行政院國家科學委員會專題研究計畫成果報告

廣義的機會式通訊：無線行動網路中之競爭、合作與感知-總計畫

Generalized Opportunistic Communications: Competition, Cooperation and Cognition in Wireless Mobile Networks

計畫編號：**NSC 96-2221-E-009-115-MY3**

執行期間：**98/08/01~99/07/31**

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中文摘要：本計畫針對廣義的機會式通訊之各關鍵性議題中做深入的探討，四個子計畫名稱分別爲：

子計畫一：動態頻譜偵測與無線電資源管理之感知傳輸設計。
子計畫二：適用於協力式無線網路之感知式跨層設計。
子計畫三：協同式感知網路之擇路協定及媒體接取控制設計。
子計畫四：協力無線系統中感知媒體存取控制協定設計與用戶/基地台選取之研究。

這些名稱充分反映了所探討的議題爲何。

首先，在子計畫一中探討頻譜估測不匹配對感知展頻傳輸系統造成的性能影響問題。在此感知系統中，是否要使用某個頻段乃是依據頻譜偵測的結果，然而估測錯誤往往是無法避免的，尤其是當頻譜使用是呈現一種時變的非穩態隨機過程(non-stationary process)時。此外當傳送端和接收端相隔較遠時，其所觀察到的頻譜環境也會不盡相同，進而導致頻譜估測不匹配的現象。爲了瞭解頻譜估測不匹配所造成的影響，我們首先分析在頻譜估測不匹配下對於一種特殊的感知展頻通訊系統，即所謂的「轉換域通訊系統」(transform domain communication system)的錯誤率表現影響。分析的結果顯示傳收兩端頻譜資訊交換的設計是必然的需求，若無良好的規約設計，將會導致不可避免的錯誤層（error floor）。我們接著探討無線電資源管理的議題。我們首先討論在具有中繼站合作下正交分頻多工存取系統如何做資源的分配。我們提出了兩個低複雜度且有良好效能的資源分配演算法。此外我們也探討多輸入多輸出正交分頻多工系統。前人的研究通常假設單一頻帶只允許單一用戶使用。爲了進一步提升系統效能，我們提出的演算法可以不受此限制。

子計畫二則是探討多封包接收無線網路之上行多媒體存取控制協定設計，不

同於之前的研究，此計畫考慮了實體層的結構並充分利用進而提升了系統效能，其考慮的範圍包含了協力式結構，適應性調變編碼，以及同質和異質網路結構。此外雖有部分的文獻探討相似的議題，但是其提出的解決方案都具有兩大瓶頸，第一個瓶頸是必須使用複雜的使用者狀態估測演算法，另一個瓶頸則是爲了配合使用者狀態估測演算法，使用者的封包會有阻絕（blocking）的限制。在此提出的上行多媒體存取控制協定設計利用了封包接收狀態自動排序出使用者的可能活躍程度，因此可以大幅降低演算法的複雜度也不會有封包阻隔的限制。

在無線電感知系統中，現存的換手機制假定無線電感知使用者可以正確的偵測每個頻帶以找到適合的頻帶進行換手，這個假設並沒有考量到偵測頻帶所花費的時間，一旦偵測所需的時間過高，主要使用者的品質將會大幅地降低，因此，新的頻帶換手機制是一個必須且重要的研究主題。子計畫三藉由部分可知的環境下的馬可夫決策過程（Partial Observable Markov Decision Process, POMDP）之幫助，可以透過探測部分的頻帶來估測整個網路環境進而提出以 POMDP 爲基準的頻帶換手機制。另一方面，由於衰減通道的影響，協力式通訊(Cooperative Communication)已被提出來降低接收錯誤率，然而大部分的文獻都是從實體層角度探討，在實際系統中，由於半多工(Half-Duplex)傳輸技術的限制導致傳輸時間的增加是無可避免的事情，爲了考量此效應，子計畫三從網路吞吐量(throughput)的觀點來探討在什麼樣的情況下協力式通訊可以增加吞吐量並基於此探討提出了兩種合作式通訊協定使網路整體吞吐量提升。

子計畫四的主要具體研究成果如下： (1) 針對頻譜決定問題，我們提出一個負載平衡的頻譜決定機制來最小化次要使用者的傳輸延遲；(2) 針對頻譜分享問題，我們提出允入控制機制來避免主要使用者被干擾並最小化次要使用者的傳輸延遲；(3) 針對頻譜換手問題，我們量化多次頻譜切換對次要使用者所造成的傳輸延遲。如上所述，我們完整的探討了這三個頻譜管理機制對次要使用者所造成的傳輸延遲。

關鍵詞：資源管理，多封包接收，部分可知的環境下的馬可夫決策過程，頻譜換手。

Abstract

This report documents our efforts and major findings for the NSC project entitled, “Generalized Opportunistic Communications: Competition, Cooperation and Cognition in Wireless Mobile Networks,” during the period 8/1/2008-7/31/2010. This 3-year joint effort consists of four subprojects entitled, respectively

(1) Spectrum sensing and management in cognitive wireless mobile networks.

(2) Cooperative Cross-Layer Design in Cognitive Wireless Mobile Networks.

(3) Cooperative Routing Protocols and QoS Control in Cognitive Wireless Mobile Networks.

and

(4) Cooperative MAC Protocol Design and User/Base Station Selection in Cognitive Wireless Mobile Networks.

In Subproject 1, we first consider the effect of spectrum mismatch. In practice, the spectrum estimate is not perfect and some estimation error is not avoidable. Moreover, when the transmitter and receiver are separable far from each other, the electromagnetic environment may be different significantly. This will result in the spectrum mismatch. Hence, we investigate the performance of transform domain communication system in the present of spectrum mismatch. Then, we focus on the resource allocation problem. We first consider the resource allocation problem in relay-based OFDMA (orthogonal frequency division multiple access) systems with fairness considerations. Two low complexity algorithms are proposed to solve the optimization problem with satisfying performance. Moreover, we also investigate resource allocation problem for MIMO-OFDMA based wireless networks. In previous work, single-user-per-subcarrier constraint or the single (strongest)-eigenmode-per-subcarrier constraint is assumed. In our work, we relax the constraint to improve the system performance significantly.

