUEs to enhance the utility of the MUEs and gain spectrum access opportunities for the FUEs.

Finally, conclusion remarks and future potential research issues are presented in Chapter 5.

Chapter 2

Cooperation Protocols for Cognitive Radio Networking

CRN has recently emerged as a promising paradigm to improve the spectrum efficiency and utilization by allowing SUs to opportunistically utilize the spectrum holes of PUs. By using spectrum sensing, SUs can access spectrum holes for secondary transmission without interfering with the PUs [18], and efficient spectrum utilization by multiple PUs and SUs requires reliable detection of PUs. Nevertheless, sensing errors are inevitable due to feedback delays, estimation errors and quantization errors in practical networks. Hence, the assumption that SUs always obtain the exact channel availability information is unreasonable. Most of the previous works have focused on opportunistic resource allocation for CRN without considering sensing errors. Only a few publications investigate the imperfection of spectrum sensing in CRN, which causes higher computational complexity. In addition, spectrum sensing must be carried out continuously and SU must terminate its transmission as soon as it senses the re-occupancy by a PU. Therefore, cooperation is exploited in CRN to solve the above mentioned problems.

2.1 Literature Review

In wireless networks, channel fading caused by multi-path propagation is a particularly severe issue that can be mitigated through the use of diversity [19]. Multiple antennas, and diversity techniques such as space, time and frequency diversity are attractive to have the performance gain. Cooperation among the users can achieve space diversity which is also referred as cooperative diversity. Cooperation protocols are widely investigated in the following areas.

2.1.1 Relaying Communications

In the literature, many works on relaying communications have been investigated. The original idea of relaying communications can be traced back to the cutting-edge work of Cover and El Gamal on the information theoretic properties of relay channel in [20]. The authors develop the capacity of a three-node network wherein contains a source, a destination, and a relay. However, in relay channels, the relays' only purpose is to help the sources, whereas in cooperative relaying communication system, the users act both as sources and relays. There are three fundamental cooperative relaying mechanisms in the wireless networks: amplify-and-forward (AF), decode-and-forward (DF) and compress-and-forward (CF). In AF cooperative relaying protocol, the signal is amplified at the relay and forwards to the destination. Besides the desired signal, the relay also amplifies and propagates the interference and noise from the source-relay link. As the relay does not decode the received signal, the relayed signal would also cause interference to the destination. The advantage of this protocol is its low cost and simplicity implementation. In DF cooperative relaying protocol, the relay decodes the signal and re-encodes it before forwarding it to the destination. With the DF protocol, noise can be completely eliminated, but the coding/decoding processes for cooperation are needed

which will increase the implementation cost. In CF cooperative relaying protocol, the relay attempts to generate an estimate of the received signal, and then compresses and encodes the signal and transmits the compressed encoded signal to the destination. The CF protocol is especially suitable for the situation where the channel between the source and the relay is worse than that between the source and the destination. In [21] and [22], the cooperation scheme in which each user acts as a relay for others adopting the AF relaying protocol is investigated. The DF and CF protocols are developed for relay networks with many relays, antennas, sources, and destinations in [23]. In [24], space-time coded cooperative diversity protocols with AF and DF for combating multi-path fading are developed to enable simultaneous transmission of all relays. A DF design which is referred as turbo-coded cooperation is proposed in [25] to achieve better performance.

2.1.2 Exploiting Cooperation in Various Networks

Cooperative communications have been extensively studied in the literature which can increase the transmission rate, save the energy, enhance the reliability and so on. Due to the benefits of cooperative networking, there is a strong benefits to introduce cooperation to the CRN to deal with challenges of spectrum sensing and better explore spectrum access opportunities.

Cooperation techniques have been widely exploited in various types of wireless networks for different reasons. In cellular networks, relays are used to enlarge the coverage areas as well as increase communication reliability [26]. A fractional base station cooperation in cellular network is developed in [27] to achieve performance gains both within the cell and at the cell-edge with limited complexity. In multi-hop ad hoc networks, relays are used to increase the transmission rate. The authors in [28] investigate the cooperation in wireless ad hoc networks, and they propose a distributed and scalable acceptance scheme which is exploited by the users to decide whether to accept or reject to be a relay for

other users. The authors in [29] derive the theoretical bounds for half-duplex cooperative channels in ad hoc network, where the two transmitters and two receivers simultaneously cooperate. In [30], the upper and lower bounds for the information-theoretic capacity of four nodes ad hoc networks using cooperative diversity are developed. In [31], relay users are introduced to enable single antenna users share their antennas to create a virtual multiple antennas transmitter. Therefore, transmission diversity is achieved and network capacity can be increased. A cooperative transmission strategy for wireless ad hoc and sensor networks is proposed in [32]. The strategy exhibits a substantial gain in throughput, especially when the coexistence gain factor is high, and a broadcast approach is incorporated into the transmission strategy suggesting further throughput benefits. The vehicular network performance using amplify-and-forward relaying technique for an inter-vehicular cooperative protocol relayed by a roadside access point is investigated in [33]. In [34], Liang *et al.* discuss the benefits and possibilities for coordinated operation with cooperative wireless networking and smart grid wireless networking. Based on that, utilities are able to improve power system operation efficiency and reliability via acquiring more accurate and timely information.

2.1.3 Cooperation Protocols

Spectrum sensing is normally adopted by SUs to probe for spectrum access opportunities and prevent harmful interference on the ongoing transmissions of PUs. However, in practice, sensing errors are inevitable in network operations, such as quantization, estimation and delayed feedback, which adversely affect the network performance. As an alternative, CCRN is proposed, in which cooperation is leveraged in CRN to avoid sensing errors, and gain spectrum access opportunity for SUs. In CCRN, SUs negotiate with PUs for their own transmissions by relaying PUs' traffic through cooperative communication techniques, such as cooperative relaying or advanced coding [35]. SUs

cooperate with PUs to improve the latter's performance in terms of transmission rate, reliability, energy efficiency and so on, and in return gain transmission opportunities. When the channel conditions of the primary links become poor, PUs are obliged to find an appropriate cooperator to relay their traffic against performance degradation. Moreover, the surrounding SUs with better channel conditions are seeking for spectrum access opportunities at the same time. Therefore, the cooperation between PUs and SUs are feasible in wireless networks and beneficial to both user parties.

In CCRN, cooperation between PUs and SUs have attracted considerable attention and have been extensively investigated in recent years. In [36], a three-phase TDMA based scheme is proposed. The PU allocates a fraction of time for the SUs to access the spectrum in exchange for cooperation in the form of relaying the primary data. In the first phase, the PU transmits the data to the relaying SUs. The second phase is used for one or multiple SUs relaying the PU's data to the primary receiver, aiming at improving the throughput of the primary link. As a reward, the SUs transmit their own traffic in the third phase. Han *et al.* in [37] present a two-phase cooperation scheme in CCRN. The PU transmits its own traffic in the first phase while the cooperating SU transmits the PU's traffic and its own traffic at the same time by using different power levels in the second phase. In [38], a two-phase cooperative scheme is proposed, which can be achieved at the expense of using multiple antenna systems. The SUs relay the primary traffic and transmit the secondary traffic by spatially located multiple antennas simultaneously. In [39], a distributed secondary user selection scheme, which optimizes the performance of the secondary system without degrading the performance of the primary system, is proposed.

Nevertheless, most of the existing works on CCRN mainly focus on cooperations between PUs and SUs at the link-level [37, 38, 40–47], i.e., on the parameter settings between one PU and multiple SUs by performing the time slot allocation for direct and

forwarding transmissions, and/or adjusting the transmission power levels. A cooperation scheme between a PU and multiple SUs in a TDMA manner is presented in [41, 42], where a time slot allocation is investigated. To maximize the QoS in terms of throughput, the PU leases an amount of spectrum to the SUs in exchange for cooperation. By performing the time slot allocation, the PU decides when to cooperate and how to cooperate with the SUs. In [37, 38, 44, 45], the cooperation schemes between a PU and an SU are studied. Han *et al.* in [37, 43] investigate the cooperative SU's power allocation in a cooperative framework. In order to improve the cooperation performance, after the PU transmits its traffic, the cooperating SU forwards the PU's traffic and transmits its own traffic at the same time by using different power levels. An algorithm is proposed in [44] to maximize the PU's throughput as long as the relaying SU's performance requirement is satisfied by adjusting the allocated time slots and the cooperating SU's power level. A cooperation scheme which adopts cooperative space time coding at the SU's transmitter to effectively cancel out the interference from the secondary transmission to the primary transmission is studied in [45]. Another two-phase cooperation scheme between a PU and single SU is investigated in [46]. Nevertheless, in a real network, the cooperation is usually more complicated since there usually exist multiple concurrent transmission pairs. Therefore, it is necessary to develop a cooperative approach from the perspective of the whole network. Yi *et al.* in [47] investigate the cooperation between a primary network and multiple secondary networks. However, it still investigates the cooperation scheme between PUs and SUs with the purpose of increasing the throughput.

2.2 System Model

In a CRN, the spectrum bands are allocated to the PUs. The SUs do not have any exclusive spectrum and can only try to opportunistically send their data by utilizing idle

primary channels [48]. In our model, the SUs do not perform sensing and supervision of the spectrum due to the complexity and cost. The PU chooses an SU for cooperation and allows the selected SU to access the idle spectrum. The objective of the cooperation is to optimize the utility of the PU when the performance requirement of the SU is also satisfied.

2.2.1 Network Topology

We consider a CCRN consisting of a pair of PU (PU-Tx and PU-Rx) and multiple SUs, as shown in Fig. 2.1. The PU owns a unique licensed channel while one of the SUs is allowed to access the channel through cooperation with the PU. As per cooperation, the PU and the selected SU use two orthogonal channels by exploiting two quadrature components of the QAM modulation to transmit simultaneously. If there is a building or a wall obstructing the communication between the PU-Tx and PU-Rx or the PU-Tx is far from PU-Rx, the quality of the primary link is reduced dramatically. In this case, there is a desire for the PU to find a relay node to send the data to its receiver. Different from previous works, where the SUs access the spectrum opportunistically by sensing, the PU chooses the best appropriate cooperating SU according to the information provided by the SUs, and allows the selected SU to access the spectrum in the remaining time. Furthermore, we assume that the PU completely trusts the SUs and there is no false information offered by the SUs. Through cooperation, the PU can improve transmission performance, while the SU can earn possibilities to access the spectrum. Therefore, our cooperation scheme is based on mutual benefit.

In Fig. 2.1, PU-Tx, PU-Rx and D-SU denote primary transmitter, primary receiver and secondary receiver, respectively. The solid line represents the primary transmission while the dash line denotes the secondary transmission. We consider a PU, with a single antenna, co-located with several SUs seeking transmission opportunities. The SUs are

equipped with two antennas. The PU-Tx broadcasts the request for cooperation when its performance is reduced dramatically, expecting to improve the performance through cooperation with the SU. The time period is then divided into two phases. In phase one, the PU-Tx transmits its packet to the cooperating SU using the in-phase channel of QPSK and this SU forwards the previously received packet to the PU-Rx simultaneously using the quadrature channel of QPSK. In phase two, the SU transmits its own traffic to the D-SU.

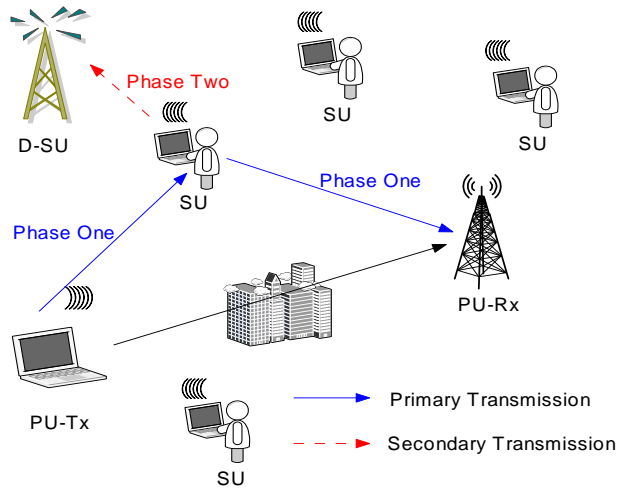


Figure 2.1: Scenario of CCRN.

Three Phase Cooperation

Usually, the cooperation scheme is performed with three-phase. The PU transmits its traffic to the BS as well as the cooperative SU during the first phase, and then, the SU relays PU's traffic to the BS in the second phase. Based on that, the SU obtains its spectrum access opportunity and transmits in the third phase. Otherwise, the PU transmits traffic to the SU in the first phase, then the PU and SU transmit PU's traffic to the BS simultaneously in the second phase. At last, the SU transmits to its destination,

the access point (AP), in the third phase. The above two three-phase cooperation scheme are shown as the following time slot frame:

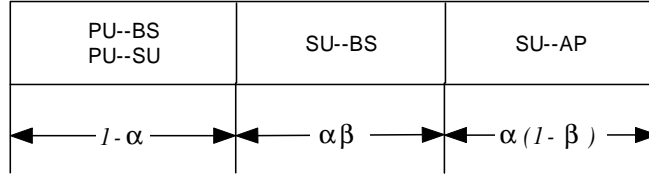


Figure 2.2: Three-phase cooperation scheme (1).

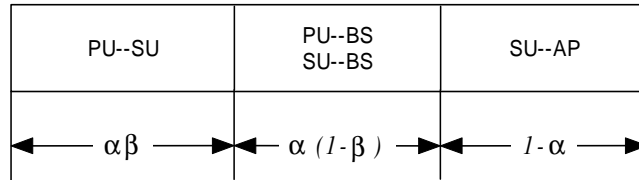


Figure 2.3: Three-phase cooperation scheme (2).

Two Phase Cooperation

Aiming at improving spectrum efficiency, many researchers focus on squeezing three-phase cooperation scheme to a two-phase cooperation scheme. In this chapter, we address the cooperation between PUs and SUs within two phase, which is illustrated in Fig. 2.4

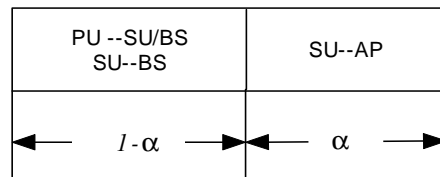


Figure 2.4: Proposed two-phase cooperation scheme.

2.2.2 Relaying Strategy

Cooperation among users in a wireless network can substantially improve the performance of communication in terms of reliability or transmission rate [21]. For direct transmission, the relaying protocols in which the relay either amplifies what it receives, or fully decodes, re-encodes, and retransmits the source message. We call these options AF and DF, respectively [49]. In this chapter, the AF mode is used by the cooperating SU to relay the PU’s traffic.

We consider a distributed CRN without the help of either information exchange among SUs or a central controller. The time slot frame structure for the PU cooperating with one SU is shown in Fig. 2.5.

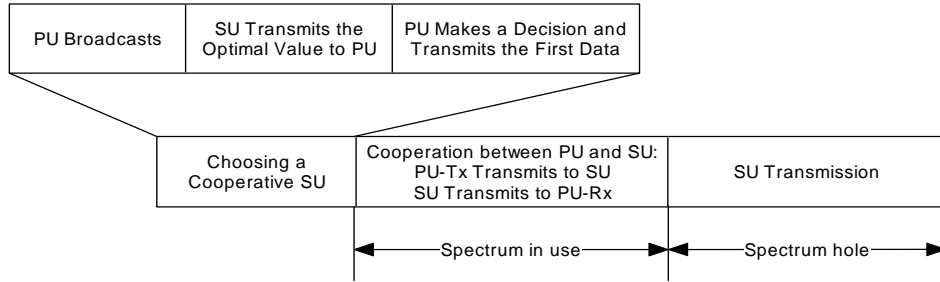


Figure 2.5: Time frame structure.

When the performance is dramatically reduced, such as the PU-Tx is far away from its corresponding PU-Rx or there are some obstacles blocking the link, the PU needs a suitable cooperator to help improve transmission performance and reliability. The PU broadcasts request for cooperation, selects a cooperator from the nearby SUs and sends its own parameters to the SUs, i.e., transmission power and the location information. Then, the SUs determine the optimal parameters for cooperation to maximize the PU’s utility and send back to the PU. Based on the information provided by the SUs, the PU chooses the most suitable SU as the cooperator and sends the first packet to the

selected SU. Likewise, PU-Tx transmits the n th packet to this SU while SU transmits the $(n-1)$ th packet received earlier to PU-Rx simultaneously using quadrature signaling. It is assumed that the SU can transmit and receive at the same time via two antennas covering two different regions. In addition, the PU and the SU cooperate using two orthogonal channels without interfering each other, which can improve the performance of the CCRN system. When there is no continuous traffic received from the PU-Tx, the SU starts to transmit its own traffic during the secondary transmission.

The duration for cooperation is denoted by T , which is further divided into two phases. Specifically, a fraction β ($0 \leq \beta \leq 1$) of time slot T is used for the cooperative transmission. The cooperating SU is allowed to transmit its own data to the corresponding destination in the remaining duration of $(1-\beta)T$. In previous work in the literature, the two-phase cooperative relaying only works on the spectrum which is utilized by the PU and the idle spectrum is wasted. In contrast, we treat the spectrum in use and spectrum hole together as a whole time slot T , wherein all the occupied spectrum is used for relaying and the spectrum hole is used for secondary transmission. With cooperative communication, there is no need for the SUs to perform spectrum sensing and spectrum monitoring. Moreover, the right for the SU to access the licensed spectrum is dedicated.

The transmission links are assumed to conform to a Rayleigh flat fading model. Therefore, the channel condition remains static during slot time T , but varies over the slots. In CRN, the channel state information (CSI) can be acquired by the SU.

2.3 Cooperation Optimization for CCRN

2.3.1 Problem Formulation

The cooperation involves the PU selecting the most suitable SU and the SU determining the power allocation coefficient to maximize the performance of the PU. We formulate the decision procedure as a nonlinear optimization problem and then derive the closed-form solution.

The PU and the selected SU cooperate by exploiting two orthogonal channels to avoid the interference between different transmissions. Let P_1 and P_2 denote the transmitting power of the PU and the SU, respectively. The SU forwards the PU's traffic with power αP_2 and transmits its own traffic with power $(1 - \alpha) P_2$. The channel gain from the PU-Tx to SU, from the SU to PU-Rx and from the SU to its own receiver in each slot are denoted as h_1 , h_2 and h_3 , respectively. C_{th} is the desired performance value of the relaying SU. To determine the SNR, we apply a Rayleigh fading channel model, where F is the fading and follows an independent exponential distribution. Let N_0 be the one-sided power spectral density of the noise and W be the bandwidth. As a result of fading channel environment, the SNR is $\frac{FP}{N_0W} = hP$, where $h = \frac{F}{N_0W}$. For simplicity, we always have $N_0 = 1$.