Subproject 2 investigates the medium access control (MAC) protocol design for the uplink of wireless networks with multi-packet reception (MPR) capability. In contrast

with previous work, this project take the structure of physical layer into account to improve the system performance. Specifically, the structure of cooperative communication, adaptive modulation, and homogeneous/heterogeneous are considered. Although these topic has been considered before, there are two bottlenecks. First, the need of active user estimation algorithm is called for and the complexity of active user estimation algorithm is usually high. Second, due to the active user estimation, the packet blocking constraint is imposed on the active users for keeping compliant with prediction. Hence, we propose a solution that can automatically produce the list of active users by observing the network traffic conditions to reduce the complexity and the packet blocking constraint is relaxed.

For most proposed cognitive spectrum handoff mechanisms, it is often assumed that the state of spectrum usage can be estimated without error and using negligible time. However, an accurate spectrum estimation usually takes a long observation period and thus the throughput performance of primary user is reduced significantly. Hence, it is important to consider a novel and more time-efficient spectrum handoff mechanism which a major focus of Subproject 3. Using the framework of partial observable Markov decision process (POMDP), we are able to estimate the whole spectrum states by using only partial information and with a relatively low complexity. Furthermore, we propose a novel POMDP-based spectrum handoff mechanism accordingly. On the other hand, cooperative communication has been developed as a new communication strategy that incorporates a relay node to assist direct point-to-point transmission. However, owing to the longer transmission time resulting from the cooperative schemes, there is no guarantee to enhance network throughput in view of the medium access control (MAC) performance. In this subproject, system throughput is used as a measure for evaluating the decision on when to initiate cooperation. We suggested two cooperative communication protocols to enhance the system throughput.

The following issues were investigated in Subproject 4:

- Spectrum decision: we propose a load-balanced decision mechanism to minimize the transmission delay of secondary user.
- Spectrum sharing: we propose a control mechanism to avoid interfering the primary user and to minimize the transmission delay of secondary user.
- Spectrum handoff: we quantify the transmission delay of secondary user due to the several spectrum handoff.

Keyword: resource allocation, multi-packet reception, partial observable Markov decision process, spectrum handoff.

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Chapter 1

Introduction

It is known that most of assigned spectrum are inefficiently utilized. For example, the United States' Federal Communication commission (FCC) had found that temporal and geographical variations in the utilization of the assigned spectrum range from 15% to 85%.[1]. As a result, cognitive radio (CR) technology, which allows an unlicensed user (secondary user) to share a spectrum with licensed users (primary users) as long as the interference to the latter is nonexistent or acceptable, has in recent years emerged as a new communication paradigm for next generation wireless mobile networks. It promises much more efficient radio resource utilization, improved system performance and novel new functionalities. The main theme of CR is the capability of a radio to sense and adapt to its environment, constantly making spectrum, transmission and networking decisions that optimize radio resources (energy/power, spectrum, cooperative nodes etc.) opportunistically. A careful examination of the nature of CR-based wireless networks reveals that the associated communication and networking processes involve competition, cooperation and cognition phases. The study of these related behaviors and the designs of algorithms and protocols that coordinate all three phases in an optimal manner shall be the major focus of our investigation. On the other hand, the realization of a CR-based network necessitates at least three core technologies, namely, (i) the software-define radio (SDR) technology, (ii) the ultra-wideband (UWB) RF technology, and (iii) the cooperative/competitive communication theory. The scope of the proposed joint efforts shall be limited to (i) and (iii), assuming the availability of UWB front ends. We shall cover all three major aspects of a cognitive cycle, i.e., spectrum sensing, spectrum analysis and spectrum management decisions. Our emphasis shall be in physical layer and MAC layer although some related upper layer issues are to be addressed as well.

A conventional mobile communication terminal often has limited computing power due to the battery life and terminal size constraints and the need to make real-time decoding and detection decisions. To simply system design and reduce the implementation cost a mobile terminal is usually designed to operate in a particular communication system only. Because of the rapid advances in DSP and microelectronic technologies, the above constraints and concerns have been considerably lessened. As a result, a new class of radio technologies called software-defined radios (SDR) has received much attention. An SDR has the capability to operate in multiple bands and multiple wireless communication systems; its architecture is reconfigurable and scalable. An obvious and direct application of SDR is CR systems.

In practice, to meet the CR requirement, a secondary user should be able to sense the spectrum accurately and should vacate the spectrum whenever a primary user appears. In the later case, the secondary user either wait and retransmit after the primary user finishes its transmission session or exploit another unused spectrum which then gives rise to the spectrum handoff issues. Apparently, how and when to have a spectrum handoff will have significant impact on the system throughput. A partial observable Markov decision process (POMDP) [6]-[9] based spectrum handoff mechanism is proposed to reduce the spectrum sensing time in Subproject 3. A key feature of POMDP is that one is able to estimate the complete spectrum state with only partial information and with relatively low complexity. The spectrum sensing scheme thus needs less time to estimate the spectrum and the secondary user can have more time to transmit. A queuing based spectrum handoff scheme is also proposed to minimize the transmission delay.

Spectrum sensing is a key issue in realize a CR system and many a studies were devoted to develop better sensing schemes in a variety of communication environments [2]-[5]. However, there is very little literature discussing the impact of sensing error or spectrum mismatch. One of the main concerns of Subproject 1 is to investigate such mismatch effects and propose feasible solutions.

Besides sharing and competing for the same spectrum, proper cooperation among users can help improving network throughput. This subject is studied in Subproject 2. More specifically, we study the medium access control (MAC) protocol design issue for the uplink of a wireless network with multi-packet reception (MPR) capability, taking into account the structure of cooperative communication, adaptive modulation, and homogeneous/heterogeneous traffics. Although similar discussions has been presented before [10]-[14], there are two major unsolved issues. First, the need of an active user estimation algorithm is called for but the complexity of such an algorithm is usually very high. Second, a packet blocking constraint is imposed on the active users for keeping compliant with active user prediction. We propose a solution that can automatically generate the active users list by observing the network traffic conditions to reduce the complexity and relax the packet blocking constraint.

Subproject 3 investigates the benefit of cooperation among users. Most of the researches on cooperative communications is based on the information theory's viewpoint and focuses on the PHY layer design. However, implementation consideration favors half-duplex mode and thus two phases are required for a basic relay-based packet communication network. As a source remains idle in the second phase the overall throughput such a cooperative scheme is reduced. We suggest two cooperative communication protocols to enhance the throughput. Moreover, low complexity resource allocation algorithms are proposed to further improve the throughput in a relay-based MIMO OFDMA system.

In the following sections we highlight the major achievements of each subproject and summarize their important results. Detailed information can be found in the reports submitted by each subproject.

Chapter 2

Spectrum sensing and management in cognitive wireless mobile networks

Several important issues related to opportunistic communications are investigated in this subproject. In the first year, we analyze the performance of a cognitive spread spectrum system called transform domain communication system (TDCS) in the presence of spectral mismatches. We then deal with the problem of combined relay selection and resource allocation for relay-based OFDMA systems in the second year. In the third year we look into similar problems for MIMO-OFDMA systems. This chapter summaries the major results associated with each subjects mentioned above.

Based on the CR concept, Chakravarthy *et al.* [17] proposed a dynamic modified direct-sequence spread spectrum (DS-SS) system to which they referred as adaptive waveform communication system (AWCS). Since the spreading sequence of AWCS is synthesized in the transform domain, the system is also called transform domain communication system (TDCS). The basic idea behind TDCS is to generate a spreading sequence whose spectrum avoids existing users or jammers within the SS band.

In most existing works, it is assumed that the channel state information is perfectly known at transmitter and receiver. In practice, the spectrum conditions at transmitter and receiver are independently estimated at both sides. If the spectrum seen (or measured) by transmitter is different from that seen at receiver, the mismatch between two spreading sequence spectra will cause performance degradation [18]. Spectra mismatches arise because of geographic separation and/or spectrum estimation errors, i.e., either the "true" spectrum represented at two sides are different or the estimated spectra are different although the spectrum representation are the same.

In the first year, we analyze the effect of spectrum estimation error induced spectrum mismatches on the symbol error rate (SER) performance in additive white Gaussian noise (AWGN) and Rayleigh fading channels, respectively. Notice that TCCS is also a multi-carrier based system and it is expected that this work can be extended to the popular multi-carrier system: orthogonal frequency division multiplexing (OFDM) system.

A block diagram of the TDCS transmitter is illustrated in Fig. 2.1. The transmitter partitions the signal band into N equal-spaced subbands (tones) and performs spectrum estimation to determine which subbands are being used. The spectrum estimator output is an N-dimensional binary vector $\mathbf{A}_x = (A_x(\omega_0), A_x(\omega_1), \cdots, A_x(\omega_{N-1}))$ with $A_x(\omega_i) =$ 1 or 0 depending on whether the ith subband is available (1) or not (0). The subscript x will be Tx or Rc to denote if the vector is associated with the transmitter (Tx) or the receiver (Rc). The binary vector $\mathbf{A}_{\text{Tx}}$ is multiplied element-wise by a user-specific random vector $(e^{j\theta(\omega_i)})$ and scaled by constant factor before being inverse discrete Fourier transformed to produce the time-domain fundamental modulation waveform (FMW). The multiplication of the random vector is to make the FMW noise-like and to provide the multiple access capability. The FMW is used to spread (or as a carrier of) the binary phase shift keying (BPSK) or cyclic code shift keying (CCSK) modulated data sequence.

Depending on the geographic distribution of wireless network users, the true spectra seen from both sides can be identical or different and spectrum mismatches might still arise even if the spectral estimations at both sides are error-free. We refer to such spectra mismatches as network geography induced spectra mismatches. Such mismatches are most likely to occur when the distance between two sides of the link is large. To simplify our analysis we define the true spectrum as such that no existing user is interfered by

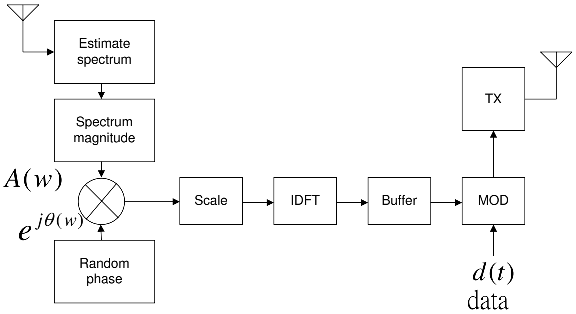

Figure 2.1: Block diagram for a TDCS transmitter

the transmitted signal and the received waveform is not interfered by any existing user if error-free spectrum estimates are available on both sides of the link.

The true spectrum represented by the binary-valued N-dimensional vector $\mathbf{A} = (A(\omega_0), A(\omega_1), \cdots, A(\omega_{N-1}))$, where N is the size of inverse discrete fourier transform (IDFT), is thus related to the error-free spectrum estimates $\mathbf{A}^o_{\text{Tx}}$ and $\mathbf{A}^o_{\text{Rc}}$ via $\mathbf{A} = \mathbf{A}^o_{Tx} \wedge \mathbf{A}^o_{Rc}$, where $\wedge$ denotes component-wise logical "and" operation.

Example 2.1. ***Network geography induced spectra mismatch*** *Suppose the spectral estimations at both sides of a 4-channel (*$N = 4$*) link are error-free and* $\mathbf{A}_{Tx} = \{0, 1, 1, 0\}$ *and* $\mathbf{A}_{Rc} = \{1, 0, 1, 0\}$*. The mismatch arises from the fact that the transmitter-centered geographic locations and distances of the existing spectrum users are different from the receiver-centered ones. There is a primary user using the first channel whose location is very close to the transmitter but is far away from the receiver. On the other hand, someone near the receiver is using channel two but it is far away from the transmitter. For this case, the true spectrum is given by* $\mathbf{A} = \{0, 0, 1, 0\}$.

We shall assume that $A(\omega_i) = 0$ with probability $1 - P_{sa}$ and $A(\omega_i) = 1$ with probability P_{sa}. Define two complementary sets of subbands (channels), $G_0 = \{\omega_i | A(\omega_i) = 0, 0 \leq i \leq N-1\}$ and $G_1 = \{\omega_i | A(\omega_i) = 1, 0 \leq i \leq N-1\}$. Then G_0 contains all subbands that are currently in use and G_1 is the set of available (unused) subbands. Let $|G_1| = N_1$ be the cardinality of G_1, then $|G_0| = N - N_1$.

Obviously, eight possible scenarios may occur, as listed in Table 2.1. For Cases 1, and 3, interference from existing users is present. In Cases 1 and 5, (additional) noise within the subband ω will be received. The received signal energy is reduced in Cases 2 and 6. If the spectrum estimation is performed in a per-channel manner and each channel is independently used, then it is reasonable to assume that the following four probabilities,

Table 2.1: Eight possible scenarios for a TDCS link.