To choose the most appropriate cooperative SU for the PU, a performance optimization problem under certain utility and power constraints is formulated. We consider that the selected SU uses the AF relaying mode to transmit the PU's traffic and maximizes the performance of the PU with the constraint that the minimum requirement of secondary transmission needs to be satisfied. The utility of the PU through cooperation is $\beta T \cdot W \log_2 \left(1 + \frac{\alpha h_1 h_2 P_1 P_2}{h_1 P_1 + \alpha h_2 P_2 + 1} \right)$. The utility of the SU is $(1 - \beta) T \cdot W \log_2 [1 + (1 - \alpha) h_3 P_2]$.

Therefore, the optimization problem is described as follows:

$$\begin{aligned}
 & \text{maximize} && \beta T \cdot W \log_2 \left(1 + \frac{\alpha h_1 h_2 P_1 P_2}{h_1 P_1 + \alpha h_2 P_2 + 1} \right) \\
 & \text{subject to} && (1 - \beta) T \cdot W \log_2 [1 + (1 - \alpha) h_3 P_2] \geq C_{th} \\
 & && P_{min} \leq P_2 \leq P_{max} \\
 & && 0 < \alpha < 1.
 \end{aligned} \tag{2.1}$$

For simplicity, we let the bandwidth $W = 1$ and $T = 1$.

2.3.2 Utility Optimization

Since β , h_1 , h_2 , h_3 , P_1 and C_{th} are all known, we can denote $c_0 = \beta$, $c_1 = h_1 P_1$, $c_2 = h_2$, $c_3 = h_3$ and $c_4 = C_{th}$. Then this optimization problem is equivalent to:

$$\begin{aligned}
 & \text{minimize} && f(\alpha, P_2) \\
 & \text{subject to} && (1 - c_0) \log_2 [1 + (1 - \alpha) c_3 P_2] - c_4 \geq 0 \\
 & && P_{min} \leq P_2 \leq P_{max} \\
 & && 0 < \alpha < 1
 \end{aligned} \tag{2.2}$$

where $f(\alpha, P_2) = -c_0 \log_2 \left(1 + \frac{\alpha c_1 c_2 P_2}{c_1 + \alpha c_2 P_2 + 1} \right)$.

The optimization problem as in (2.1) or (2.2) is very complex to solve. It is preferable to linearize and solve the optimization in dual space, but the resultant computation is intensive. For our purpose, it is feasible to solve the problem as discussed below.

Using First-Order Necessary Conditions, we are considering the following program. Since the objective function is a continuous function, we can rewrite the constraints as $P_{min} \leq P_2 \leq P_{max}$ and $0 \leq \alpha \leq 1$, which implies the feasible solution of this optimization problem is a closed set.

Proposition: In problem (2.2), there must be a feasible solution and the solution reaches the optimal point at the boundary.

Proof: Let $x_0 = (\alpha^*, P_2^*)$ be an optimal solution and we assume that the point x_0 is not at the boundary, which means x_0 is within the region $P_{min} < P_2 < P_{max}$ and $0 < \alpha < 1$. The resulting optimization formulation can be rewritten as:

$$\begin{aligned} & \text{minimize} && f(x) \\ & \text{subject to} && c_i(x) \geq 0, i \in I \end{aligned} \tag{2.3}$$

x_0 is defined as the feasible solution of problem (2.3). Therefore, the active set is $\mathcal{A}(x_0) = \{i \in I : c_i(x_0) = 0\}$.

Lemma (LICQ): Given the point x and the active set $\mathcal{A}(x)$, we say that the linear independence constraint qualification (LICQ) holds if the set of active constraint gradients $\{\nabla c_i(x), i \in \mathcal{A}(x)\}$ is linearly independent.

According to the above lemma, LICQ holds at x_0 if and only if $\{\nabla c_i(x), i \in \mathcal{A}(x)\}$ are linearly independent. In our case, there is only one active set $c_i(x)$, which is $(1 - c_0) \log_2 [1 + (1 - \alpha) c_3 P_2] - c_4 \geq 0$. We have,

$$\nabla c_i(\alpha, P_2) = \begin{pmatrix} \frac{(1 - c_0) c_3 P_2 \ln 2}{1 + (1 - \alpha) c_3 P_2} \\ \frac{(1 - c_0) (1 - \alpha) c_3 \ln 2}{1 + (1 - \alpha) c_3 P_2} \end{pmatrix} \tag{2.4}$$

Because of $0 < c_0 < 1$, $P_2 > 0$ and $0 < \alpha < 1$, $\nabla c_i(\alpha, P_2)$ is not equal to 0 which means the set of $\{\nabla c_i(x), i \in \mathcal{A}(x)\}$ is linearly independent. Since x_0 is a local solution, if LICQ holds at x_0 , Karush-Kuhn-Tucker (KKT) conditions must be satisfied. Using the Lagrange multiplier method, we have

$$\mathcal{L}(\alpha, P_2, \lambda) = f(\alpha, P_2) - \lambda g(\alpha, P_2) \tag{2.5}$$

where $f(\alpha, P_2)$ is the same as in formulation (2.2) and $g(\alpha, P_2) = (1 - c_0) \log_2 [1 + (1 - \alpha) c_3 P_2] - c_4$. The gradient of (2.5) is:

$$\nabla \mathcal{L}(\alpha, P_2, \lambda) = \begin{pmatrix} \frac{\partial \mathcal{L}(\alpha, P_2, \lambda)}{\partial \alpha} \\ \frac{\partial \mathcal{L}(\alpha, P_2, \lambda)}{\partial P_2} \end{pmatrix} \tag{2.6}$$

where,

$$\begin{aligned} \frac{\partial \mathcal{L}(\alpha, P_2, \lambda)}{\partial \alpha} &= -c_0 \cdot \frac{c_1 c_2 P_2 (c_1 + 1) \ln 2}{(c_1 + \alpha c_2 P_2 + 1) \cdot A} \\ &\quad + \lambda (1 - c_0) \cdot \frac{c_3 P_2 \ln 2}{1 + (1 - \alpha) c_3 P_2} \end{aligned}$$

$$\begin{aligned} \frac{\partial \mathcal{L}(\alpha, P_2, \lambda)}{\partial P_2} &= -c_0 \cdot \frac{c_1 c_2 \alpha (c_1 + 1) \ln 2}{(c_1 + \alpha c_2 P_2 + 1) \cdot A} \\ &\quad - \frac{\lambda (1 - c_0) (1 - \alpha) c_3 \ln 2}{1 + (1 - \alpha) c_3 P_2} \end{aligned}$$

where $A = (c_1 + \alpha c_2 P_2 + \alpha c_1 c_2 P_2 + 1)$. Since $\lambda \geq 0$, $0 < c_0 < 1$, $c_i > 0$ ($i = 1, 2$ and 3), $P_2 > 0$ and $0 < \alpha, \beta < 1$, we can obtain that equation 2.6 does not equal to 0, which is in conflict with the KKT conditions.

As mentioned above, we can see that the LICQ holds but the KKT conditions are not satisfied. Therefore, the assumption is not true and the optimal solution should be reached at the boundary. In Fig. 2.7, we notice that the value of the objective function increases while P_2 becomes larger, so we have $P_2^* = P_{max}$. Then, the optimal power of SU can be expressed as:

$$\alpha^* = 1 - \frac{2^{\frac{c_{th}}{1-\beta}} - 1}{h_3 P_{max}}. \quad (2.7)$$

2.4 Numerical Results

In this section, we present the numerical results to show the performance of the proposed scheme in terms of SUs' power consumption, cooperation time allocation and so on. First, energy efficiency is illustrated with different time allocation coefficient β . Then, simulations are carried out to evaluate the performance of the PU in cooperation with the selected SU, which is compared to that of the PU without cooperation. Moreover, different scenarios are considered and compared in the simulations. Afterwards, the

performance effected by the factor β , which indicates the cooperative transmission time slot ratio, is discussed. In addition, the utility of the PU for different time allocation coefficients β with different power is demonstrated. Finally, we compare the proposed cooperation scheme with a traditional cooperation scheme.

Fig. 2.6 shows the energy efficiency with respect to the transmission power of the SU, for different time allocation coefficient β , given the PU's transmission power is fixed. The power of PU is 1mW, the power of SU varies from 0.1mW to 1mW, and time slot window length is 1s. It can be seen that the cooperation performance cannot be always increased as β grows. Actually, a larger β leads to a smaller optimal transmission power of SU, and vice versa. The reason is that for a greater allocation time β , the SU needs less transmission power to relay PU's traffic as it takes a longer time. However, as the duration for cooperation becomes longer, the selected SU may be reluctant to relay PU's traffic with less transmission power since they desire for larger transmission opportunity. Hence, there is a tradeoff between the allocation time β and SU's transmission power. But it is worth noting that β is not the only factor for the SU to choose its transmission power, and the channel condition also matters.

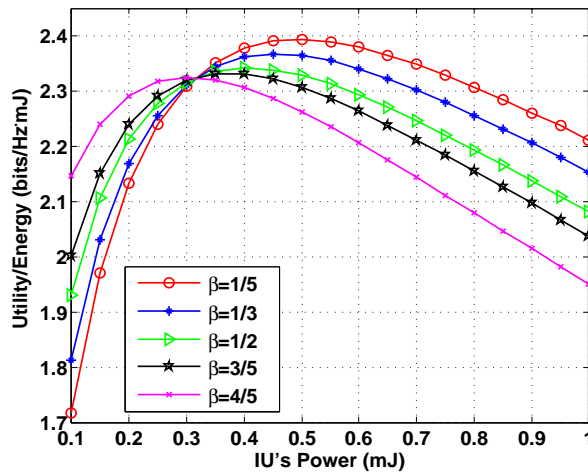


Figure 2.6: The relationship between time allocation β and SU's consuming power.

The simulation parameters are set as follows: $h_1 = 25.2$, $h_2 = 26.1$ and $h_3 = 12.3$; the power of PU is set as 1mW, P_{min} and P_{max} represent the minimum power and maximum power of SU which are set as 0.3mW and 1.2mW, respectively; the desired utility of SU is $C_{th} = 1$ and $\beta = \frac{3}{5}$. It is shown in Fig. 2.7 that the performance of PU improves as α increases whereas the performance of SU decreases. It can be explained that the more energy the cooperating SU spends for transmitting PU's traffic, the less energy is devoted to its own transmission. In addition, an increment in the SU's power consumption for relaying and its own transmission will result in an increment in the performance of both PU and SU. For the scenario that the PU-Tx is far away from its receiver or the link between the PU-Tx and PU-Rx is blocked by buildings, the performance with cooperation is much better than that without cooperation when α is beyond a certain threshold. In Fig. 2.7, it is necessary for the PU to choose the SU to cooperate with SU's maximum power when α is larger than 0.09 and the SU with its minimum power when α is larger than 0.35, respectively.

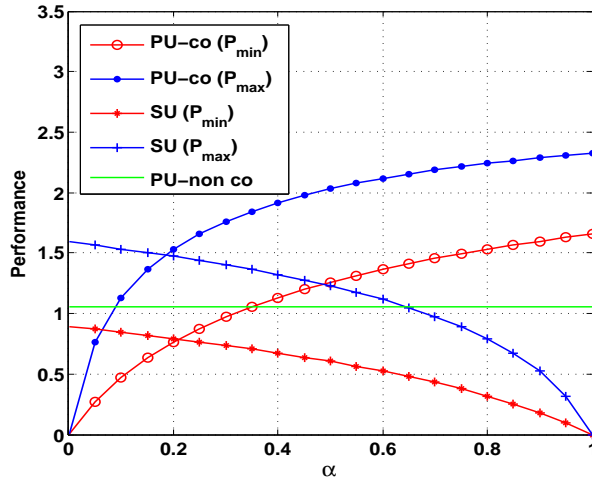


Figure 2.7: Comparison performance of PU and SU with different α .

In Fig. 2.8, the maximum performance of the SU is achieved when α is around 0.68

while the desired utility of SU is also satisfied, which is consistent with the result obtained from (2.7). We analyze the following three cases shown in Fig. 2.8. We have randomly generated two groups of uniform distributed channel coefficients which refers as poor channel condition group and strong channel condition group, and the average value of two groups are set as 5 and 40 respectively. Case 1 corresponds to the scenario that the SU is within the region, which is in the middle of the links from the PU-Tx to the cooperating SU and from the SU to PU-Rx. In case 2, h_1 and h_2 fall in the poor channel condition group and strong channel condition group, which means the link between the SU and the PU-Rx is strong whereas the link between the PU-Tx and the SU is weak since the cooperating SU is far away from PU-Tx, which is the same as PU's receiver. In case 3, h_1 and h_2 fall in the strong channel condition group and poor channel condition group, respectively, which correspond to the scenario that, even the link between the PU-Tx and the SU is strong, while the link between the SU and the PU-Rx is weak due to shadowing or deep fading. It is seen that, in cases 2 and 3, the performance of PU is much poorer than that in case 1.

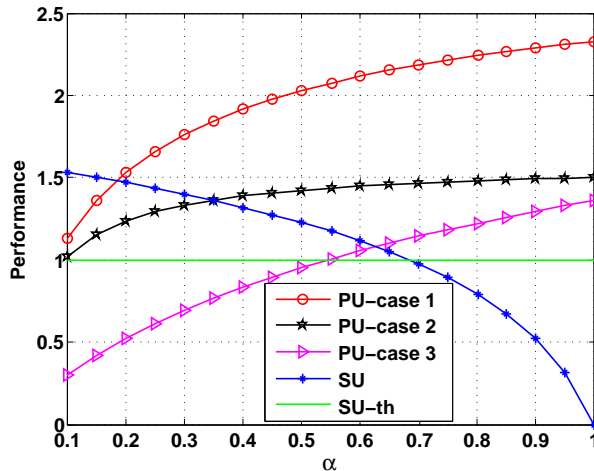


Figure 2.8: Performance of variation of PU and SU & Three different cases of the performance of PU.

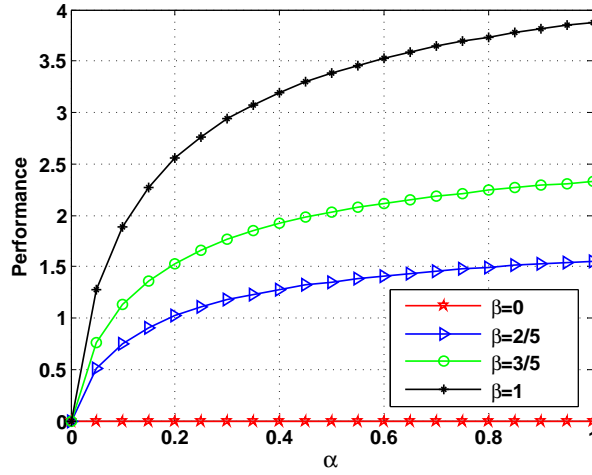


Figure 2.9: The performance of PU effected by the factor β .

Fig. 2.9 shows the trends of the PU's performance versus the power allocation coefficient α , for different parameters of β (the fraction of time slot used for relaying transmission). It is seen that the performance of the PU increases with α , and as the factor β increases, the performance is improved accordingly. Specially, when $\beta = 1$, the SU only helps forward the PU's traffic without transmitting its own traffic, which is referred to as the conventional relaying scenario. When $\beta = 0$, the SU transmits its own traffic without relaying the PU's traffic.

Fig. 2.10 shows the utility of the PU for different time allocation coefficients β . The power of SU is fixed to 2mW, and the power of PU varies from 1mW to 3mW. It can be seen that when $\beta = 1/3$, the PU's utility through cooperation with the SU is even lower than that with the direct transmission. Therefore, in this case, the PU will not choose to cooperate. However, for $\beta = 3/5$ and $\beta = 3/4$, the PU's utility is much better through cooperating with the SU, compared with that using the direct transmission. Therefore, the PU is willing to cooperate with the SU.

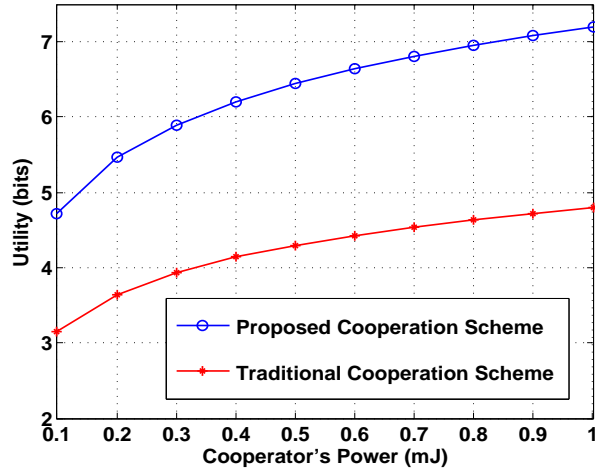


Figure 2.11: Comparison of the traditional cooperation scheme and the proposed cooperation scheme.

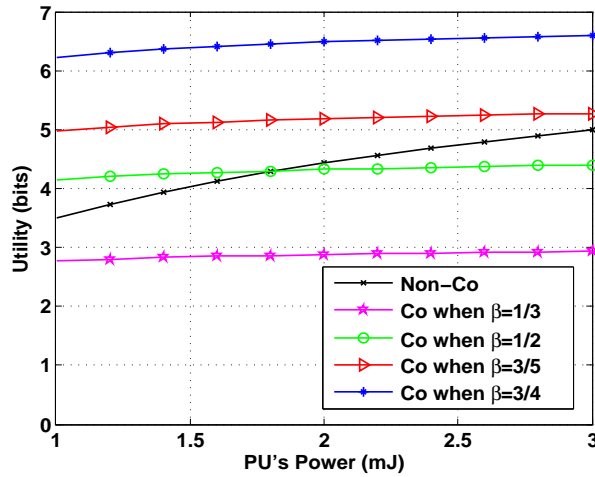


Figure 2.10: PU's utility with and without cooperation with the SU.

Fig. 2.11 compares the performance of the proposed cooperation scheme with the traditional cooperation scheme. In traditional cooperation scheme, the PU transmits the traffic to the BS first, and then the cooperating SU relays the traffic. Finally, the SU acquires the remaining time slot spectrum for its own transmission. From this figure,

it can be seen that with the proposed cooperation scheme outperforms the traditional one. In addition, it can also be seen that the utility of SU increases, given the PU's performance remains the same.