Case	$(A(\omega), A(\omega)_{\text{Tx}}, A(\omega)_{\text{Rc}})$	The effect of non-ideal match
0	$(0,0,0)$	None
1	$(0,0,1)$	additional noise and interference are introduced in the subband ω
2	$(0,1,0)$	introduce interference to an existing user and reduce the received signal energy
3	$(0,1,1)$	introduce interference to an existing user and interference from existing user to the receiver
4	$(1,0,0)$	None
5	$(1,0,1)$	additional noise in the subband ω is introduced
6	$(1,1,0)$	received signal energy is reduced
7	$(1,1,1)$	None

$$
\begin{aligned}
P_{t0} &= \mathrm{P}_r\{A_{\text{Tx}}(\omega) = 1 | A(\omega) = 1\} \\
P_{t1} &= \mathrm{P}_r\{A_{\text{Tx}}(\omega) = 0 | A(\omega) = 0\} \\
P_{r0} &= \mathrm{P}_r\{A_{\text{Rc}}(\omega) = 1 | A(\omega) = 1\} \\
P_{r1} &= \mathrm{P}_r\{A_{\text{Rc}}(\omega) = 0 | A(\omega) = 0\},
\end{aligned}
$$

and their complementary probabilities are independent of ω_i. The above assumptions imply that $\mathbf{A}$ is binomial distributed with parameter P_{sa} and furthermore, $\mathbf{A}_{\text{Tx}}$ and $\mathbf{A}_{\text{Rc}}$ are obtained by modifying $\mathbf{A}$ based on P_{t0} (P_{r0}) and P_{t1} (P_{r1}), respectively.

It can be proved that in a AWGN channel with one-sided power spectral density of N_0 W/Hz, the bit error rate (BER) expression is given by (2.2) in the next page. where we assume that each (independent) incorrectly estimated subband cause additional in-

$$\begin{aligned} P_s \;=\; & \sum_{N_1=0}^{N}\sum_{i=0}^{N_1}\sum_{j=0}^{N-N_1}\sum_{k_1=0}^{i}\sum_{l_1=0}^{j}\sum_{k_2=0}^{N_1-i}\sum_{l_2=0}^{N-N_1-j}\binom{N}{N_1}P_{sa}^{N_1}(1-P_{sa})^{N-N_1} \\ & \binom{N_1}{i}P_{t0}^{i}(1-P_{t0})^{N1-i}\binom{N-N_1}{j}P_{t1}^{N-N_1-j}(1-P_{t1})^{j}\binom{i}{k_1}P_{r0}^{k_1}(1-P_{r0})^{i-k_1} \\ & \binom{N_1-i}{k_2}P_{r0}^{k_2}(1-P_{r0})^{N_1-i-k_2}\binom{j}{l_1}P_{r1}^{j-l_1}(1-P_{r1})^{l_1}\binom{N-N_1-j}{l_2} \\ & P_{r1}^{N-N_1-j-l_2}(1-P_{r1})^{l_2}P_e\left(\frac{E_s(\frac{k_1+l_1}{\max(i+j,1)})}{N_0(1+\frac{k_2+l_2}{\max(k_1+l_1,1)})+\frac{l_1+l_2}{\max(k_1+l_1,1)}N_I}\right) \end{aligned} \tag{2.2}$$

terference that is represented by a zero-Gaussian random variable with identical variance $N_I/2$.

We show that the simulation of the performance of TDCS agrees with the performance for different case by simulation. The size of IDFT N is set equal to 8. Here, we just show one of examples and the others are included in the report of subproject 1.

Example 2.2. ***The effect of*** P_{t1} *The effect of* P_{t1} *is illustrated in Fig. 2.2. The parameters are set as followed:* $P_{t0} = P_{r0} = P_{r1} = 0.9$ *and* $N_I = 0$ *dB. A interesting thing is that they are intersected for different* P_{t1}*. It can be explained by observing that only* $j = N - N_1$ *has nonzero value in (2.2) if* $P_{t1} = 0$*. Since* $j = N - N_1$*,* $l_2 = 0$*. This implies it is possible that interference is smaller than other cases at high* $\frac{E_b}{N_0}$*. To illustrate the argument, consider Fig. 2.3. In Fig. 2.3,* $P_{t0} = P_{r0} = 1$*, and* $\frac{E_b}{N_I} = 0$ *dB. When* $P_{r1} = 0.7$*, interference is more serious and centered at higher* l_1 *than that in* $P_{r1} = 0.9$*. For* $P_{t1} = 0$*, it is possible to reduce interference at cost of* E_b*.*

The SER in AWGN/flat Rayleigh and Nakagami-m for coherent demodulation is also investigated in this subporject.

In conclusion, the effect of spectra mismatches due to spectral estimation error is investigated. SER expressions for coherent modulation signals in various channel are given. It is shown that the spectral estimation error results in error floor. As expected,

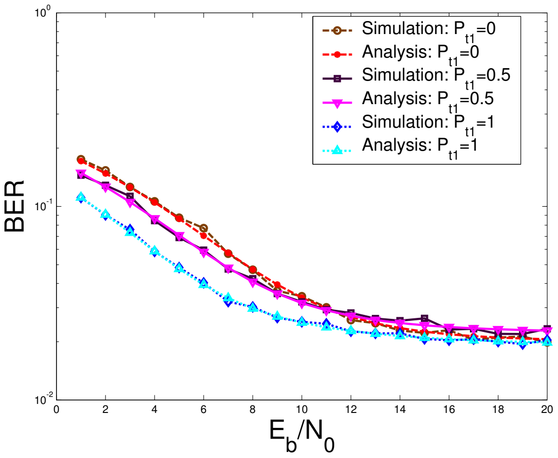

Figure 2.2: BER performance for different P_{t1}'s

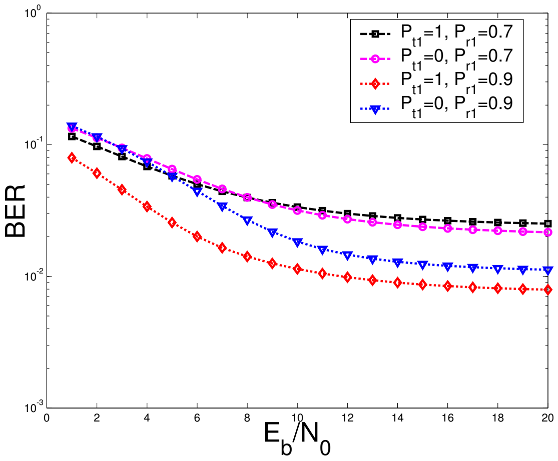

Figure 2.3: The effect of interference

the BER/SER performance is improved and the error floor is reduced when the per-tone (single-subcarrier) detection error decrease. Increasing the number of subcarriers (processing gain) in the SS band also has similar effect. Based on this, it suggests that the best access police is to choice all subbands in terms of BER/SER if the subbands are estimated as idle state. We also find that the BER/SER performance is more sensitive to the spectral estimation error at the receiver than that at the transmitter.