2.5 Summary

In this chapter, we have proposed a novel cooperative strategy in CRN, based on quadrature signaling. By employing the two orthogonal channels, the three-phase relaying process can be integrated into two-phase without interference. We have considered the underutilized spectrum and spectrum hole as a whole time slot. When the channel condition between the PU and its receiver is poor, the PU's performance can be improved through cooperation with an assistant cooperative relaying SU. We have formulated this model as a nonlinear optimization problem. Through exploiting the optimal algorithm, the PU's utility can achieve the optimal value. As a reward, the second phase is allocated to the SU for its own traffic. The optimal power allocation have been analyzed and the closed-form solution has been derived for AF mode.

Chapter 3

PCN/SCN Cognitive Radio Networking

A salient feature of a cluster of PUs is that every member has equal channel access ability. Collectively, a cluster of PUs will have more power and multiple heads to connect with multiple cluster heads of multiple clusters of SUs. Thus, in PCN/SCN, the system is capable of supporting multiple PCN and SCN connections. PCN/SCN is fair and robust.

3.1 Literature Review

3.1.1 Cooperative Partner Selection

In PCN/SCN, cooperation is adopted to achieve higher transmission rate and lower energy consumption. However, the first step of cooperation is how to select the best cooperator to cooperate. Therefore, cooperative partner selection which is also referred as relay selection has raised many interest in recently years.

Some works investigate in relay selection [50–54]. In [50], a partner selection algorithm

is studied in cellular networks, and a novel non-bipartite stable matching algorithm is developed in which the overall energy-consumption rate is minimized in the network by appropriately grouping users and setting their power levels according to their QoS requirements. A relay selection problem which takes the effect of PU interference into consideration is proposed in cognitive radio networks in [51]. In [52], a QoS aware optimal relay selection, power allocation and subcarrier assignment approach under a total power constraint is proposed, and the authors simulate the relay selection scheme based on LTE-Advanced (LTE-A) network. Partner selection schemes both in distributed and centralized manner are investigated in [53] for cooperative communication in wireless networks. In [54], cooperative relaying in an IEEE 802.15.4 compatible wireless sensor network is investigated, and the simulation shows that cooperation can provide a significant energy saving by pursuing a similar performance in terms of outage and error rate compared with non-cooperation scenario.

In CCRN, PU has the privilege to determine its relay nodes while SUs evaluate their own utility gains in the cooperation with the specific PU, which are the unique features in the relay selection. Therefore, to improve the performance of CCRN, it is essential to study how to choose an appropriate relaying SU set.

3.1.2 Spectrum Sharing

Spectrum sharing plays an important role in CRN because it can eventually result in more efficient utilization of spectrum. There are many ways to category spectrum sharing: centralized and distributed, cooperative and non-cooperative. In centralized spectrum sharing, the spectrum allocation and access procedures are controlled by a central entity. In [55], competition by users is considered through a central spectrum policy server, while in distributed spectrum sharing, spectrum allocation and access are based on local (or possibly global) policies that are performed by each node distributively [56]. A common

technique used in cooperative spectrum sharing schemes is forming clusters to share interference information locally. This localized operation provides an effective balance between a fully centralized and a distributed spectrum sharing mechanism. A single-hop flow spectrum sharing with five rules that tradeoff performance with communication costs and implementation complexity in a non-cooperative manner is considered in [57]. Since interference in other CR nodes is not considered, non-cooperative spectrum sharing may result in reduced spectrum utilization. However, non-cooperative spectrum sharing do not require exchanging message frequently between neighbors as in cooperative spectrum sharing.

Recently, many spectrum sharing mechanisms have been proposed: game theory based methods [58, 59], contract based schemes [60, 61], auction based approaches [62, 63], etc. However, the aforementioned works only address the scenario of a single PU. In reality, there are multiple PUs and multiple SUs coexisting in the network. Hence, a more complicated scenario brings some new challenges, which require new designs. Various extended frameworks are proposed to investigate the multiple PUs scenario in CRN. Evolutionary games are applied in [64, 65] to implement the spectrum allocation in dynamic spectrum sharing networks with multiple PUs. In [66], the scenario of multiple PUs interacting with multiple SUs through a coalitional game is discussed. Unfortunately, similar to the single PU scenario, these works still consider the cooperation individually. Therefore, we investigate the spectrum sharing problem based on cluster, in which each PU has equal spectrum access ability and can be the cluster head who cooperates with the selected SU. The CRN is integrated as a PCN/SCN, and the PCN/SCN system can support multiple connections between PUs and SUs.

3.1.3 Matching Theory

Matching theory can describe the mutually beneficial relationships between two disjoint groups [67]. In the matching, agents in one group are matched to the agents in the other group based on their declared preference ranking lists. It is essential to study how to choose an appropriate relaying SU set. Maximum weighted matching (MWM) algorithm is employed in [68–70]. In [68], MWM is adopted to solve the data retrieval scheduling problem in a wireless data broadcast system, and the scheduling problem in vehicular networks and in wireless ad hoc networks are investigated in [69] and [70], respectively. However, the MWM algorithm used in CCRN is different since we need to consider the utility of both the primary network and the secondary network.

3.2 Problem Definition

In CRN, there are two parties of users: PUs and SUs. On one hand, PUs desire to improve their utility. On the other hand, SUs want to obtain the spectrum access opportunity. Therefore, cooperation is adopted to benefit both sides of users in the CRN. However, only the cooperating SUs who help the PUs relay primary traffic can benefit. In fact, a large number of SUs are searching for spectrum. Each PU cooperates with multiple SUs may be one solution for the above starving SUs problem, but more cooperator SUs will lead to higher cooperation cost for the PUs. To this end, a cluster based two-phase spectrum sharing mechanism among the users in CRN is proposed.

In order to improve the performance of primary network, the PUs find the cooperators from the SUs to cooperate. Nevertheless, in practice, some SUs might not be willing to cooperate with the PU, as it is quite energy consuming to relay the PU's traffic while the utility gain might be relatively low, i.e., the ratio of utility to power consumption is low. But the SUs still desire to gain secondary transmission opportunity so as to improve their

utility. Moreover, only the SUs who cooperate with the PUs can benefit, while there may be many starving SUs in the surrounding areas. Some works concentrate on a scenario that a PU cooperates with multiple SUs to benefit more SUs, but the PU may not be always willing to do so. On one hand, the coordination overhead and the complexity of the allocation algorithm grow with the number of participating SUs. If the SUs are not selected carefully, it would become a big issue and may nullify the benefit from multiuser diversity due to the increasing coordination cost. An appropriate SU selection process should guarantee that the PU can improve its QoS through cooperation, and it would be sufficient even if one single SU can achieve the goal. On the other hand, under current relay-and-pay strategy in which only the relaying SU can access the remaining time slot, while other SUs may be starving due to the less attractive relay capability. In this case, the spectrum access opportunities will be reduced from the perspective of the whole network. Therefore, the fairness of the network needs to be further considered.

To address the aforementioned issues, a group of users, IUs, are assigned by the PCN clusters. After obtaining the spectrum access opportunity by cooperating with the PUs who are the cluster head of PCN, the selected IUs cooperate with other SUs to share the spectrum to benefit these SUs in the cluster of SCN. However, an IU may not be always selected as the cooperator of the PU, it sacrifices itself and expects to obtain benefit in the future when it is not selected as the IU. Because of such kind of mechanism, the cooperation framework have the motivations to keep working.

The research objective of this chapter is to develop a spectrum sharing mechanism in CRN to improve spectrum efficiency as well as network utility. First, the PUs are formed clusters of PCN based on their locations, and the cluster heads are chosen. Then, a subset of SUs which are referred as IUs are selected to relay the head PUs' traffic. In this way, head PUs' utility can be improved. After the IUs cooperate with the head PUs, the IUs form clusters with other SUs and assume the role of cluster heads of SCN. Hence,

the head PU only conducts transactions with the cluster head of SCN as the first phase in the cooperative networking which will reduce the cooperation cost compared with PU cooperating with every SU in SCN. The sharing of transmission opportunities within the cluster is the second phase of the cooperation so that the members in the cluster can acquire the spectrum access opportunities. Therefore, the proposed spectrum sharing mechanism benefits the PU, the cluster head IU as well as every SU in the cluster.

3.3 System Model

3.3.1 Network Model

It is considered that a CCRN consists of PCN and SCN. In PCN/SCN, a base station (BS), PUs, IUs and SUs are uniformly located in the same area. The BS serves the PUs, and the IUs who relay for the PUs can also communicate with the BS. The PUs form the PCN clusters, and some of them can be the cluster heads who cooperate with selected SUs (IUs). Spectrum frequencies of the cluster heads of PCN are assigned with bandwidth W_i ($i = 1, 2, \dots, M$). When the performance of PCN cluster becomes poor or the PUs desire to improve the cluster's performance, the PCN's cluster head asks the BS broadcasting the availability of spectrum opportunities to SUs over a dedicated control channel. If an SU wants to cooperate with this head PU, it will send its feedback to the BS through the control channel. Then, the selected SU works as the IU by relaying traffic for head PU. Head PUs select the IUs based on their cooperation utility, and each IU may be selected by one or multiple cluster heads of PCN. Each cluster head PU uses $\beta_i T$ for transmission and leases $(1 - \beta_i)T$ to the IU, where T is the slot time, and β_i denotes the cooperation time fraction. The IU then allocates the acquired spectrum to its cluster members of SCN. This scheme can be implemented through a TDMA based medium access control (MAC) strategy in a way similar to the MAC in IEEE 802.16

standards. As mentioned above, the scenario can be separated into two parts: PCN and SCN, which are shown in Fig. 3.1 and Fig. 3.2, respectively.

In Fig. 3.1, the PUs form PCN clusters which are shown by clouds in the figure, in which every PU can act as cluster head for channel access, i.e., each PU has equal right. The cluster heads of PCN can cooperate with the IUs. Within the cluster of PCN, the PUs who are performed as the cluster heads of PCN act as a local control center to coordinate the transmission. In order not to be confused, the following mentioned PUs are referred to the cluster head PUs. The cluster size can be optimized by low energy adaptive clustering hierarchy (LEACH) protocol which is proposed in [71]. The transmission time of PUs is divided into time slot, and the proposed scheme uses slotted TDMA for channel access. In Fig. 3.2, without leading confusion, only the cluster heads of PCN are shown. Each IU forms its own cluster with surrounding SUs who are desiring for spectrum access, and within the SCN cluster, the IU and SUs share the aggregated spectrum together.

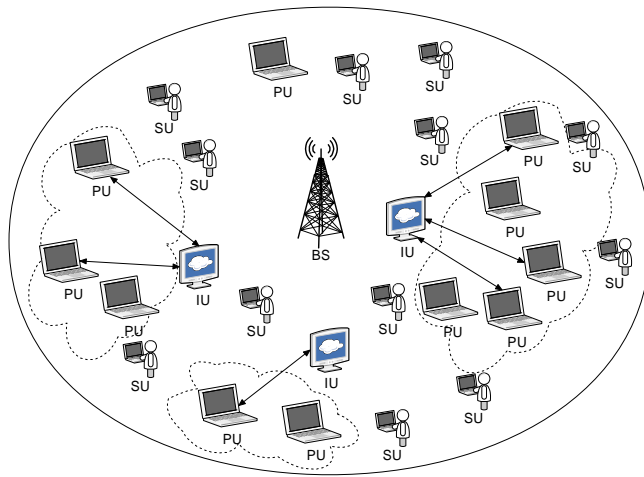


Fig. 3.1: Primary cooperative networking (PCN) scenario.

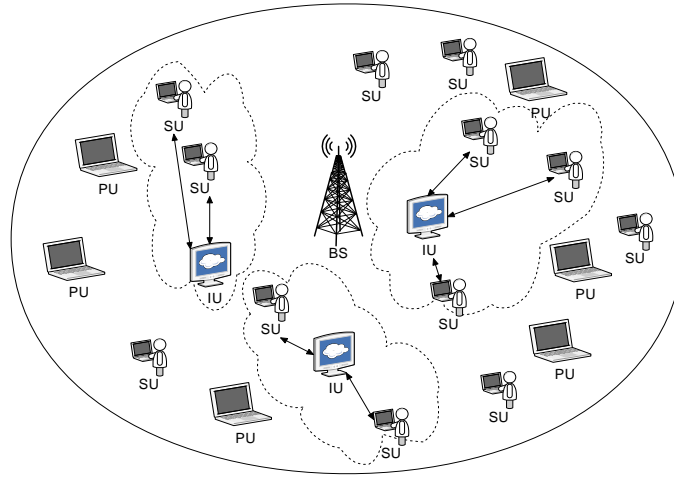


Fig. 3.2: Secondary cooperative networking (SCN) scenario.

3.3.2 Channel Model

Transmission channels are assumed to conform to a Rayleigh flat fading model in which the channel conditions are stable during a fix time slot T , but vary independently from one slot to another. The CSI is assumed perfect, but it is estimated in practice using techniques such as minimum mean-square-error (MMSE) estimation, least squares (LS) estimation, fusion and sampling, etc., indicating that CSI is imperfect in practice.

Primary Cooperative Network (PCN)

In PCN, the cooperation between cluster heads of PCN and selected IUs is implemented. After the BS send the cooperation request from the PUs in PCN cluster, the SUs who accept the request will send their feedback to the BS. Each PCN cluster will be considered as a whole while selecting the IUs, and the cluster heads choose the same the cooperator IU based on the total utility they can acquire through cooperation. When an SU is selected as the IU by multiple PUs, it relays the traffic from the PUs to the BS using M-ary phase shift keying (MPSK) modulation with different power levels.

During the cooperation between PUs and the selected IU, the received signal from PU_i ($i = 1, 2, \dots, M$) at the BS and IU_q ($q = 1, 2, \dots, Q$) in a fixed time slot can be written respectively as follows:

$$r_{i0} = \sqrt{P_i}h_{i0}x_i + n_{i0} \quad (3.1)$$

$$r_{iq} = \sqrt{P_i}h_{iq}x_i + n_{iq} \quad (3.2)$$

where P_i is the transmission power of PU_i , and x_i is the transmission signal of PU_i . The channel fading coefficients from PU_i at the BS and the IU_q are denoted by h_{i0} and h_{iq} , respectively. n_{i0} and n_{iq} are AWGNs with variance N_0W_i (N_0 denotes the one-sided power spectral density of the noise, and W_i is the bandwidth of PU_i), where $N_0 = 1$ for simplicity.

Each cooperative IU employs an AF scheme to relay PU's traffic. When an IU is selected by the PCN cluster with multiple cluster heads PUs, its power is divided for relaying PUs' traffic. After IU_q receives the signal r_{iq} from the PU_i , it relays the signal by transmitting

$$r_{q0} = \sum_{i=1}^{L_x} \left(\sqrt{\xi_i P_q} h_{q0} \gamma_q r_{iq} \right) + n_{q0} \quad (3.3)$$

where P_q is the total transmission power of IU_q , and L_x is the number of cluster head PUs in each PCN cluster. ξ_i is the power fraction of P_q which is allocated for delivering PU_i 's traffic, and h_{q0} represents the channel fading coefficient from IU_q to the BS. n_{q0} is also the AWGN, and γ_q is the amplification gain.

The utility of PU_i obtained through cooperation is

$$U_i = \beta_i T \cdot W_i \log_2 \left(1 + h_{i0}^2 P_i + \frac{\xi_i h_{iq}^2 h_{q0}^2 P_i P_q}{h_{iq}^2 P_i + \xi_i h_{q0}^2 P_q + 1} \right) \quad (3.4)$$

where β_i is the time fraction used for cooperative transmission between PU and IU. Each PU has equal bandwidth for simplicity which means $W = W_i$ ($i = 1, 2, \dots, M$). For Rayleigh channels, h_{i0}^2 , h_{iq}^2 and h_{q0}^2 follow exponential distribution.

Before the handshake of the selected IU and PCN cluster, the selected IU need to optimize the total utility that they can help with the PUs within the same PCN cluster. The formulated optimization problem is shown as follows:

$$\begin{aligned}
 & \underset{\xi_i}{\text{maximize}} && \sum_{i=1}^{L_x} \beta_i T \cdot W_i \log_2 \left(1 + h_{i0}^2 P_i + \frac{\xi_i h_{iq}^2 h_{q0}^2 P_i P_q}{h_{iq}^2 P_i + \xi_i h_{q0}^2 P_q + 1} \right) \\
 & \text{subject to} && 0 < \xi_i < 1 \\
 & && \sum_{i=1}^{L_x} \xi_i = 1
 \end{aligned} \tag{3.5}$$

where $i = 1, 2, \dots, L_x$. The above optimization function is a convex function. Therefore, according to KKT conditions, we can obtain the following equations:

$$\begin{aligned}
 \frac{\partial U}{\partial \xi_1} &= \frac{\partial U}{\partial \xi_2} = \dots = \frac{\partial U}{\partial \xi_{L_x}}, \\
 \sum_{i=1}^{L_x} \xi_i &= 1
 \end{aligned} \tag{3.6}$$

where U is given by the objective function of (3.5). We can solve above equations, and obtain the values of ξ_i , since $\frac{\partial U}{\partial \xi_i} > 0$, and $\sum_{i=1}^{L_x} \xi_i = 1$, we can obtain the optimal solutions of ξ_i which are feasible.

Secondary Cooperative Network (SCN)

If the IU excludes the rewarded spectrum bands, the utility of IU_q through cooperation with PCN cluster can be shown as

$$U_q = (1 - \beta_i) \cdot L_x W_i \log_2 (1 + h_q^2 P_q) \tag{3.7}$$

where P_q denotes the transmission power of IU_q , and h_q represents the channel gain of IU_q transmitting to its own destination. L_x is the member of cluster heads in PCN cluster.

Otherwise, if the IU forms the SCN cluster, and shares the acquired spectrum bands with other surrounding SUs, the SNR of user j within cluster i is described by

$$SNR_{ij} = \frac{h_j^2 P_{ij}}{N_0 W_i} \quad (3.8)$$

where $i = 1, 2, \dots, M$, and $j = 0, 1, 2, \dots, Y$ ($j = 0$ denotes IU, other j s denote the SUs; Y is the number of users in SCN cluster). P_{ij} represents the transmission power of user j who joins in cluster i , and h_j denotes the channel gain of user j joining in a cluster. The transmission rate of user j associated with cluster i is

$$R_{ij} = L_x W_i \log_2 (1 + SNR_{ij}). \quad (3.9)$$

Therefore, the utility of user j associates with cluster i of SCN is given by

$$V_{ij} = t_{ij} \cdot R_{ij} \quad (3.10)$$

where t_{ij} denotes the time slot assigned to user j within cluster i .