In the second year, we focus on the resource allocation for relay-based OFDMA systems with fairness considerations. We restrict our investigation to a single-cell system with several cooperative relay stations and mobile stations. An IEEE 802.16e-like TDD scenario is assumed and only the uplink transmission with the base station handling the resource allocation is of concern. In cooperative communications, decode-and-forward (DF) and amplify-and-forward relaying has been investigated and, here, DF relaying is adopted.

The problem of resource allocation in conventional orthogonal frequency division multiple acceess (OFDMA) systems or in relay-aided OFDMA system has been intensively studied. For example, a centralized utility maximization framework was considered in [19]. By introducing a set of pricing variables as weighting factors with the goal of maximizing the utility function of the application layer, they solved the optimization of physical layer transmission strategies (relay strategies and resource allocation) in an efficient manner. Fairness aware adaptive resource allocation in a single-hop OFDM system was considered in [20]. Here, we present two low-complexity resource allocation schemes for an OFDMA network with an aim to maximize the overall sum rate and fairness performance while satisfying the quality of serves (QoS), rate, and maximum transmit power constraints.

The resource allocation problem can be formulate as

$$\begin{aligned}
&\text{maximize}[R\ F]^T \\
&\text{subject to} \\
&\sum_{n\in S_R} \rho_{n,k} \log(1+P_{R_m}(n,k)\alpha_{R_m}(n,k)) + \sum_{n\in S_D} 2\rho_{n,k} \\
&\log(1+P_D(n,k)\alpha_D(n,k)/2) \geq R_{k,min}, \quad \forall k && (2.3) \\
&\sum_{k=1}^{K} \rho_{n,k} = 1, \quad \rho_{n,k} \in \{0,1\} \ \ \forall\ k,n && (2.4) \\
&\sum_{k=1}^{K} \left[\sum_{n\in S_R} P_{R_m}(n,k) + \sum_{n\in S_D} P_D(n,k) \right] = P_T \\
&P_D(n,k) \geq 0, \quad P_{R_m}(n,k) \geq 0, \quad \forall\ k,n && (2.5)
\end{aligned}$$

The definition of the notations in this formula can be found in the report of this subproject. Constraint (2.3) guarantees that the minimum rate requirements $R_{k,min}$ are met. Constraint (2.4) implies that a subcarrier serves only one user such that the transmitted signals do not interfere with other users' signals. The total transmit power of BS and relay nodes is limited by the constraint (2.5). The object of assigning subcarriers and relays to all MS users with a proper power distribution to maximize the sum rate and fairness index is a mixed integer programming problem. Notice that the algorithm find the optimal solution of this problem is not known up to now and it is difficult to find a optimal solution in polynomial time if it is possible. Hence, we present low-complexity suboptimal algorithms that offer near-optimal performance for the problem in hand.

In fact, we propose two suboptimal algorithms to solve the resource allocation problem. The first algorithm called Algorithm A consists of 4 steps while the other algorithm (Algorithm B) has three steps. Steps 2 and 3 for both algorithms are the same. The difference between the two algorithms is the first step. The last step of Algorithm A is to fine-tune the relay allocation. Each source can have multiple cooperative relay nodes and is determined in a per-subcarrier fashion. A subcarrier is limited to have at most one relay node but the local optimal relay node can always be selected for transmission. For more detail of algorithm A and B, please refer to the report of this subproject.

To show the advantage of the proposed algorithm, we compare the sum rate and fairness performance of our algorithms with that of the Awad-Shen (AS) algorithm [21]. Because the AS algorithm considers amplify-and-forward cooperative relay and allow each source to use at most one relay node, we modify it so that the comparison with ours is as fair as possible. We consider a network with four MS nodes that are random distributed within a 120-degree section of the 600-meter radius circle centered at the BS. The relay stations are placed on a circle with a 200-meter radius with a equal angular spacing. Each transmitted signal experiences attenuation with a path loss exponent value of 3.5 and, in any direct or relay link, each subcarrier suffers from independent Rayleigh fading.

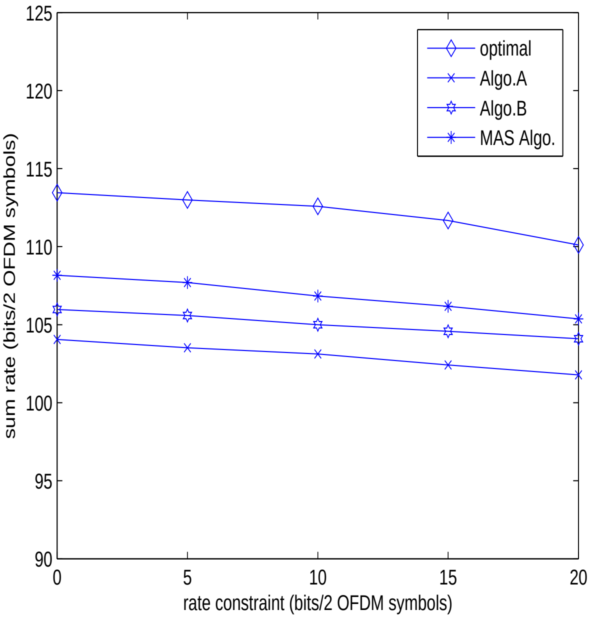

Figure 2.4: Comparison of the sum rate performance for the proposed algorithms and the AS algorithm; 2 MSs, 3 relay nodes, $N = 8$, $P_T = 80$, BER $= 0.001$.

In Fig. 2.4 and Fig. 2.5 we compare our algorithms to optimal sum rate and the algorithm in [21]. We consider the system contains 2 MSs and 3 relay nodes. The number of subcarriers are 8, the total power is 80 W and the BER is 0.001. We find that our algorithms achieve about 94% of the optimal sum rate but the corresponding fairness indices are significant better than that offered by the optimal sum rate algorithm. The sum rate of MAS algorithm is about 5% higher than that of our algorithms while our fairness index performance is also much improved.

To sum up, in the second year, two algorithms that maximize the sum rate and fairness index while meeting the individual user's minimum rate and QoS (bit error rate) requirements are proposed. No practical optimal solution to the problem discussed here is known, the computational complexities of our algorithms are only moderate but is much less than that of exhaustive search approach.