3.4 Proposed Spectrum Sharing Mechanism

A cluster based two-phase spectrum sharing mechanism is proposed. When an IU is selected by the PU as the relay, the IU forms a cluster with other SUs and assumes the role of cluster head. The PU only conducts transactions with the SCN cluster head as the first phase in the cooperative networking. The sharing of transmission opportunities within the SCN cluster is the second phase of the cooperation. The proposed spectrum sharing scheme benefits the PU, the IU as well as every SU in the cluster.

3.4.1 Overview of the Spectrum Sharing Structure

The spectrum sharing frame structure consists of three parts: uplink transmission, downlink transmission and a guard period (GP), which is required between the uplink and

downlink to avoid transmission interference. Uplink transmissions are from the users to the BS, while the downlink transmissions are from the BS to the users. The spectrum sharing adopted during the uplink transmission period is studied, and the downlink transmission can be analyzed in a similar way. The spectrum sharing structure for one time slot is illustrated in Fig. 3.3. The IU selection is performed in advance of the two-phase cooperation, and then the two-phase cooperation is performed. IUs are a subset of SUs, who have better link conditions such as channel fading coefficients, power levels and locations than other SUs. Each of the IUs, acting as a cluster head of SCN, forms a cluster with other SUs, who act as cluster members. The IU shares the spectrum gained by assisting the cluster heads of PCN with all cluster members of SCN in a fair manner.

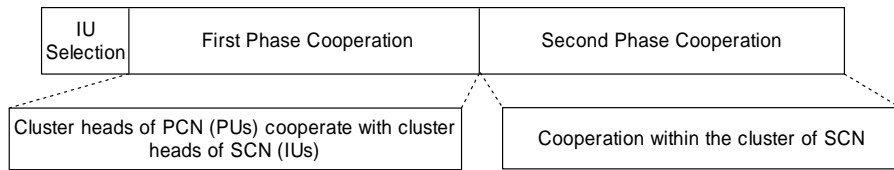


Figure 3.3: Spectrum sharing frame structure.

3.4.2 IU Selection

In order to improve the performance of the primary network, the PUs find the cooperators from the SUs to cooperate. However, in practice, some SUs might not be willing to cooperate with the PU, as it is quite energy consuming to relay the PU's traffic and the utility gain might be relatively low, i.e., the ratio of the utility to the power consumption is low. But these SUs still desire to gain the secondary transmission opportunity so as to improve the utility. Based on the aforementioned, a group of IUs are selected. After obtaining the spectrum access opportunity by cooperating with the PU, the selected IU cooperates with other starving SUs to share the spectrum to benefit these SUs in the cluster. Therefore, we address the cooperation by the introduction of IUs. An IU may

not be always selected as the cooperator of the PU. In this case, the SU expects to obtain the benefits in the future when it is not selected as the IU. Nevertheless, with whom to cooperate is a challenging issue since it affects the performance of the cooperation pair. We perform the MWM to solve the IU selection and maximize the cooperation utility of the PUs and IUs.

The procedure is as follows: the PUs let the BS broadcasts the cooperation selection requirement which includes the information of cluster number i , the number of cluster head in cluster i and the transmission power of each cluster head to the SUs. The SUs, who participate in the cooperation with the PUs, send feedbacks wherein contains their transmission power values P_q which they want to devote in delivering PUs' traffic to the BS as well as the value of ξ_i . After the BS collects all of the information, it chooses the optimal value of β_i , and calculates the ratios of utility to energy consumption of the PUs and SUs through cooperation which will be formulated later in (3.15), and then performs the bipartite maximum weighted matching to obtain the cooperation pairs of the network, which means the IUs are selected.

3.4.3 Cluster based Two-phase Cooperation

The cluster based two-phase cooperation is depicted in Fig. 3.4. We only illustrate the case that PCN has one cluster head (PU) to simplify the statement. The IU cooperates with the PU in a TDMA manner. The PU broadcasts its traffic to the BS and cooperating IU, and then the IU relays PU's traffic to the BS. The aforementioned first phase cooperation is shown in the left part of Fig. 3.4. The right part of Fig. 3.4 illustrates the second phase cooperation, where the SCN cluster consists of one cluster head IU and two cluster members (the cluster size needs to be optimized, which is not the main focus of this thesis).

As per cooperation in phase I, the PU and the selected IU cooperate with each

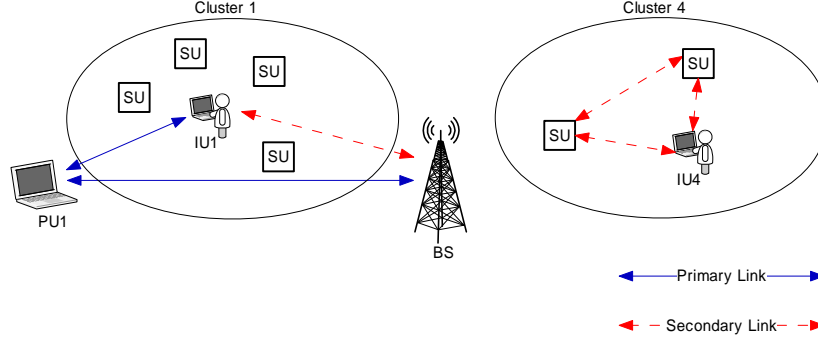


Figure 3.4: Two-phase cooperation process.

other. During phase II, the IU initializes the cluster with surrounding SUs, and the SCN cluster is formed with the SUs who have better link conditions than other users who are not selected as cluster members. Each cluster is formed with the size based on its own capability, and the spectrum in a cluster is divided into orthogonal channels shared by cluster members. The IUs transmit their traffic to the corresponding access points (APs), and then each cluster member SU combines IU's traffic and its own traffic through network coding and transmits to the AP. It is worth noticing that the network coding is only adopted when the channel condition between the IU and the AP is poor, such as when the IU is far away from its AP or there is a building blocking the link between the IU and its AP. Otherwise, the SUs only transmit their own traffic to the AP.

3.4.4 Weights Calculation

In a time slot T , after cooperation with PUs, the IU can acquire the remaining time slot $(1 - \beta_i)T$ as well as a factor $\omega_{ij}^*(t)$ as a reward, and $\omega_{ij}^*(t)$ is a ratio between 0 and 1. The factor $\omega_{ij}^*(t)$ will affect the time allocation of the spectrum sharing process within the cluster and can be calculated by

$$\omega_{ij}^*(t) = G_i \cdot \frac{P_{ij}}{P_{max}^j} \quad (3.11)$$

where t represents the t th ($t = 1, 2, 3, \dots$) spectrum sharing process, and G_i is an adjustable factor determined prior to the IUs being selected. The IU selection competition will become more intensive as the value of G_i increases. P_{ij} denotes the transmission power of IU in cluster i , and P_{max}^j is the power limitation of the IU.

When the spectrum sharing is implemented for the first time, i.e., $t = 1$, the weights are initialized for each user within cluster i which is given by

$$\omega_{ij}(t) = \begin{cases} \omega_{ij}^*(t) + \frac{1 - \omega_{ij}^*(t)}{K_i + 1}, & j = 0 \\ \frac{1 - \omega_{ij}^*(t)}{K_i + 1}, & j \geq 1 \end{cases} \quad (3.12)$$

where $j = 0, 1, 2, \dots, K_i$, $j = 0$ and $j \geq 1$ denote the IU and the SUs in the cluster, respectively. K_i is the number of SUs in cluster i . Hence, there are $K_i + 1$ users in the cluster including the cluster head IU and cluster members SUs.

During the spectrum sharing process, the users may cooperate with each other when some poor links exist among them. If a user cooperates with others, it will receive a reward $\omega_{ij}^+(t)$, a positive value. Otherwise, if it receives help from other users, a penalty $\omega_{ij}^-(t)$, a negative value, will be assigned. In each round of the spectrum sharing with cooperation transmission, $\omega_{ij}^-(t) = -\frac{\omega_{ij}^+(t)}{L_i}$ is required to guarantee the stability of the rewards, where L_i is the number of cooperators.

The rewards of users in the cluster at the beginning of the next round spectrum sharing are calculated by

$$\omega_{ij}(t+1) = \begin{cases} \omega_{ij}(t) + \omega_{ij}^*(t+1) + \omega_{ij}^+(t) + \omega_{ij}^-(t), & j = 0 \\ \omega_{ij}(t) + \omega_{ij}^+(t) + \omega_{ij}^-(t), & j \geq 1 \end{cases} \quad (3.13)$$

where $\omega_{ij}^+(0) = 0$ and $\omega_{ij}^-(0) = 0$.

In addition, at the beginning of each round of time slot allocation, the reward of each user will be a part of the total rewards of the users in the cluster to ensure the summation

of the rewards equals to 1, i.e., $\sum_{j=0}^{K_i} \omega_{ij}(t) = 1$ for $\forall t, i$. Therefore, each SU's weight will change proportionally to the weight of IU, which may effect the preference ranking lists of the SUs.

3.5 Optimization Design for Spectrum Sharing

3.5.1 Maximum Weighted Matching

IU selection is performed over the network to select the IUs who cooperate with PUs, with the objective of maximizing the total utility of both the PUs and the IUs.

The IU candidates (SUs) can obtain the utility through cooperation represented by

$$U_{ij} = (1 - \beta_i) \cdot L_x W_i \log_2 (1 + h_j^2 P_j) \quad (3.14)$$

where P_j denotes the transmission power of SU_j , and h_j represents the channel gain of SU_j transmitting to its own destination. L_x denotes the number of cluster heads in each PCN cluster which SU_j cooperates with, and β_i should be the same within each PCN cluster.

Energy efficiency is considered in the system by using a ratio of utility to energy, which enables a tradeoff between utility and energy consumption, and the IU selection is formulated as the following optimization problem:

$$\begin{aligned} & \underset{a_{ij}}{\text{maximize}} && \sum_{i=1}^X \sum_{j=1}^N \mu_{ij} \cdot a_{ij} \left(\frac{\sum_{x=1}^{L_i} U_i + U_{ij}}{\sum_{x=1}^{L_i} E_i + E_{ij}} \right) \\ & \text{subject to} && \sum_{j=1}^N a_{ij} \leq 1, a_{ij} \in \{0, 1\} \\ & && \mu_{ij} \in \{0, 1\}, \forall i, j \\ & && 0 < P_{ij} \leq P_{max}^j \end{aligned} \quad (3.15)$$

where U_i is described in (3.4) while U_{ij} is given in (3.14). E_i and E_{ij} represent the energy consumption of PU $_i$ and SU $_j$ during the cooperation, respectively. L_i denotes the number of cluster heads in PCN cluster i . μ_{ij} and a_{ij} are binary numbers which belong to the set $\{0, 1\}$. Let $\mu_{ij} = 1$ define that SU $_j$ can be selected as the potential IU with PCN cluster i . If $a_{ij} = 1$, it means SU $_j$ is selected as the IU to cooperate with PCN cluster i . The power limitation of SU $_j$ is P_{max}^j . The objective function is expressed by the ratio of the integrated throughput to energy consumption, which denotes the utility obtained per joule energy.

The optimization problem of the IU selection described in (3.15) is transformed into an MWM problem on an $X \times N$ bipartite graph indicating X PCN clusters, N SUs. This MWM problem can be solved in polynomial time in a centralized network. The value of the utility/power is taken as the objective function, since it can save the transmission power. It is not true that the more energy devoted, the more gain obtained. It is necessary for each IU to choose an appropriate transmission power in order to make a tradeoff between the gain and the cost.

We focus on the case that channels of the PUs are orthogonal in which no interference exists between PUs and IUs. An edge represents the link that exists between PCN cluster i and SU $_j$ of a bipartite graph if SU $_j$ can be selected as the cooperator node by PCN cluster i ($i = 1, 2, \dots, X$ and $j = 1, 2, \dots, N$). The weight of this edge is given by $(\sum_{x=1}^{L_i} U_i + U_{ij}) / (\sum_{x=1}^{L_i} E_i + E_{ij})$, which forms the weight matrix Φ .

The PCN clusters and the SUs form a set V of vertexes in the graph, and E represents the cooperation relationship between PCN clusters and SUs. Φ is a weight matrix for matching V and E in which the weights denote the total utility per joule of the PCN cluster and the cooperating SU obtained from the cooperation. $G = (V, E)$ is a bipartite graph, where $x \in \mathcal{S}$, $y \in \mathcal{T}$, $V = \mathcal{S} \cup \mathcal{T}$, and $(x, y) \in E$. Given weights on the edges $w(x, y)$ from matrix Φ for each $(x, y) \in E$, define the feasible labeling as a function:

$$\ell(x) + \ell(y) \geq w(x, y);$$

$$\ell(x) = \max_{y \in \mathcal{T}} w(x, y), \text{ if } x \in \mathcal{S};$$

$$\ell(y) = 0, \text{ if } y \in \mathcal{T};$$

$$E_\ell = \{(x, y) \in E | \ell(x) + \ell(y) = w(x, y)\}.$$

Hence, an equality subgraph of $G = G_\ell$ has been defined, i.e., $G_\ell = (V, E_\ell)$. By using equality subgraph, any maximum matching \mathcal{M} found is an optimal matching \mathcal{M}^* . If we do not have a maximum matching, we have to modify $G_\ell \rightarrow G_{\ell^*}$ by updating $\ell^*(v)$ and continue to find another matching \mathcal{M} in G_{ℓ^*} . Then, the matching with the maximum utility to energy consumption ratio can be obtained. The maximum weighted matching algorithm is illustrated as in Algorithm 1.

Algorithm 1 Maximum weighted matching algorithm.

Input:

A set of PCN clusters \mathcal{S} , a set of SUs (IU candidates) \mathcal{T} , and a weight matrix Φ ;

Output:

The cooperation pairs, maximum matching \mathcal{M}^* ;

- 1: Construct a weighted bipartite graph $G(V, E)$;
 - 2: Random select a matching \mathcal{M} in G ;
 - 3: **if** set \mathcal{T} is saturated **then**
 - 4: current \mathcal{M} is the maximum matching \mathcal{M}^* ;
 - 5: **else**
 - 6: flip current matching \mathcal{M} , and update G ;
 - 7: **end if**
 - 8: **repeat**
 - 9: step 3 – step 7;
 - 10: **until** find the maximum weighted matching \mathcal{M}^* .
-

The current matching updated process can be described by the steps as follows:

1. Starting with $\ell(x)$, $\ell(y)$ as above, determine G_ℓ and choose Q in G_ℓ . Let u be an unsaturated vertex in X , $\mathcal{S} \leftarrow \{u\}$, $\mathcal{T} \leftarrow 0$;
2. If $N_{G_\ell(s)} \supset \mathcal{T}$, go to step 3); else $N_{G_\ell(s)} = \mathcal{T}$, $\nexists Q^*$ in G_ℓ , determine ℓ^* to modify G_ℓ and compute $\alpha_\ell = \min_{x \in \mathcal{S}, y \notin \mathcal{T}} \{\ell(x) + \ell(y) - w(x, y)\}$. If $v \in \mathcal{S}$, $\ell^*(v) = \ell(v) - \alpha_\ell$; if $v \in \mathcal{T}$, $\ell^*(v) = \ell(v) + \alpha_\ell$; otherwise, $\ell^*(v) = \ell(v)$. Update $\ell(v)$ by $\ell^*(v)$, and G_ℓ by G_{ℓ^*} ;
3. Expand matching, choose y in $N_{G_\ell(s)} \setminus \mathcal{T}$. If y is saturated, with $x, y \in Q$, replace \mathcal{S} by $\mathcal{S} \cup \{x\}$, \mathcal{T} by $\mathcal{T} \cup \{y\}$ and go to step 2); else let Q be augmenting (u, y) path in G_ℓ , and substitute \mathcal{M} by Q .

When there is no such maximum matching result, i.e., there is no appropriate SU to be selected, the BS will not perform the matching until all the PCN clusters have the candidates IUs. However, this seldom happens in practice. We give an example by forming a scenario as shown in the following matrix. The values in the matrix μ_{ij} are attained based on the feedback information from the IU candidates SUs. If the SU desires to cooperate with the cluster head PU in PCN cluster, the value is 1 in the matrix, otherwise, the value is 0.

$$\mu_{i,j} = \begin{pmatrix} 1 & 1 & 1 & 0 & 0 & 0 \\ 0 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 0 & 0 & 1 & 0 & 1 & 1 \end{pmatrix}$$

There are four PCN clusters and six SUs in the CCRN given in our example. The utility per joule attained through cooperation between the PCN cluster and the SUs can

be represented by a 4×6 weight matrix Φ as follows:

$$\Phi = \begin{pmatrix} 3 & \boxed{5} & 4 & 1 & 2 & 1 \\ 1 & 5 & 6 & \boxed{5} & 1 & 1 \\ 2 & 1 & \boxed{7} & 1 & 4 & 5 \\ 1 & 1 & 6 & 2 & 5 & \boxed{6} \end{pmatrix}$$

The values in the matrix can be attained through the connection states shown in matrix μ_{ij} and the objective function described in (3.15). After maximum matching by the proposed algorithm, the results are attained. The total utility of the matched network is $u_{1,2} + u_{2,4} + u_{3,3} + u_{4,6} = 23$ (individual values in the squares as shown in the weight matrix), and the matching results are cluster 1, cluster 2, cluster 3, cluster 4 cooperating with SU_2 , SU_4 , SU_3 , SU_6 , respectively, i.e., the maximum weighted matching is obtained by using the bipartite matching algorithm. Therefore, the maximum utility per joule of the cooperation pairs is acquired. According to our assumption, SU_3 can serve cluster 1, cluster 2 and cluster 4. However, it can only make an agreement with one cluster finally, since there are no selected node in the same column. The result can also be shown in Fig. 3.5.

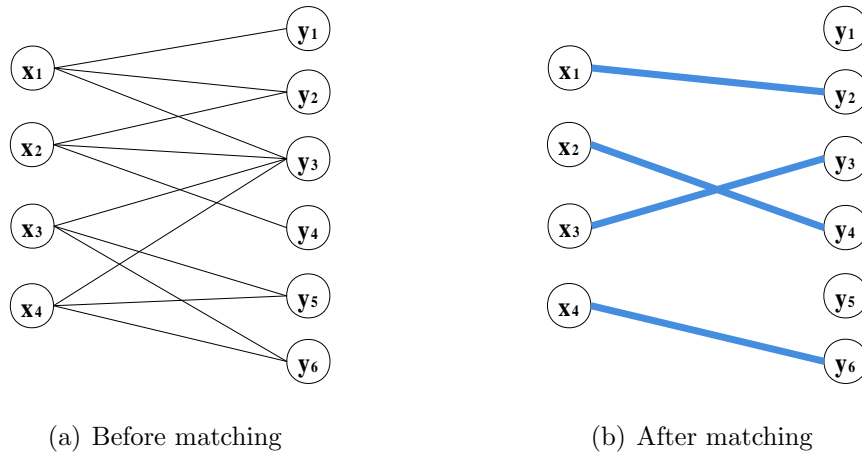


Figure 3.5: Solving the partner selection problem in a bipartite graph.

3.5.2 Cluster based Spectrum Sharing Formulation

In CCRN, the PUs who are the cluster heads of PCN cooperate with the selected IUs, who are cluster heads of SCN, aiming at improving their transmission performance. Then, the IUs acquire a fraction of spectrum as a reward for relaying PUs' traffic, aggregate and share the acquired spectrum with other cluster members of SCN in a fair manner.

Let $a_{ij} = 1$ denote SU_j joins into cluster i of SCN, and $a_{ij} = 0$ represent the opposite. For each SU, since it can only access one cluster, we have the constraint $\sum_{i=1}^X a_{ij} \leq 1$ to satisfy the aforementioned condition. In addition, for each cluster, the number of SUs, who access the cluster, is limited by the factor of channel capability and spectrum efficiency, and we consider the case that every user is "completely" matched. Hence, the constraint $\sum_{j=1}^N a_{ij} = K_i$ is added to ensure the above requirement. Finally, we formulate the proposed spectrum sharing problem as follows:

$$\begin{aligned}
 & \underset{a_{ij}, t_{ij}}{\text{maximize}} && \sum_{i=1}^X \left(\prod_{j=0}^N (V_{ij} - V_{min}^j)^{a_{ij} \cdot \omega_{ij}} \right) \\
 & \text{subject to} && V_{ij} \geq V_{min}^j \\
 & && \sum_{j=0}^N t_{ij} = (1 - \beta_i) T, \forall i \\
 & && \sum_{j=0}^{K_i} \omega_{ij} = 1, \forall i \\
 & && \sum_{i=1}^X a_{ij} \leq 1, \forall j \\
 & && \sum_{j=1}^N a_{ij} = K_i, \forall i \\
 & && a_{ij} \in \{0, 1\}
 \end{aligned} \tag{3.16}$$

where V_{ij} is given by (3.10), and V_{min}^j denotes the minimum utility requirement for user j . ω_{ij} represents the weight of user j who associates with cluster i of SCN, and $\sum_{j=0}^{K_i} \omega_{ij} = 1$

for any i . $(1 - \beta_i)T$ is the time slot for spectrum sharing among the IU and SUs, and K_i represents the number of SUs assigned to each SCN cluster. The value of K_i varies from cluster to cluster according to the cluster channel capability C such as the size of the aggregated channels, i.e., bandwidth. For instance, if $C_{i-1} < C_i < C_{i+1}$, then $K_{i-1} < K_i < K_{i+1}$.

However, the above optimization problem is a combinatorial nonlinear problem, which is NP-hard. As mentioned earlier, we decompose the problem into two-subproblems: bandwidth allocation and time allocation. First, we form the clusters according to the requirements of both the IU and the SUs, such as the location and bandwidth, i.e., attain the combination values of a_{ij} . Then, we optimize the utility of the clusters by assigning the IU and SUs different time slots.

Usually, the bandwidth allocation (cluster formation) problem is performed among the SUs, and the goal is to maximize the SCN clusters' total performance, such as throughput, utility and transmission rate, which are considered only from the users' side since there is no priority for the bandwidth to select the users. However, the allocation problem for our work is different since we consider the allocation problem as a cluster formation problem. From the IU's perspective, it is willing to share the spectrum with the members who have better link conditions or have more powerful transmission capabilities, i.e. the power level, in order that they can share the spectrum more efficiently and cooperate with each other when it is necessary. Meanwhile, from the SUs' perspective, they desire to access the frequency band or cluster with a wider bandwidth or more sharing time to gain higher utility. Consequently, we implement the spectrum sharing scheme by taking into consideration the interests of both sides. The users, both the IUs and the SUs, have their own preference ranking lists associated with each side's preference, ranging from the most preferred ones to the least preferred ones. According to the ranking lists, a stable matching can be established by deploying the two-sided many-to-one matching

algorithm, and the stable matching indicates that there is no more IU and SU who prefer each other over their matching results in the matching.

Moreover, for fairness, the spectrum sharing of the SCN is performed based on weights by scaling the contributions of the users during previous spectrum sharing process. Within each cluster, the time slots are assigned to each member depending on the weights they have, and the objective of time allocation is to optimize the total utility of the SCN cluster.

Cluster Formation

When the cooperation between the PUs and the IUs is completed, the IUs have the opportunity to access the remaining spectrum, and share the acquired spectrum with other SUs. The IU and SUs form the SCN cluster in which the IU works as the cluster head and the SUs are the cluster members. Bandwidth allocation (i.e., channel allocation) is the first step of the spectrum sharing process.

Regarding spectrum sharing for CRN in this dissertation, bandwidth allocation is formulated as a cluster configuration problem, and there are two groups of users: IUs and SUs. From IUs' perspective, they want to form a cluster that the cluster members have higher transmission rate so that the spectrum efficiency can be further improved. However, from the SUs' perspective, they intend to choose the cluster which can provide them the longer transmission time, which is effected by many factors such as channel bandwidth, IU's weight and cluster size. Therefore, not only the location and power factors, but also the spectrum bandwidth and channel conditions are taken into consideration. In order to satisfy both sides of the users, we solve the cluster formation problem by using two-sided stable matching algorithm.

Therefore, with the aim to solve the optimization problem described in (3.16), we first need to solve the subproblem, i.e., bandwidth allocation, which is also referred as

cluster formation of SCN. The cluster formation problem consists of two sets of users: the set $I = \{x_1, x_2, \dots, x_M\}$ of IUs, and the set $S = \{y_1, y_2, \dots, y_N\}$ of SUs (where $M < N$). Each user has a preference ranking list of acceptable users on the other side. Without loss of generality, we assume that IU finds SU acceptable if and only if SU finds IU acceptable. In this case, we define (x, y) is an acceptable pair. IU_x finds at least K SUs acceptable, and each SU finds at least one IU acceptable. The positive integer K represents IU_x 's quota, the number of SUs that IU_x can tolerate, which means IU_x is allowed to admit up to K SUs joining the cluster. Note that we consider a restrictive model of responsive preferences in which the IUs have preferences over individual SUs rather than groups of SUs. Each user in set I (or S) has preferences over each user in set S (or I). Let $\psi(x)$ be the preference function of user x in set I , and let $\varphi(y)$ be the preference function of user y in set S . Hence, the IUs have preference set $\psi(x)$ for cluster members, which are sorted by transmission rate R_{ij} , and each SU also has its own preference set $\varphi(y)$, which are ordered by the expression $\frac{(1-\omega_{ij}) \cdot L_x W_i}{K_i}$. The objective of the matching is to find a stable matching solution.

It is true that in some cases we may find many possible stable matchings for the bandwidth allocation problem, i.e., cluster formation problem. However, we will choose the matching that provides the highest network utility. Therefore, the stable matching in our scenario is unique.

Based on the above statement, we perform the algorithm in Algorithm 2.

Algorithm 2 Stable matching algorithm.

Input:

A set of IUs \mathcal{I} , a set of SUs \mathcal{S} , and preference ranking lists $\psi(i)$, $\varphi(j)$ of the IUs and SUs, respectively.

Initialize $\mu = \emptyset$ and $\ell = 1$;

Output:

The cluster formations in SCN, i.e., many-to-one matching result μ ;

- 1: **while** (IU x is not fully subscribed) and $(\psi(x) \neq \emptyset)$ **do**
 - 2: IU x proposes to the SUs who are the first ℓ th choice in the preference ranking list $\psi(x)$.
 - 3: **if** IU x is the first choice in SU y 's preference ranking list $\varphi(y)$ **then**
 - 4: $\mu = \mu \cup \{(x, y)\}$, and update the ranking lists $\psi(x)$, $\varphi(y)$ of the IUs and SUs, respectively;
 - 5: **else**
 - 6: $\ell = \ell + 1$, and go back to step 2;
 - 7: **end if**
 - 8: **end while**
 - 9: μ is a stable matching.
-

In order to specify the cluster formation process, we give an example as follows: there are three IUs looking for their cluster members from seven SUs. The ranking preference lists of the IUs and SUs are shown in Table 3.1 and Table 3.2, respectively. After applying algorithm 2, we can obtain the cluster formation results described by Table 3.3.

Table 3.1: Quotas and preference lists for the IUs.

IUs	Capacity	$\psi(x)$
x_1	2	$y_2, y_3, y_6, y_5, y_4, y_1, y_7$
x_2	3	$y_6, y_4, y_3, y_2, y_1, y_7, y_5$
x_3	2	$y_7, y_1, y_4, y_6, y_2, y_3, y_5$

Table 3.2: Preference lists for the SUs.

SUs	$\varphi(y)$
y_1	x_2, x_1, x_3
y_2	x_1, x_2, x_3
y_3	x_1, x_2, x_3
y_4	x_2, x_1, x_3
y_5	x_1, x_2, x_3
y_6	x_2, x_1, x_3
y_7	x_3, x_2, x_1

Table 3.3: Matching results.

IUs	SUs
x_1	y_2, y_3
x_2	y_1, y_4, y_6
x_3	y_5, y_7

Optimization for the Weights based Time Allocation

After the SCN cluster formation problem is solved, the weights based time allocation is described by

$$\begin{aligned}
 & \underset{\mathbf{T}}{\text{maximize}} && \prod_{j=0}^{K_i} (V_{ij} - V_{min}^j)^{\omega_{ij}} \\
 & \text{subject to} && V_{ij} \geq V_{min}^j, \forall i, j \\
 & && \sum_{j=0}^{K_i} t_{ij} = (1 - \beta_i) T, \forall i \\
 & && \sum_{j=0}^{K_i} \omega_{ij} = 1, \forall i
 \end{aligned} \tag{3.17}$$

where \mathbf{T} represents the time allocation matrix of each cluster, and V_{ij} is the utility of user j within cluster i , which is given by (3.10). ω_{ij} represents the weights of user j joining in cluster i . In order to simplify the optimization function, we rewrite the function as

follows:

$$\begin{aligned}
 & \underset{\mathbf{T}}{\text{maximize}} && \sum_{j=0}^{K_i} \omega_{ij} \log_2 (V_{ij} - V_{min}^j) \\
 & \text{subject to} && V_{ij} \geq V_{min}^j, \forall i, j \\
 & && \sum_{j=0}^{K_i} t_{ij} = (1 - \beta_i) T, \forall i \\
 & && \sum_{j=0}^{K_i} \omega_{ij} = 1, \forall i
 \end{aligned} \tag{3.18}$$

Since we transform the previous objective function into the above objective function which becomes a convex function, the proposed problem can be solved by the KKT condition. The Lagrangian function of (3.18) as a function of t_{ij} can be given by

$$\mathcal{L} = \sum_{j=0}^{K_i} \omega_{ij} \log_2 (V_{ij} - V_{min}^j) + \sum_{i=1}^M \lambda_i \left(\sum_{j=0}^{K_i} t_{ij} - (1 - \beta_i) T \right) \tag{3.19}$$

where λ_i is the Lagrangian multiplier. By using the KKT condition, we take the derivative of (3.19) with respect to t_{ij} , and obtain

$$\begin{aligned}
 \nabla \mathcal{L}(\mathbf{T}, \lambda) &= \sum_{j=0}^{K_i} \frac{\omega_{ij} L_x W_i \log_2 (1 + SNR_{ij})}{[L_x W_i t_{ij} \log_2 (1 + SNR_{ij}) - U_{min}^j] \cdot \ln 2} \\
 &+ \sum_{i=1}^M \lambda_i = 0
 \end{aligned} \tag{3.20}$$

where we have $K_i \times M$ equations. Hence, the time assignment matrix \mathbf{T} can be obtained.

3.5.3 Spectrum Sharing within the SCN Cluster

Network coding is adopted during the second spectrum sharing phase. Furthermore, multiple cluster members can relay the IUs' traffic cooperatively if necessary. Therefore, network coding among the SUs can further improve the performance of both the IU and

the SUs, but the cooperation complexity will be increased. However, the tradeoff between performance benefit and increased cooperation cost need to be balanced.

Two cases are considered in the scenario if multiple SUs help relay the IU's traffic: the first case is called non-inter-cooperative network coding (NICNC) and the other one is called inter-cooperative network coding (ICNC). For the NICNC case, the cooperating SUs do not exchange their data in advance, while the SUs exchange data in advance for the ICNC case. By performing NICNC, each relayed transmission only contains information of the IU and one SU's packets. However, by performing ICNC, losses in some transmissions could be compensated, since each relayed transmission contains linear combinations of the IU and all the cooperating SUs' packets. Therefore, the original packets could be recovered from the correctly received transmissions. Consequently, by exploiting network coding, the performance of both the IU and the relaying SUs can be improved.

For the NICNC case, after the cooperating SUs obtaining the packets from the IU, the SUs transmit their own packets as well as IU's packets to the AP. Therefore, the destination AP can receive all the data together as follows:

$$\begin{aligned}
 & \begin{pmatrix} \xi_{00}X_0 \\ \xi_{10}X_0 + \xi_{11}X_1 \\ \vdots \\ \xi_{G0}X_0 + \xi_{GG}X_G \end{pmatrix} \\
 &= \begin{pmatrix} \xi_{00} & 0 & \cdots & 0 \\ \xi_{10} & \xi_{11} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \xi_{G0} & 0 & \cdots & \xi_{GG} \end{pmatrix} \cdot \begin{pmatrix} X_0 \\ X_1 \\ \vdots \\ X_G \end{pmatrix}, \tag{3.22}
 \end{aligned}$$

where ξ_{ij} ($i = 0, 1, \dots, G$ and $j = 0, 1, \dots, G$) denotes the coding coefficient, and G is the number of cooperating SUs. The first row represents the data from the IU and the

remaining G rows denote the data from the cooperative SUs. Therefore, the AP can recover the source data X_0, X_1, \dots, X_G from the IU and G cooperative SUs as long as the above coefficient matrix has full rank, which means

$$\begin{vmatrix} \xi_{00} & 0 & \cdots & 0 \\ \xi_{10} & \xi_{11} & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ \xi_{G0} & 0 & \cdots & \xi_{GG} \end{vmatrix} \neq 0.$$

For the ICNC case, since the SUs are exchanged their data in advance, the AP can acquire the data as follows:

$$\begin{aligned} & \begin{pmatrix} \xi_{00}X_0 + \xi_{01}X_1 + \cdots + \xi_{0G}X_G \\ \xi_{10}X_0 + \xi_{11}X_1 + \cdots + \xi_{1G}X_G \\ \vdots \\ \xi_{G0}X_0 + \xi_{G1}X_1 + \cdots + \xi_{GG}X_G \end{pmatrix} \\ &= \begin{pmatrix} \xi_{00} & \xi_{01} & \cdots & \xi_{0G} \\ \xi_{10} & \xi_{11} & \cdots & \xi_{1G} \\ \vdots & \vdots & \ddots & \vdots \\ \xi_{G0} & \xi_{G1} & \cdots & \xi_{GG} \end{pmatrix} \cdot \begin{pmatrix} X_0 \\ X_1 \\ \vdots \\ X_G \end{pmatrix}. \end{aligned} \quad (3.23)$$

Similarly, the AP can recover the source data X_0, X_1, \dots, X_G from the IU and G cooperative SUs as long as the above coefficient matrix has full rank.

In order to specify the network coding process, an example that two SUs help relay the IU's traffic is given as follows. The IU transmits the source data X_0 to the AP. After the surrounding SUs obtain this data, the two cooperating SUs combine the IU's data and their own data X_1 and X_2 into $\xi_{10}X_0 + \xi_{11}X_1 + \xi_{12}X_2$ and $\xi_{20}X_0 + \xi_{21}X_1 + \xi_{22}X_2$, respectively. Then, they transmit the combined data to the AP. Therefore, the

destination AP can obtain three pieces of data together as described below:

$$\begin{pmatrix} \xi_{00}X_0 + \xi_{01}X_1 + \xi_{02}X_2 \\ \xi_{10}X_0 + \xi_{11}X_1 + \xi_{12}X_2 \\ \xi_{20}X_0 + \xi_{21}X_1 + \xi_{22}X_2 \end{pmatrix}, \quad (3.21)$$

where $\xi_{01} = \xi_{02} = 0$ in our example. If the cooperating SUs exchange their data in advance, $\xi_{12} \neq 0$ and $\xi_{21} \neq 0$; otherwise $\xi_{12} = 0$ and $\xi_{21} = 0$. Eq. (3.24) can be rewritten as follows

$$A = \begin{vmatrix} \xi_{01} & 0 & 0 \\ \xi_{11} & \xi_{12} & \xi_{13} \\ \xi_{21} & \xi_{22} & \xi_{23} \end{vmatrix} \neq 0.$$

Only if matrix A is full rank will enable the receiver-AP to recover the source data as well as other SUs' data from the information it receives. Therefore, $\det(A) \neq 0$ is required, which is equivalent to $\xi_{01}\xi_{12}\xi_{23} \neq \xi_{01}\xi_{13}\xi_{22} \implies \xi_{12}\xi_{23} \neq \xi_{13}\xi_{22}$ since $\xi_{01} \neq 0$. For the NICNC case, $\xi_{13} = 0$ and $\xi_{22} = 0$. Hence, $\xi_{12}\xi_{23} \neq 0$ is required, which indicates that the AP can encode the data only when both SUs transmit successfully. For the ICNC case, the data of the IU and the other SUs can be encoded as long as both SUs do not lose the data at the same time. Therefore, with cooperation among the cooperating SUs, the probability of successful transmission can be increased. Generally, there are two ways to perform decoding, i.e., block decoding and early decoding. Block decoding is that the receiver collects enough received packets to invert coefficient matrix, and then decodes the data. In early decoding, the receiver performs Gaussian elimination after each received packet. Moreover, each node detects and discards non-innovative packets. Since the coefficient matrix tend to be lower triangular, it usually requires fewer copies to decode cooperative users' packets. Therefore, early decoding achieves shorter decoding delay than block decoding.