In the final year, we consider the resource allocation problem in MIMO-OFDM

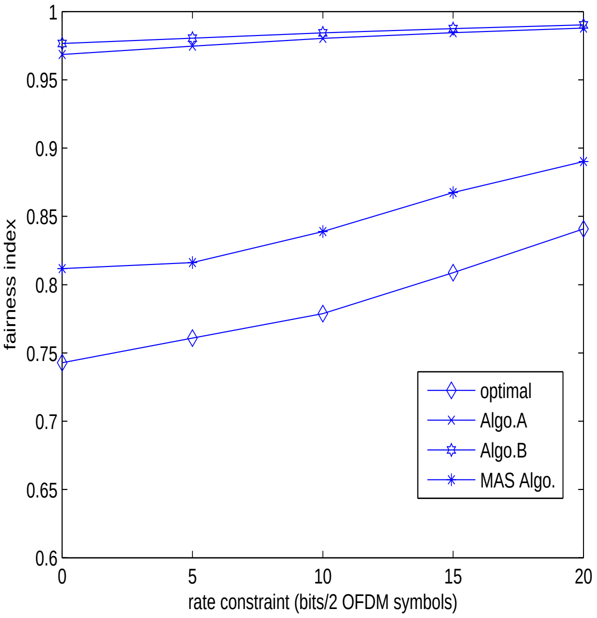

Figure 2.5: Comparison of the fairness performance for the proposed algorithms and the AS algorithm; 2 MSs, 3 relay nodes, $N = 8$, $P_T = 80$, BER $= 0.001$.

based wireless network. Adaptive resource allocation methods for maximizing the capacity or throughput have been proposed [22]-[26]. Taking users' QoS requirement into account, [27]-[31] proposed adaptive RA algorithms that minimize the total transmit power. These results either have the single-user-per-subcarrier constraint or the single (strongest)-eigenmode-per-subcarrier constraint. In contrast, the proposed new resource allocation schemes for MIMO-OFDM systems is free of these constraints and permit assigning eigenchennels on the same subcarrier to different users. Moreover, our schemes can be used for uplink and downlink transmissions.

To decouple multiple user signals over the same subcarrier at the receiver, we use the Singular Value Decomposition (SVD) for different users through proper linear combinations of the singular vectors. Based on the above concept, we propose an orthogonal precoding scheme for the MIMO-OFDMA systems. The advantage of the scheme is that resource allocation process is more easily because once the eigen-channel assignment is done, users can do their own bit and power management individually without consider other user' effects. However, the user number on the same subcarrier of the orthogonal precoding scheme will be bounded by the rank of the MIMO channel matrix such that the spectrum efficiency may be constrained. In order to improve the efficiency of the radio resource utilization, we bring up another precoding scheme which not only provides orthogonal but also non-orthogonal eigenchannels for transmission. In this scheme, we allow more users to transmit data on the same subcarrier than the first scheme to improve spectrum efficiency.

For the first (orthogonal) scheme, we propose two adaptive resource allocation algorithms that take care of subcarrier assignment, pre-processing and post-processing vectors selection and bit allocation. They are designed to minimize the total power and meet each user's QoS requirement. Similarly, we propose an adaptive resource allocation algorithm for the non-orthogonal scheme according to its system structure. The adaptive algorithm also aims to minimize the total consuming power while each user's QoS requirement is guaranteed. In addition to the two SVD based precoding schemes we design, we also take the precoder with limited feedback into account. For such the codebook based precoding scheme, we perform subcarrier assignment and dynamic power loading in order to minimize the average BER.

We focus on the the comparison of orthogonal and non-orthogonal scheme here; more simulation results and discussions can be found in the report of this subproject.

The performance of the non-orthogonal precoding scheme and the orthogonal precoding scheme for downlink transmissions with different channel matrix rank value is shown in Fig. 2.6 and 2.7 respectively. The average power is normalized by that of the single-user case, i.e., when a single user has access to all eigenchannels and all subcarriers. We define the average power ratio at BER= B as :

$$P_B \quad = \quad 10\log_1 0\left(\frac{P_{ave,B}}{P_{ave,10^{-5},single}}\right)$$

where $P_{ave,B}$ represents the average transmit power for a given modulation scheme at

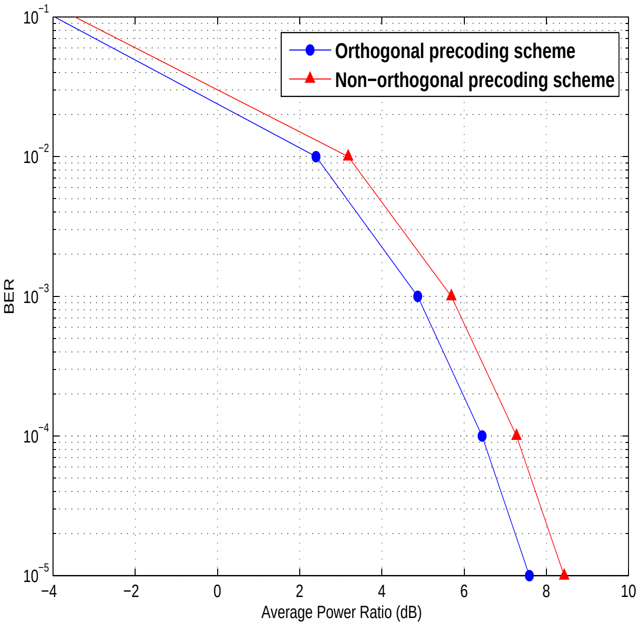

Figure 2.6: Comparison of the sum rate performance for the proposed algorithms and the AS algorithm; 2 MSs, 3 relay nodes, $N = 8$, $P_T = 80$, BER $= 0.001$.

BER$=$ B and $P_{ave,10^{-5},single}$ represents the average transmit power for the single user case at BER$=10^{-5}$. We assume the number of the antenna at the BS and the MS are the same. The antenna number is from 3 to 5. Each entry of the channel matrix is i.i.d. zero-mean, unit variance complex Gaussian The system has eight different modulation modes, BPSK, QPSK, 8QAM, 16QAM, 32QAM, 64QAM, 128QAM and 256 QAM, respectively. For simplicity, we assume that the required data rate and BER are the same for all users. We can notice that when the rank of the channel matrix is 3, the performance of the non-orthogonal precoding scheme is about 1 dB worse than the orthogonal precoding scheme. However, when we increase the rank to 4, the performance of the nonorthogonal precoding scheme is better than the orthogonal precoding scheme by 0.7.