3.6 Numerical Results

In this section, we present numerical results to evaluate the performance of the proposed spectrum sharing from different aspects. First, the IU selection is compared with random selection scheme and nearest selection scheme. Then, the utility comparison of each cluster with bandwidth division and power division is illustrated. Afterwards, the probabilities of successful transmission during the cooperation between the IU and the SU with and the one without network coding are compared and illustrated. Moreover, the cooperation transmission rate is illustrated in four cases, and the fairness among the users within a cluster of SCN is demonstrated. In addition, the proposed joint bandwidth-time allocation scheme is evaluated and compared with the optimal solutions, and the simulation results show that the solution of the time allocation is close to the optimal solution. Finally, the utility of IU with and without spectrum sharing with other SUs is compared.

In Fig. 3.6, we compare the performance obtained by the proposed IU selection (IS) scheme, random selection (RS) scheme and nearest selection (NS) scheme. RS scheme is that the IUs are selected from the SUs randomly, and for NS scheme, the PUs select the cooperative IUs from the SUs who are geographically closest to them. The powers of PUs and IUs vary from 1mW to 2mW and from 0.5mW to 1.5mW, respectively. The users are uniformly distributed in a square area. We run the simulation with 20 synthetic cases for 50 independent rounds with randomly selected channel condition and nodal transmit power level in each round. It can be seen that the proposed IU selection scheme achieves a higher network utility than both the random selection scheme and nearest selection scheme. This is because we find the best pairing using the maximum weighted matching algorithm in the IU selection scheme, and the proposed scheme consider the benefits for cluster head and members together.

In Fig. 3.7, the utility comparison of each cluster with bandwidth division and power division is shown. During the first phase cooperation, the IU can choose two ways

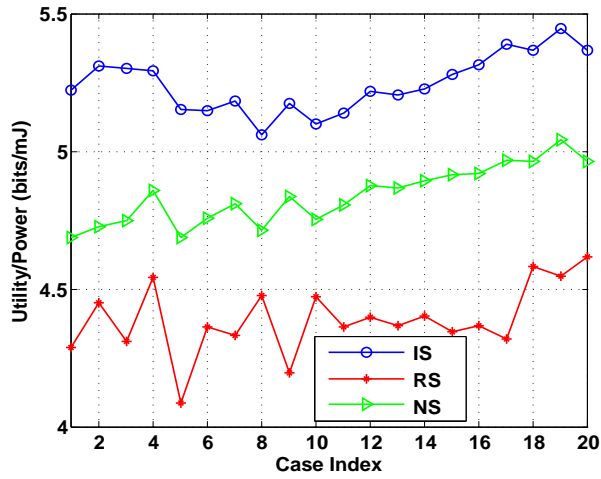


Figure 3.6: The comparison of the performance attained by three different schemes.

for relaying multiple PUs' traffic, transmitting on different spectrum bands (bandwidth division) and transmitting with different powers (power division). From the figure, we can see that dividing bandwidth leads to more decreasing in utility compared with dividing power.

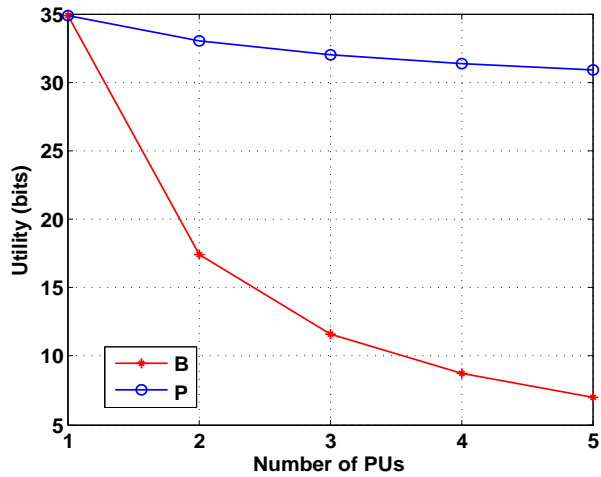


Fig. 3.7: Utility comparison of each cluster with bandwidth division and power division.

Fig. 3.8 shows the probabilities of successful transmission with and without network

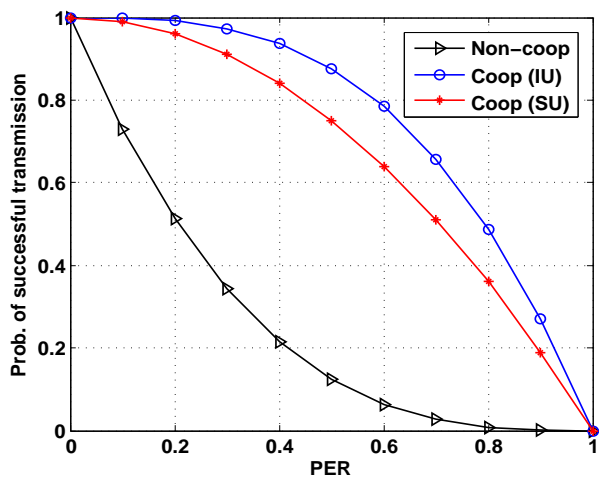


Figure 3.8: Probability comparison.

coding. Packet error rate (PER) denotes the probability of error transmission for the IU and the cooperating SU, which is assumed to be equal for both, and PER varies from 0 to 1. The blue line and red line show the probabilities of successful transmission of IU and SU achieved by cooperation, respectively. The black line illustrates the probabilities of successful transmission of the IU and SU without using the network coding. It can be seen that the successful transmission probabilities with network coding outperform those without network coding. Therefore, the SU can enhance the IU’s transmission reliability as well as its own through the cooperation with IU by exploiting network coding.

Fig. 3.9 shows the IU’s transmission rate with respect to the normalized distance for different number of SUs. The comparison of cooperation transmission rate is illustrated in four cases: one SU cooperating with IU, two SUs cooperating with IU, three SUs cooperating with IU and IU transmitting alone. SUs relay IU’s traffic in a decode and forward manner, so the transmission rate will be the minimum transmission rate between the rate from the IU to the cooperative SUs and the rate from the IU to the BS. The power of IU is 2mW, and the power limitation of SUs are 1.5mW. Time slot window is

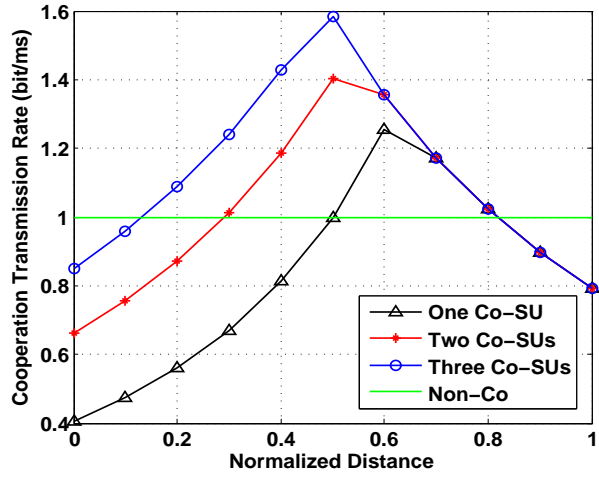


Figure 3.9: Second phase cooperation transmission rate.

1ms, and time allocation coefficient is fixed to 0.5. The straight line corresponds to the scenario without cooperation. It can be seen that with more surrounding SUs involved in the cooperation, the regional area for cooperation becomes wider. Even with more other SUs involved in the cooperation, the IU’s performance stays the same in the final stage when the other SUs stay away from the IU.

In Fig. 3.10, we demonstrate the fairness within one cluster consisting of three users, including one IU and two SUs. The weights of the IU and SUs are 0.4, 0.3 and 0.3, respectively. Moreover, the fairnesses are compared under three schemes: our proposed time allocation (PA), equal time allocation (EA) and demand based time allocation (DA). Since the weights of three users are 0.4, 0.3 and 0.3, the utility ratio of three users approximately equals to 4 : 3 : 3, and the utility shown in the figure is weight based. It is shown that our scheme achieves better fairness than the other two schemes.

Moreover, we compare the time allocation solutions attained by our proposed scheme against the optimal time allocation solutions. The simulation is performed in a cluster with three users, and the time slot assigned for them are drawn in Fig. 3.11. Blue lines

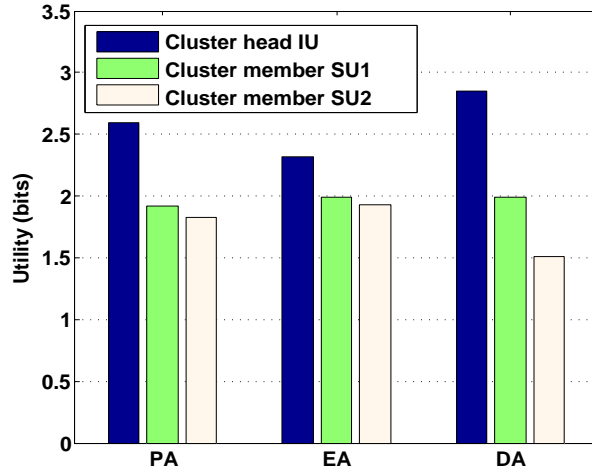


Fig. 3.10: Fairness comparison of three different time allocation schemes in a cluster with $K_i = 2$.

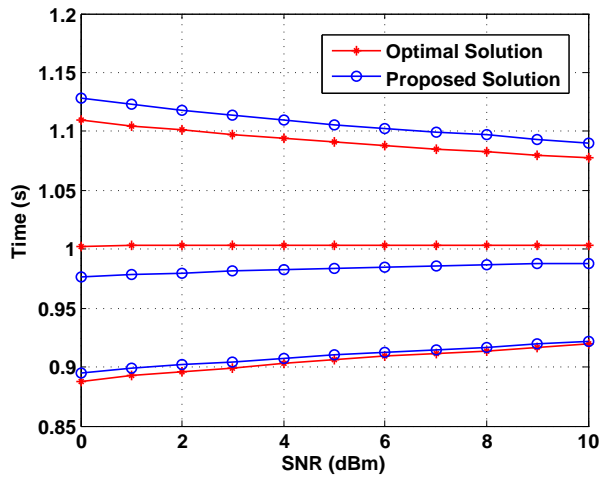


Fig. 3.11: Solutions compared between optimal solutions and our solutions.

represent our solutions while red lines denote the optimal solutions. It is clear that our solutions are very close to the optimal ones.

In addition, the total utility of the cluster achieved by exploiting the proposed spectrum sharing scheme is compared with the optimal value under different SNR environment. In Fig. 3.12, it is demonstrated that the total utility achieved by using our proposed scheme is very close to the optimal value.

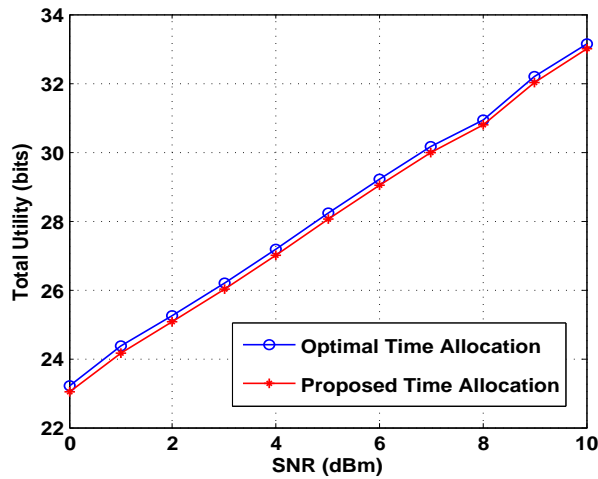


Fig. 3.12: Utilities compared by the optimal allocation scheme and proposed allocation scheme under different SNR.

The utility obtained by our proposed scheme and the optimal utility are illustrated in Table 3.4, and the bias between them is evaluated. We notice that the bias is reduced as the SNR value increases.

Table 3.4: Utility comparison under different SNR (*dBm*).

SNR	0	2	4	6	8	10
Proposed	23.03	25.06	26.99	29.03	30.79	33.00
Optimal	23.23	25.25	27.17	29.20	30.95	33.15
Bias	0.90%	0.75%	0.66%	0.58%	0.52%	0.45%

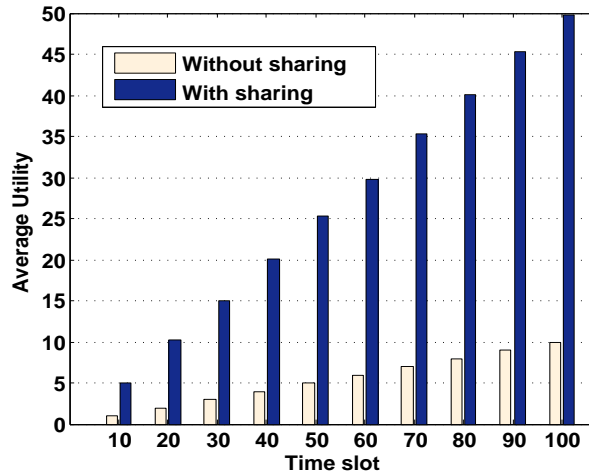


Figure 3.13: The comparison of the utility attained of IU with and without sharing with other SUs.

Fig. 3.13 shows the average utility for the cases with and without spectrum sharing in the cluster, respectively. We assume the chance for an SU to be the selected IU is 10%, and the simulation is repeated 100 times to obtain the average utility of the IU. It can be seen that the utility attained by IU alone is lower than that by sharing with other SUs.

Moreover, the difference becomes more significant when the time slots increase. From this figure, it implies that the IUs have the motivation to share the acquired spectrum with other surrounding starving SUs.

3.7 Summary

In this chapter, we have proposed a cluster based PCN/SCN spectrum sharing scheme in a CCRN. First, the cooperation between cluster heads of PCN and SCN has been investigated. Then, the spectrum sharing have been formulated as a combinatorial non-linear optimization problem which is NP-hard. Afterwards, we have decomposed this problem into cluster allocation and time assignment. The cluster allocation is solved by a stable matching algorithm, which is a classical method in matching theory and is very suitable for addressing our situation. In addition, by solving an optimization problem, the time allocation results are close to the optimal solutions. Moreover, simulation results have shown that the utility obtained by performing the proposed aggregated spectrum sharing scheme can achieve the near optimal performance in our CCRN.

Chapter 4

Uplink Spectrum Sharing for Heterogenous Networks

4.1 Literature Review

Mobile users are desiring for ubiquitous wireless spectrum access with high transmission rate and reliable services, which brings the new challenges for future mobile communication systems, such as massive device connectivity, higher capacity, higher transmission rate, lower end to end latency, reduced cost and consistent QoS [72]. It is indicated that there will be more than 50 billion connected devices by 2020 [73], and the wireless industry has taken on the challenge of cost-effectively supporting a 1000-fold increase in traffic demand over the next decade [74]. By solving those challenges, the next 5G generation wireless network is proposed and aim at achieving 1000 times the system capacity, 25 times the average mobile user's throughput, 10 times the data rate (tens of thousands of users 1Gbps), energy efficiency, and spectrum efficiency of existing the fourth generation (4G) system [75, 76], as well as the significantly lower latency.

Due to the increasing demand for higher spectrum efficiency and data transmission

rates, femtocells have emerged as a solution to expand coverage area and improve system performance of the next 5G generation wireless networks [77]. Femtocells can be configured in three different types of access modes to either allow or block unsubscribed users as follows: closed access, open access and hybrid access [78–80]. In closed access mode, the femtocell base station (FBS) allows only its own subscribed users to establish connection. Most femtocells deployed in residential areas employ this access mechanism for security reasons. All types of users, both subscribed femtocell users as well as non-subscribed macrocell users, are allowed to access the FBS in the open access mode. In hybrid access mode, non-subscribed users are allowed to access the femtocell but are limited by the capability of femtocell spectrum resources. According to a survey [81], femtocell users (FUEs) prefer femtocells with closed access mode, hence we investigate a cooperation framework based on closed access mode in this chapter.

Deployment of 5G wireless network requires new spectrum management schemes for serving mobile users exploiting spectrum efficiently and accessing spectrum constantly [82]. Particularly, an important enabler towards the proper deployment of 5G wireless networks is the CR technology [83, 84]. CR enables the exploitation of centralized network architectures [85], and improve spectrum efficiency [86]. Femtocell based on CR technology has the ability to perform sensing, power and frequency adjustment. Thus, it can monitor and adapt to the surrounding environments [87, 88]. In other words, cognitive femtocell networks (CFNs) can efficiently cope with spectrum scarcity as well as exploit spectrum resource management in small areas to obtain high transmission rate for indoor communications. However, such a CFN system needs high capability to satisfy the required QoS when sharing channels with many other users in the same area. Moreover, macrocell cannot provide good services for indoor users due to spectrum limitations, particularly with the expected increase in the number of users in the near future. Lots of works focus on those challenges in CFNs [89–91]. Lien *et al.* in [89] investigate the

spectrum resource management problem in CFNs, and they propose a cognitive scheme which can guarantee the QoS in terms of delay for the femtocell networks. In [90], a spectrum sensing scheme for the overlay CFNs is proposed, and the throughput using a Markov chain model is analyzed. Xiang *et al.* in [91] focus on the downlink spectrum sharing problem in CFNs. Moreover, mitigating interference is a crucial factor in the femtocell networks [92], especially in closed access mode. In order to mitigate interference, the FBSs have to avoid allocating occupied spectrum that belongs to the macrocell networks. The key idea of interference mitigation in CFNs is that all FUEs should autonomously estimate the spectrum usage of the macrocell and report the sensing result. Therefore, the FBSs periodically allocate subframes for FUEs to perform channel sensing. However, in this case, spectrum sensing may not be accurate, and spectrum handover is required for the FUEs when the macrocell users (MUEs) reappear. FUEs may either wait to resume sending data in the original channel or switch to another temporarily idle channel. To this end, it is important to establish a spectrum coordination framework between the macrocell network and the femtocell network for coexistence and interference reduction.

The cooperation frameworks in macrocell network and femtocell network have been visited in some literatures. In [93], an FUE acts as a relay for an MUE. In return, each cooperative MUE grants the FUE a fraction of its superframe, and the cooperation is formulated by a coalitional game. Pantisano *et al.* in [94] investigate the cooperation among femtocells as a coalitional game in partition form, wherein cooperative femtocells use advanced interference alignment techniques to improve their downlink transmission rate. In [95], a control scheme for cooperation between FUEs and MUEs under both cooperative relay model and interference model is studied. A subchannel allocation problem is formulated as a cooperative game among FUEs under the hybrid overlay/underlay access mode in [96]. A game-theoretic scheme for strategic resource and power allocation

problem in cooperative femtocell networks with a high density of femtocell access points is proposed in [97], and the problem is formulated as an operations research game.

Different from previous work, we develop the cooperation based on stable many-to-one matching. Examples of two-sided matching problems include marriage problem, kidney donors and patients matching, college admissions problem, and hospital-intern matching, etc. The two-sided matching algorithm was first proposed by Gale and Shapley in [98], in which the authors solved the marriage problem by developing a one-to-one matching algorithm. In the marriage problem, agents on one side of the market are matched with at most one agent on the other side. The channel access control problem and spectrum sensing problem in CRN are investigated in [99] and in [100], respectively, by using the stable marriage matching algorithm. User-cell association in small cell networks are studied in [101, 102]. A hospital-intern matching and college admissions matching are studied in [103, 104] by Alvin, which both belong to a many-to-one matching problem. A cooperation between FBSs and MUEs by many-to-one stable matching is proposed in this thesis, so one of the main advantages of this cooperation scheme is that the matching can be realized by using Gale-Shapley algorithm, which is implemented in a distributed manner. Another advantage is stability, which is desirable in a non-regulated heterogeneous network since stability can enhance the network robustness.

4.2 System Model

4.2.1 Network Topology

We consider the uplink transmissions of an orthogonal frequency division multiple access (OFDMA) heterogeneous network wherein one macrocell base station (MBS) is deployed, and multiple FBSs are formed temporarily based on the SUs who are desiring for spectrum access opportunity. The femtocell networks are underlaid with the macro-

cell networks, and within the femtocell networks, neighboring FBSs are allocated over orthogonal frequency subchannels. In CFN, it is assumed that each femtocell senses the spectrum occupation of the adjacent femtocells, and then, the femtocell occupies a disjoint set of subchannels, thus, avoiding interference from the neighbor femtocells. Let $\mathcal{M} = \{1, 2, \dots, M\}$ and $\mathcal{N} = \{1, 2, \dots, N\}$ denote the sets of MUEs and FUEs within each cellular, respectively. Let $k = \{1, \dots, K\}$ represent the set of FBSs, and these FBSs are facilitated with dual operation modes: transmission mode and relaying mode. Both the MUEs and FUEs are equipped with single antenna.

We assume that all channel realizations are i.i.d Rayleigh fading. The results can be easily extended to other channel models at the price of more complicated expressions. The system model is illustrated in Fig. 4.1. The solid lines and dash lines represent the transmission links with and without cooperation, respectively.

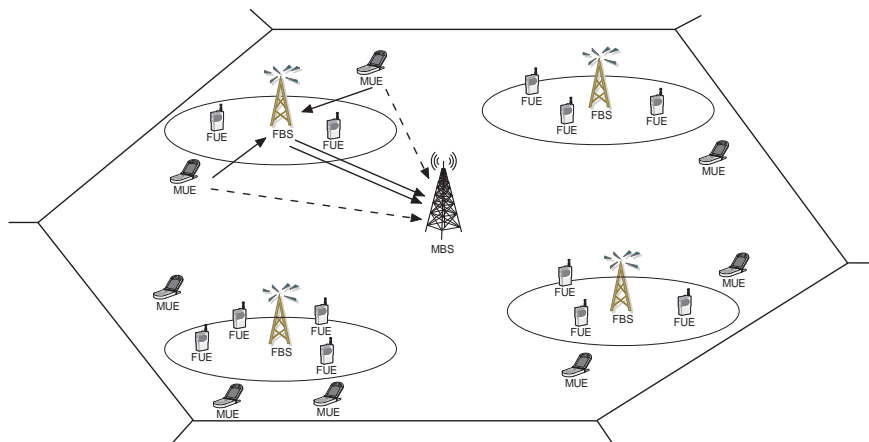


Fig. 4.1: Scenario of Macrocell-Femtocell Network.

4.2.2 Channel Model

The cooperation between the MUEs and FBSs operates in a time-slotted manner. Transmission links are conformed to a Rayleigh flat fading model, and the channel conditions

are considered to be stable during a fix time slot T , but vary independently from one slot to another. The CSI can be available by the users with CR, but in real heterogenous networks, CSI needs to be estimated by exploiting techniques such as MMSE estimation and LS estimation [105].

In the non-cooperative approach, the utility of MUE $_m$ ($m = 1, 2, \dots, M$) to the MBS can be written as:

$$U_m = T \cdot B \log_2 \left(1 + \frac{h_{m,0}^2 P_m}{\sum_{n \in \Theta_m} h_{n,0}^2 P_n + \sigma^2} \right) \quad (4.1)$$

where B is the bandwidth, and T represents the duration of one time slot. P_m is the transmission power of MUE $_m$, and P_n is the transmission power of FUE $_n$. The channel fading coefficients from MUE $_m$ to the MBS and from FUE $_n$ to the MBS are denoted by $h_{m,0}$ and $h_{n,0}$, respectively. $n \in \Theta_m$ is the set of FUEs operating on the same subchannel with MUE $_m$, and σ^2 is the variance of the AWGN.

Mitigating interference is a crucial factor in the femtocell network, especially in closed access mode that gives permission to register a user with an FBS. In this case, any unregistered users approaching the FBS will experience harmful interference. The utility of FUE $_n$ ($n = 1, 2, \dots, N$) to the FBS $_k$ ($k = 1, 2, \dots, K$) is calculated by

$$U_n = T \cdot B \log_2 \left(1 + \frac{h_{n,k}^2 P_n}{\sum_{m \in \Theta_n} h_{m,k}^2 P_m + \sigma^2} \right) \quad (4.2)$$

$h_{n,k}$ denotes the channel fading coefficients from FUE $_n$ to FBS $_k$, and $h_{m,k}$ represents the channel fading coefficients from MUE $_m$ to FBS $_k$. $m \in \Theta_n$ is the set of FUEs operating on the same subchannel with MUE $_n$.

The outage probability of MUE and FUE can be computed as the probability of the signal to interference plus noise ratio (SINR) below a certain threshold θ_m and θ_n , and are given by

$$P_{out_m} = P_r \left\{ \frac{h_{m,0}^2 P_m}{\sum_{n \in \Theta_m} h_{n,0}^2 P_n + \sigma^2} \leq \theta_m \right\} \quad (4.3)$$

$$P_{out_n} = P_r \left\{ \frac{h_{n,k}^2 P_n}{\sum_{m \in \Theta_n} h_{m,k}^2 + \sigma^2} \leq \theta_n \right\} \quad (4.4)$$

FUEs are limited by the interference from adjacent MUEs and by the capacity in terms of the number of available subchannel spectrum resources. On the contrary, MUEs' performance is decreased by the interference from surrounding FUEs. Hence, cooperation is adopted between macrocell network and femtocell network to improve both parties' utility. Therefore, in cooperation mode, the utility of the MUE_m is expressed as

$$U_m^C = \beta T \cdot B \log_2 \left(1 + \frac{1}{\sigma^2} \cdot \frac{h_{m,k}^2 h_{k,0}^2 P_m P_k}{h_{m,k}^2 P_m + h_{k,0}^2 P_k + \sum_{n \in \Phi_m} h_{n,k}^2 P_n + \sigma^2} \right) \quad (4.5)$$

P_k is the transmission power of FBS_k, and β is a time fraction factor. $h_{m,k}$ denotes the channel fading coefficients from MUE_m to FBS_k, and $h_{k,0}$ represents the channel fading coefficients from FBS_k to MBS. Φ_m is the set of FUEs operating on the same subchannel with MUE_m but not cooperating with the FBS.

Correspondingly, in cooperation mode, the utility of FUE_n can be increased through cooperation with the MUE is shown as

$$U_n^C = (1 - \beta) T \cdot B \log_2 \left(1 + \frac{h_{n,k}^2 P_n}{\sum_{m \in \Phi_n} h_{m,k}^2 P_m + \sigma^2} \right) \quad (4.6)$$

where $\Phi_n \in \Theta_n$, and Φ_n is the set of MUEs operating on the same subchannel with FUE_n but not cooperating with the FBS.

4.3 Problem Formulation

Due to supporting users' mobility for a wireless network, innovative procedures are required, which are essential, such as handover, routing, and location updating. In open access mode, all the users of a cellular provider are allowed to access the femtocells. This is a hotspot scenario like that in a restaurant or shopping mall. However, the disadvantage of this mode is increasing number of handovers and signaling, and some security

issues. In close access mode, the aforementioned disadvantages are overcome. Therefore, we formulate our problem under the closed access mode.

The femtocell networks are temporarily formed based on the spectrum requirement from geographically close FUEs. The FBSs cooperate with the MUEs who are suffering from a bad throughput performance, and then the FBSs serving the corresponding FUEs are operated as relays to help MUEs transmit data, since the FBSs have more relaying capability than the FUEs. The cooperation between the MUEs and FBSs is a win-to-win game such that the MUEs can improve their performance, and the FBSs can help their serving FUEs acquire more spectrum access opportunities.

4.3.1 Cooperation Framework

While the transmission links of the MUEs are in poor condition, they need to find some cooperators to improve their performance, and they broadcast the searching cooperators information to surrounding FBSs. Then, the FBSs who are requiring spectrum access opportunities will accept the requests, and send the feedback information together with their relaying power P_k and cooperation time fraction β to the MUEs. The MUEs and FBSs generate their own cooperating preference lists. Subsequently, by solving a many-to-one stable matching problem, matching cooperation pairs between one FBS and multiple MUEs can be obtained. After the cooperation is established, the MUEs become the subscribed users and are allowed to connect to the FBS.

During the cooperation process, FBS cooperates with multiple MUEs within interval βT . In return, the FBS acquires the remaining time slot $(1 - \beta) T$ frequency bands for its serving FUEs.

4.3.2 Many-to-one Stable Matching

Gale and Shapley in 1962 raised the college admission problem which is an example of a two-sided many-to-one matching market. It is closely-related to the stable marriage problem, but these two problems are not equivalent since the outcome of college admission problem can only be one side optimal. In addition, for one-to-one marriage problem, the men-optimal stable matching and the women-optimal stable matching are symmetric of each other, while the student-optimal stable matching and the college-optimal stable matching are not for many-to-one college admission problem. In this dissertation, we focus on solving the cooperation problem by using many-to-one stable matching.

Notations and Terminologies

The cooperation consists of two sets of agents: K FBSs which are denoted by $\mathcal{K} = \{k_1, k_2, \dots, k_K\}$, and M MUEs which are expressed by $\mathcal{M} = \{m_1, m_2, \dots, m_M\}$. Each agent has a strict, transitive, preference ordering of the acceptable agents on the other side. Let $\Gamma \subseteq \mathcal{K} \times \mathcal{M}$ denote the set of acceptable pairs. Associated with FBS k is a positive integer q_k representing its quota, and the interpretation for FBS k is to allow it to admit up to q_k MUEs. Without loss of generality, we assume that (i) k finds m acceptable if and only if k finds m acceptable, and in this case, we say that (m, k) is an acceptable pair; (ii) FBS k finds at least q_k MUEs acceptable, and each MUE finds one FBS acceptable. Note that we consider the somewhat restrictive model of preferences in which the FBSs have preferences over individual MUEs, not over groups of MUEs.

The two-sided many to one matching approach takes both parties' interests into consideration. Therefore, each user has a preference ranking list of acceptable users on the other side. Each user in set \mathcal{K} (or \mathcal{M}) has preference over each user in set \mathcal{M} (or \mathcal{K}). Let $\psi(k)$ be the preference function of user k in set \mathcal{K} , and let $\varphi(m)$ be the preference function of user m in set \mathcal{M} . Hence, the FBSs have a preference set $\psi(k)$ for MUEs, which

are sorted by MUEs' geographic locations, and each MUE also has its own preference set $\varphi(m)$, which are ordered by the expression U_m^C . The incidence matrix x^μ is defined by: $x_{k,m}^\mu = 1$, if $(k, m) \in \mu$, and $x_{k,m}^\mu = 0$ otherwise (the superscript is omitted when it is not needed). The objective of the matching is to find a stable matching solution. The following problem formulation contains a straightforward formulation of a stable matching in terms of its incidence matrix. It is immediately evident that μ is a stable matching of (Γ, q_k) if and only if its incidence matrix x verifies the following inequalities:

$$\sum_{k:(k,m) \in \Gamma} x_{k,m} \leq 1, \quad \forall m \in \mathcal{M} \quad (4.7)$$

$$\sum_{m:(k,m) \in \Gamma} x_{k,m} \leq q_k, \quad \forall k \in \mathcal{K} \quad (4.8)$$

$$q_k x_{k,m} + q_k \sum_{i \succ_m k} x_{i,m} + \sum_{j \succ_k m} x_{k,j} \geq q_k, \quad \forall (k, m) \in \Gamma \quad (4.9)$$

Indeed, the first two inequalities ensure that μ is a matching, and the last inequality guarantees that the matching is stable. Expression $i \succ_z j$ represents user z prefers i to j .

MUE-optimal stable matching

There are M MUEs who are applying for cooperation with FBSs, and there are K FBSs that these MUEs can apply for. Each MUE has a strict preference ordering over all FBSs, and each FBS also has a strict preference ordering over all MUEs. By strict preference, it means an MUE is not indifferent between two FBSs, and vice versa. In reality, it is impossible for an FBS to accept all the MUEs who apply for it, due to limited resources. In fact, an FBS only accepts a specific number of MUEs (quotas). So, every MUE cannot possibly get into their top choices. On the other hand, an MUE also can accept offer of admission from only one FBS. Thus, it is not guaranteed that all MUEs whom an FBS has made offers of admission will accept the offers.

The MUE-optimal stable matching can be summarized by the following steps:

- first, the MUEs calculate the transmission rates obtained by cooperating with each FBS to get the strict preference lists of all FBSs, and sort the preference from the highest to the lowest. In addition, the FBSs generate their preference lists based on MUEs' locations.
- at step $\ell = 1$, each MUE proposes to its first choice of FBS. Each FBS tentatively holds the most preferred proposals up to its quota and rejects all other MUEs.
- at step $\ell \geq 2$, each MUE rejected in step $(\ell - 1)$ proposes to its next highest choice. Each FBS considers both new applicants and the MUE (if any) held at step $(\ell - 1)$, tentatively holds the most preferred acceptable MUEs up to its quota from the combined set of MUEs, and rejects all other MUEs.
- Terminate when no more proposals are made. Termination happens in finite time.

Since we consider the MUE-optimal stable matching by deferred acceptance algorithm, wherein we think of an FBS as q_k different colleges with one position each. Then, the theorem for one-to-one marriage matching applies.

FBS-optimal stable matching

The first step is the same as in MUE-optimal stable matching, the MUEs calculate the transmission rates obtained by cooperating with each FBS to get the strict preference lists of all FBSs, and sort the preference from the highest to the lowest. In addition, the FBSs generate their preference lists based on MUEs' locations. Then, each FBS proposes to its top-ranked choice (If a FBS has a quota of q_k , then the q_k MUEs are top-ranked on its ranking list), and then the MUE checks whether one of the proposals from the FBSs is its most preferred MUE according to its preference ranking list. If no such matchings

are found, the algorithm proceeds to the next step, where the second ranked MUE on each FBS's ranking list is matched with the top-ranked MUEs on the FBS's list. In any step where no matches are found, the algorithm proceeds to the next step. Otherwise, the matched pairs are under the tentative-assignment-and-update state. Finally, when the pairs are under the tentative-assignment-and-update state from the ℓ th step, the tentative matched pairs, i.e., FBSs and MUEs, are updated in the following way:

- Any FBS who ranks lower than the MUE's tentatively assigned cluster is deleted from its ranking list, i.e., the updated ranking of the MUE who is tentatively assigned to its ℓ th choice lists only is its ℓ th first choice;
- MUE is deleted from the ranking list of any FBS who was deleted from the MUE's ranking list.

Since this algorithm is more complicated than the MUE-optimal one, we specify the algorithm according to the above statement in Algorithm 3.

Theorem 1. *A pair $(k, m) \in \Gamma$ blocks μ if (i) k prefers m to at least one of its assigned MUEs in μ , or if k is assigned fewer than q_k MUEs, and (ii) m prefers k to its assigned FBS in μ , or if m is unmatched.*

Theorem 2. *A matching result μ is stable if it is not blocked by any pair of users.*

Theorems 1 and 2 follow from the following propositions.

Proposition 1. *Stable matching can be obtained based on the two-sided many to one matching algorithm.*

Proof. We prove the proposition by contradiction. Let μ be the matching result obtained by using the two-sided many-to-one matching algorithm. Suppose (k, m) will block μ , i.e., FBS k and MUE m are not matched indicating that the pair (k, m) does not belong

Algorithm 3 Two-sided many to one matching algorithm.

Input:

A set of FBSs \mathcal{K} , a set of MUEs \mathcal{M} , and preference ranking lists $\psi(k)$, $\varphi(m)$ of the FBSs and MUEs, respectively.