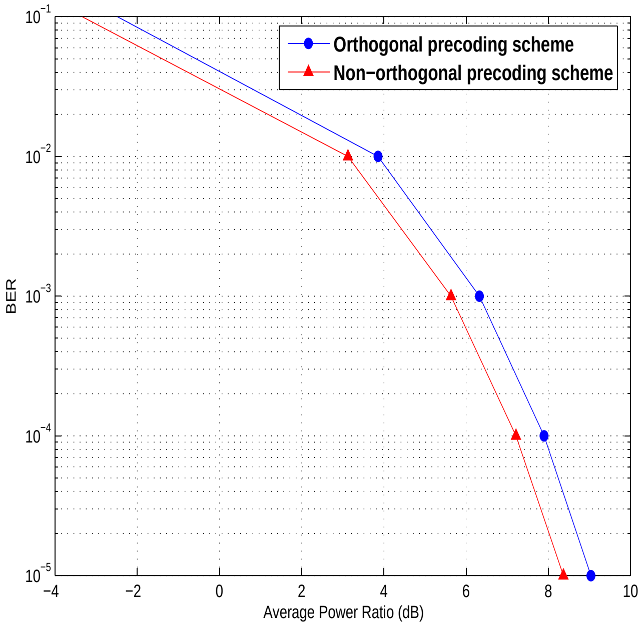

Figure 2.7: Comparison of the fairness performance for the proposed algorithms and the AS algorithm; 2 MSs, 3 relay nodes, $N = 8$, $P_T = 80$, BER $= 0.001$.

Chapter 3

Cooperative Cross-Layer Design in Cognitive Wireless Mobile Networks

This project focuses on the medium access control (MAC) protocol design for the uplink of wireless networks with multi-packet reception (MPR) capability and we summary the contributions of this project briefly. For more detail, please refer to the final report of this subproject.

In the first year, a multi-group priority queueing (MGPQ) MAC protocol is proposed. The proposed approach relies on flag-bit assisted knowledge about the presence of buffered packet as well as priority user grouping strategy. Specifically, a single flag-bit is appended on the tail of the transmitted packet for indicating the existence of the following packet in the buffer. The flag-assisted information can greatly simplify the channel access which can be reserved directly for the users with packets ready to transmit. Based on this process, two major performance bottlenecks inherent in the existing MPR MAC protocols can be overcome. First, the proposed solution can automatically produce the list of active users by observing the network traffic conditions, remove the need of active user estimation algorithm, and thus can largely reduce the algorithm complexity. Second, the packet blocking constraint imposed on the active users for keeping compliant with prediction is relaxed. Moreover, the proposed MGPQ is not only applicable to both homogeneous and heterogeneous (in traffic) cases, but also outperforms the existing MPR MAC protocols.

To show that the proposed MGPQ can improve the throughput, we consider a CDMA network with random spreading. The packetlength, spreading gain, number of correctable errors in a packet, and noise variance are, 200, 6, 2, and 10 dB as adopted in [14]. As illustrated in Fig. 3.1, the network throughput can be improved by about 40% for $p = 0.3$ and 14% average as compared with the well-known dynamic queue (DQ) MAC protocol [14], where the throughput is defined as the average of successful packet transmission per slot. S stands for the waiting period and the optimal waiting period selection is also investigated in this project. The delay performance, which is measured by the average elapsed time slots for a packet to be successfully received by central controller (CC), is compared in Fig. 3.2. The proposed method yields a smaller mean delay with light traffic ($p \leq 0.4$) since the MGPQ method tends to reserve the channel access for those who are more likely to have packets to send, thus avoiding the time latency incurred by the procedure of network-wide active user prediction. In heavy-traffic environment, the DQ protocol will block the incoming packets; hence, the mean delay is reduced. However, this make the larger packet loss ratio (PLR), which is defined as the average ratio of the number of blocked packets to the number of generated packets, as evidenced in Fig. 3.3.

Moreover, MAC protocol design for cooperative networks over MPR channels is investigated. There are two challenges in the design of cooperative MAC protocol for MPR channels. First the CC may require the knowledge of the MPR channels of all links, as well as the traffic conditions of all users, to determine the access set. This will call for extra communication overheads and will degrade the system-wide throughput, especially in a large-scale mobile network. Second, when packet reception failure occurs due to collisions, a certain portion of the users may have to serve as the relay for data retransmission. Without properly designed MAC protocol for cooperative user scheduling, there would be a large throughput penalty incurred by the latent of packet relaying phase. To our best knowledge, this has not been addressed in the literature.

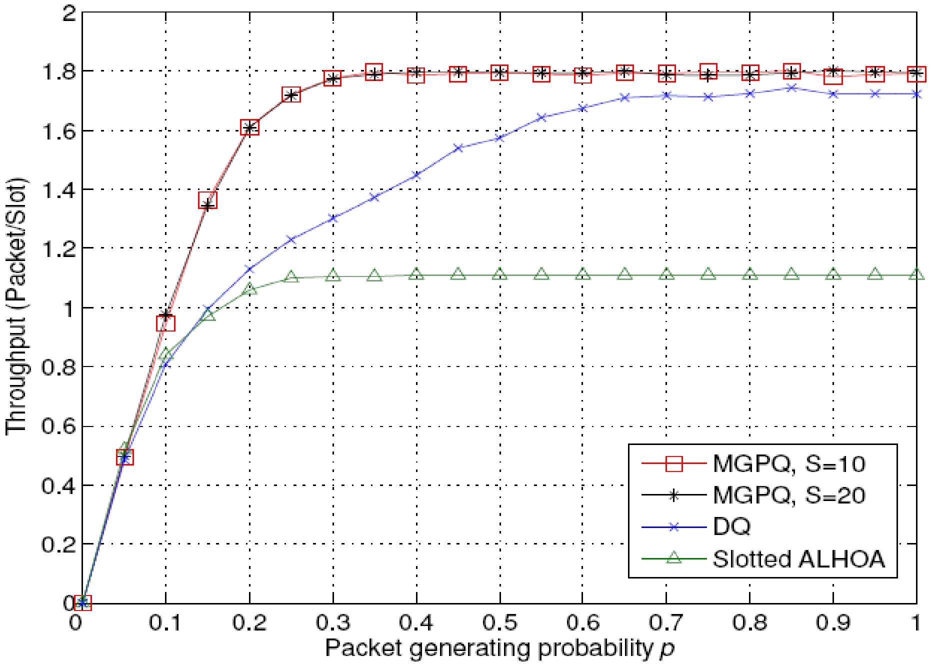

Figure 3.1: Throughput performance comparison between MGPQ and DQ. The slotted ALOHA with optimal retransmission probability[14] is also included.