Initialize $\mu = \emptyset$ and $\ell = 1$;

Output:

The cooperation pairs formation, i.e., many to one matching result μ ;

- 1: **while** (FBS k is not fully subscribed) and ($\psi(k) \neq \emptyset$) **do**
 - 2: FBS k proposes to the MUEs who are the first ℓ th choice in the preference ranking list $\psi(k)$.
 - 3: **if** FBS k is the first choice in MUE m 's preference ranking list $\varphi(m)$ **then**
 - 4: $\mu = \mu \cup \{(k, m)\}$, and update the ranking lists $\psi(k)$, $\varphi(m)$ of the FBSs and MUEs, respectively;
 - 5: **else**
 - 6: $\ell = \ell + 1$, and go back to step 2;
 - 7: **end if**
 - 8: **end while**
 - 9: μ is a stable matching.
-

to μ , but they prefer each other more. Therefore, MUE m prefers FBS k more than other FBSs on its preference ranking list $\varphi(m)$, i.e., $k \succ_m \mu(m)$. Moreover, FBS k must have proposed to MUE m before the matching algorithm stops. However, they do not match each other in the matching result μ , which suggests that MUE m must reject the proposal of FBS k . In this case, there must be some FBS k' who has a higher priority in MUE m 's preference ranking list in μ . As a result, (k, m) will not block μ , which contradicts the assumption. Hence, matching result μ is a stable matching since there is no user blocking it. \square

Proposition 2. *Stable matching for the cooperation pair selection problem is unique.*

Proof. We prove the proposition by induction on M . Let K be the number of FBSs with quota q_k , M be the number of MUEs, and μ be the matching for matrix $\Gamma_{\mathcal{K} \times \mathcal{M}}$. When $M = 1$, the stable matching is definitely unique since the first and best MUEs will be assigned to the only FBS; when $M \geq 2$, let μ be the matching result which can make the FBSs choose the nearest MUEs for Γ , and let μ' be the matching we attain by deleting a FBS k and MUE m to attain Γ' . Suppose μ' is the unique stable matching for Γ' . If μ is a stable matching, then $\mu(k) = m$, and $\mu \setminus \{(k, m)\}$ must be a stable matching. By induction, we can conclude that $\mu := \mu' \cup \{(k, m)\}$ is the unique stable matching for Γ . Therefore, μ is the unique stable matching for Γ . \square

Proposition 3. *The proposed cooperator matching scheme always converges to a stable matching.*

Proof. To see that the scheme converges, note that each MUE can only be rejected at most K times. Consequently, for each MUE, there exists ℓ high enough such that in all rounds of the algorithm past ℓ , the MUE is assigned the same FBS, so the pointwise limit exists. To see that the limit is a matching, we only have to prove that the measure of MUEs assigned to each FBS is no more than its capacity. At each round ℓ of the algorithm, let R_ℓ be the measure of rejected MUEs. Again, because no MUE can be rejected more than K times, we have $R_\ell \rightarrow 0$. But at round ℓ , the excess of MUEs assigned to each FBS has to be at most R_ℓ , so in the limit, each FBS is assigned at most its quota. Also, if the measure is less than the quota, then we know the FBS has not rejected any MUEs throughout the algorithm. \square

4.4 Numerical Results

In this section, the proposed macrocell-femtocell cooperation scheme is simulated and evaluated. The performance of the exploited stable matching algorithm is compared with the optimal solution. In addition, the performance and interference level of MUEs and FUEs with and without cooperation are compared, respectively. Moreover, the relationship between cooperation time fraction β and the power of FBS is illustrated, and energy efficiency of the FBSs with two operation modes is also shown. Finally, we compare the transmission rate by using three different matching methods.

We consider a single hexagonal macrocell with a radius of 300m within which M MUEs, and N FUEs are uniformly distributed, and the FUEs are overlaid with the MUEs on the same subchannels. The MBS serves M MUEs scheduled over M OFDMA subcarriers with same wide bandwidth. K FBSs serve N FUEs which are also using OFDMA spectrum access manner, and the FBSs are equipped with dual modes. The AF mode is used by the cooperating FBS to relay the MUEs' traffic. For both FUEs and MUEs, we assume that power control fully compensates for the path loss. A closed access policy is adopted at each FBS. We set each FBS with maximum transmit power to $P_{r_{max}} = 30dBm$ for relay mode and $P_{t_{max}} = 40dBm$ for traditional mode, and the power limitation of MUE is $20dBm$.

We compare the scenario of which $q_k = 1$ in our many-to-one matching algorithm with the Hungarian algorithm which gives the optimal solutions. The number of FBSs is $K = 50$, and the number of MUEs M varies from 10 to 100. As we consider $q_k = 1$ in our simulation, the number of FBSs K equals to M . As shown in Fig. 4.2, the blue stars are the optimal results obtained by the Hungarian method, and the red circles are the results obtained by our proposed stable matching method, which are very close to the optimal solutions.

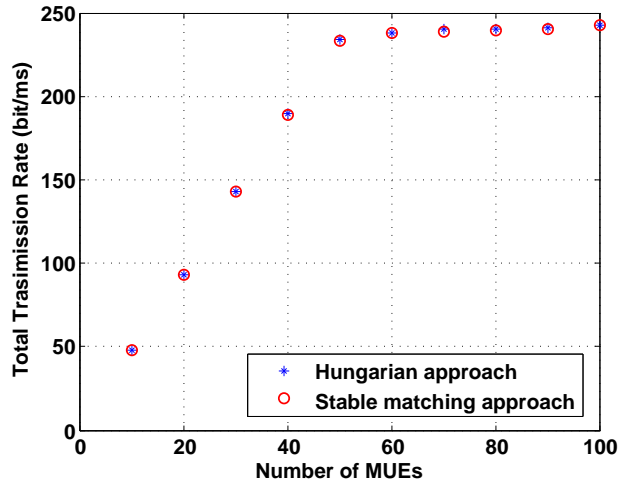


Fig. 4.2: Matching results of proposed approach compared with that of the optimal approach.

The number of MUEs M varies from 50 to 500. The number of FBSs N is 10, and each FBS serves 3 FUEs; in other words, the quota of the FBS is $q_k = 3$. The transmission power of the MUEs, FBSs and FUEs are set to $20dBm$, $30dBm$, and $20dBm$, respectively. In Fig. 4.3, we compare the total utility of macrocell and femtocell network attained with and without cooperation, respectively. It can be observed that the utility obtained with cooperation outperforms that without cooperation, and the reason is not only because of FBSs' relay transmission, but also due to the fact that cooperation between FBSs and MUEs mitigate the interference to both femtocell and macrocell networks. The total utility of macrocell network increases as the number of MUEs becomes larger, while the total utility of femtocell network does not vary too much.

In Fig. 4.4, the interferences to MUE and FUE (with and without cooperation) are illustrated, respectively. It is indicated that the interference to both MUE and FUE are mitigated due to the cooperation between the FBS and MUEs. The reason for the interference mitigation of the FUE is that the cooperative MUEs surround the corresponding

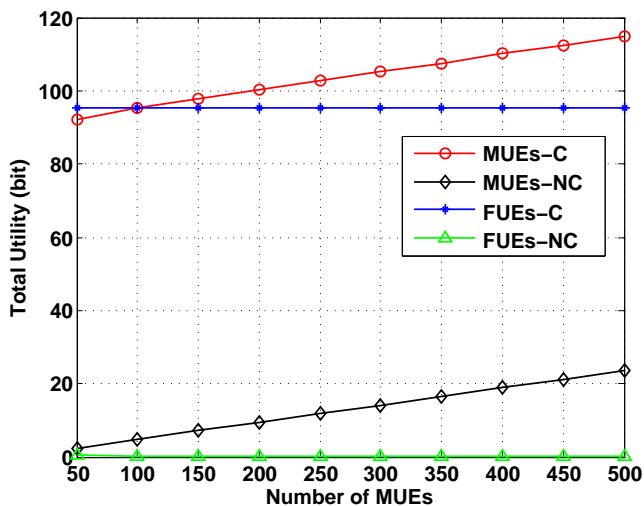


Fig. 4.3: Utility comparison with and without cooperation.

FBS stop the continuous retransmissions to the MBS since the FBS help them relay their traffic to the MBS.

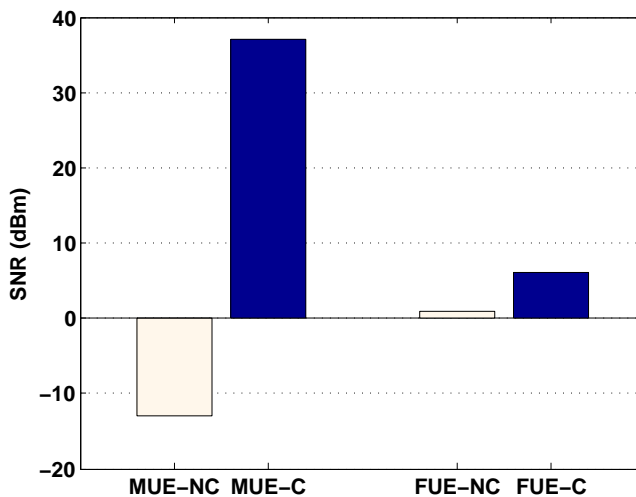


Fig. 4.4: Interference to MUE and FUE with and without cooperation.

In Fig. 4.5, we show the relationship between cooperation time fraction β and the power of FBS P_k with low, medium and high minimum total utility requirement, and

from this figure it is observed that the value of P_k decreases dramatically as the increment of β . Therefore, the FBS does not need to sacrifice by increasing P_k to gain smaller β , i.e., acquiring more time slot for its serving FUEs. It is wise for the FBS to choose the proper value of P_k , which is selected to meet the minimum total utility requirement. Therefore, energy consumption of the FBS with two operation modes in our work is reduced compared with traditional FBS which works only with one mode.

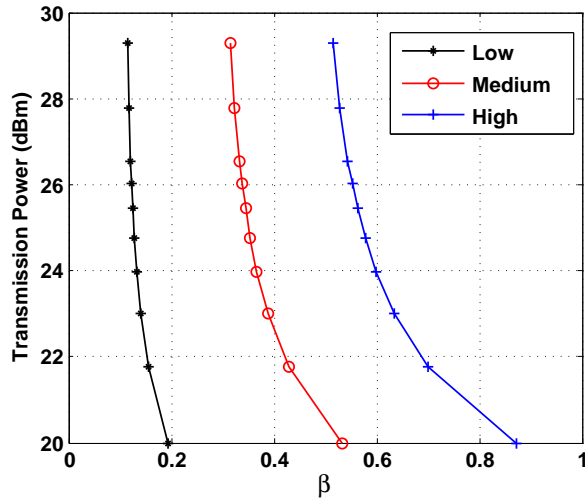


Fig. 4.5: Relationship between β and P_k with different levels of minimum total utility requirements.

Let P_r (relaying power) and P_t (base station transmission power) represent the value of P_k , and $P_r = 10\text{mdB}$, $P_t = 40\text{mdB}$. As shown in Fig. 4.6, increasing the value of P_k does not lead to dramatical utility improvement, and this is the reason why we formulate the FBS equipped with dual modes: relay mode and traditional base station mode with different power levels. Therefore, while the FBS cooperates with MUEs, it operates in relay mode with lower power level for relaying MUEs' traffic.

A simple macrocell-femtocell network scenario wherein there are $M = 3$ IUs and $N = 15$ SUs uniformly distributed is configured in Fig. 4.7. The MBS is represented by

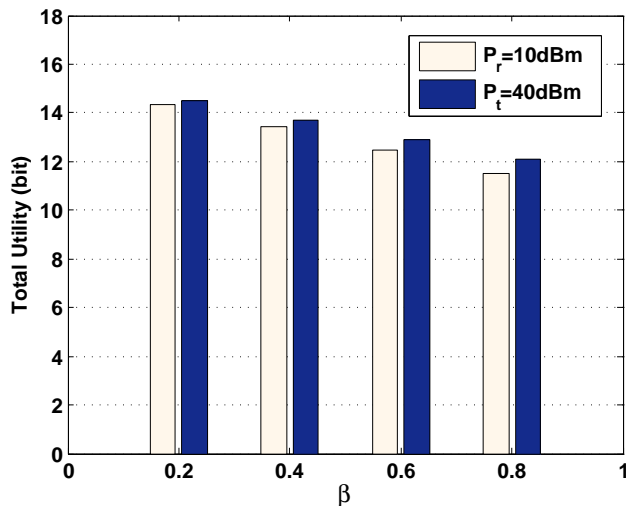


Fig. 4.6: Total utility as a function of β with different values of P_k .

a solid square which is located at the origin. MUEs and FBSs are deployed uniformly on the $300 \times 300\text{m}^2$ area, and the FBSs are represented by the blue stars serving as the center of a disc of radius 10m in which FUEs are randomly located. Green triangles denote the FUEs, and red circles represent the MUEs who communicate with the MBS. The preference ranking lists of the IUs are obtained according to the CCRN configuration which is illustrated in Fig. 4.7. The quotas of three IUs are $K_1 = 3$, $K_2 = 2$, and $K_3 = 2$, respectively. Then, based on the information retrieved from the common control channel, the SUs can modify their preference lists using the ratio of transmission rate to IU's weight. In Fig. 4.8, we compare the cluster total transmission rate attained by the three different cluster formulation schemes: random matching, maximum power matching and two-sided many-to-one stable matching, and we also change the member of SUs who are starving for accessing the spectrum. The random matching process is simulated for 1000 times and the mean value is calculated. It can be observed that the stable matching scheme outperforms the other two scheme, and the total transmission rate increases as the number of SUs becomes larger.

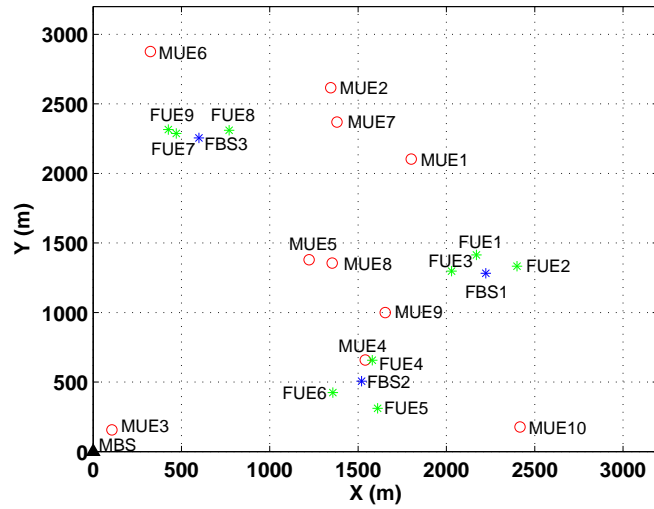


Fig. 4.7: Macrocell-femtocell network deployment.

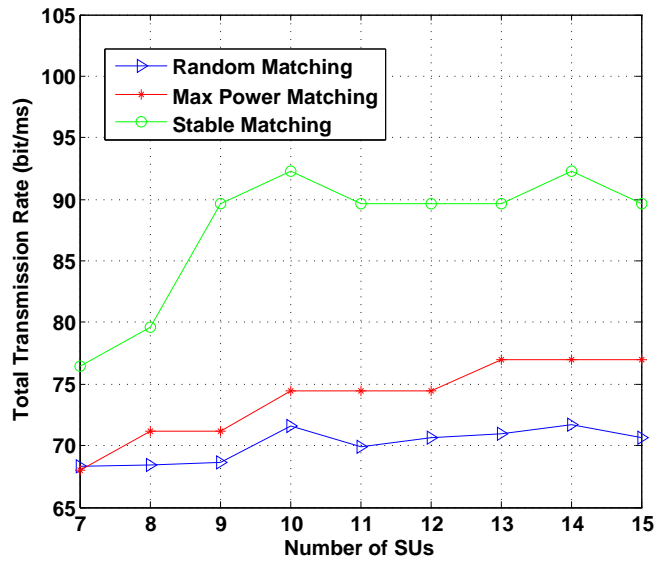


Fig. 4.8: Total transmission rate comparison among random matching, maximum power matching and proposed stable matching.

4.5 Summary

In this chapter, we have proposed a macrocell-femtocell network cooperation scheme under closed access mode. The cooperator selection problem is formulated as a many-to-one stable matching problem, and the matching result is stable and takes both FBSs' and MUEs' benefits into consideration. In addition, the FBSs are operated by dual modes. Therefore, energy consumption can be reduced, and the interference to the macrocell network can be decreased. Moreover, simulation results show that the utility obtained by performing the proposed many-to-one stable matching scheme can achieve the near optimal performance in our scenario, and cooperation can improve both the MUEs' and FUEs' utility compared with the non-cooperation case under closed access mode. Moreover, we obtain the solution of cooperation time fraction factor β , which can guarantee the minimum cooperation pairs' utility.

Chapter 5

Conclusions and Future Work

In this chapter, we mainly summarize the contributions of this thesis and propose future research work.

5.1 Conclusions

This research aims at developing spectrum sharing mechanism for cognitive radio networking. We are working on different cooperation aspects, including cooperator selection, power allocation, time allocation and cluster based bandwidth sharing. Particularly, in this thesis, we have

- proposed a novel cooperative strategy in CRN, based on quadrature signaling. By employing the two orthogonal channels, the three-phase relaying process can be integrated into two-phase without interference. We have considered the underutilized spectrum and spectrum hole as a whole time slot. When the channel condition between the PU and its receiver is poor, the PU's performance can be improved through cooperation with an assistant cooperative relaying SU. We have formulated

this model as a non-linear optimization problem. Through exploiting the optimization algorithm, the PU's utility can achieve the optimal value. As a reward, the second phase is allocated to the SU for its own traffic. The optimal power allocation have been analyzed and the closed-form solution has been derived for AF mode.

- proposed a cluster based PCN/SCN spectrum sharing scheme in a CCRN. First, the cooperation between cluster heads of PCN and SCN has been investigated. Then, the spectrum sharing have been formulated as a combinatorial non-linear optimization problem which is NP-hard. Afterwards, we have decomposed this problem into cluster allocation and time assignment. The cluster allocation is solved by our proposed matching algorithm, which can obtain stable matching results. In addition, by solving an optimization problem, the time allocation results are close to the optimal solutions. Moreover, simulation results have shown that the utility obtained by performing the proposed aggregated spectrum sharing scheme can achieve the near optimal performance in our CCRN.
- proposed a macrocell-femtocell network cooperation scheme under closed access mode. The cooperator selection problem is formulated as a many-to-one stable matching problem, and the matching result is stable and takes both FBSs' and MUEs' benefits into consideration. In addition, the FBSs are operated by dual modes. Therefore, energy consumption can be reduced, and the interference to the macrocell network can be decreased. Moreover, simulation results show that the utility obtained by performing the proposed many-to-one stable matching scheme can achieve the near optimal performance in our scenario, and cooperation can improve both the MUEs' and FUEs' utility compared with the non-cooperation case under closed access mode. Moreover, we obtain the solution of cooperation time fraction factor β , which can guarantee the minimum cooperation pairs' utility.

5.2 Future Work

In this dissertation, we mainly focus on the cooperative spectrum sharing in cognitive radio networking. Along this path, there are several research directions towards a more practical, spectrum and energy efficient cognitive radio networking as listed below.

- The proposed cooperation strategy might be extended to the multiple cooperating SUs case with the decode-and-forward relaying mode adopted. In addition, the parameters can be adjustable in order to obtain better performance not only the PU but also the SUs. Moreover, imperfect CSI would be considered.
- Investigate the relationship between the remaining spectrum capability of the IU and the maximum number of SUs that can be tolerated in a cluster, and develop a mechanism to dynamically form clusters and investigate the optimal cluster size.
- Security is a very important and challenge issue during cooperation, since the co-operation pair needs to trust with each other.

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