Here, we propose a cooperative multi-group priority (CMGP) based MAC protocol to exploit the cooperation diversity for throughput enhancement over MPR channels. In the proposed scheme, the users are allowed to access the channel according to some prescribed service priority. There is no need for active user selection through exhaustive search over the channel knowledge and local traffic conditions. This will thus considerably reduce the communication overheads in dense cooperative networks. In addition, the flag-bit can provide the CC with the knowledge of each user's buffer status. Combined with the multi-group service priority, the channel access can then be reserved for both direct data transmission and packet relaying in a more balanced fashion. Hence, in a high collision environment, the throughput penalty incurred by the relay phase can be largely reduced.

By means of a Markov chain model, the worst-case throughput analysis is conducted. Specifically, we derive (i) a closed-form upper bound for the throughput penalty of the

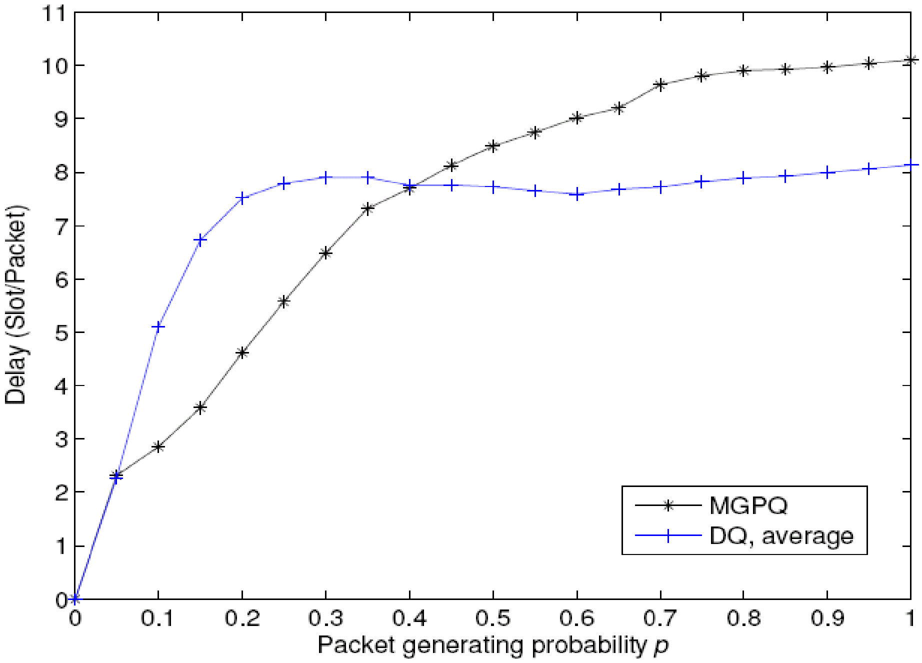

Figure 3.2: Delay performance comparison between MGPQ and DQ.

direct link that is caused by the interference of concurrent packet relay transmission; (ii) a closed-form lower bound for the throughput gain that a user with packet transmission failure can benefit thanks to cooperative packet relaying. The results allow us to investigate the throughput performance of the proposed CMGP protocol directly in terms of the MPR channel coefficients.

To show the enhancement of throughput via cooperation, we consider a CDMA network with random spreading. The packetlength, spreading gain, and number of correctable errors in a packet are, respectively, 200, 6, and 2. We assume that there are a total number of $M = 8$ users in the network, among which user 2, 4, 5, and 7 are nearby the CC and user 1, 3, 6, and 8 are located far away from the CC. Fig. 3.4 compares the throughput performance with $S = 4$ when the number of the near-end users participating in cooperative communication increase from one to four. The full operation, which means that all the eight users are involved, is also considered. As can be seen, the performance is improved with the increase of the number of near-end

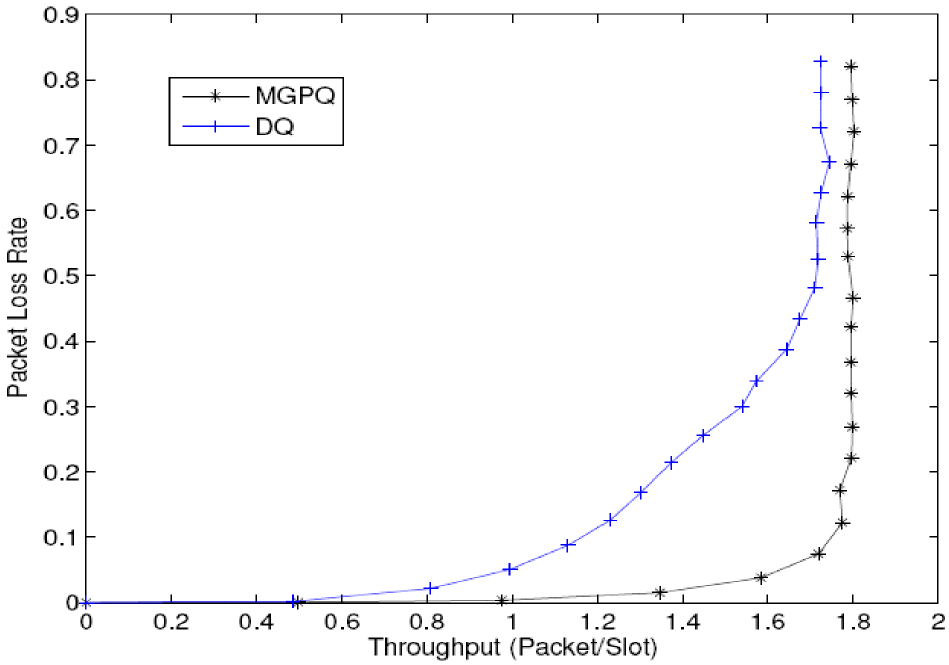

Figure 3.3: Packet loss ratio performance comparison between MGPQ and DQ.

user. Since the far-end user are typically subject to worse channel conditions, including them does not improve the performance significantly compared with four nearby users. Moreover, in a heavy traffic environment (large p, the packet generating probability), the channel access phase will be fully reserved for direct data transmission and idle periods are seldom available for cooperative packet relaying. Therefore, cooperation can not improve the performance significantly. For more discussions under various conditions, please refer to the chapter 3 in the report of the subproject 2.

Wireless channel is inevitably degraded with many kinds of fading. Probability density function based statistics, e.g. cell edge reliability and cell area reliability, are used to measure the effect of shadowing. However, in practice even one user with poor link may severely degrade the system throughput because the CC needs to allocate channel resource for such an inefficient access. To overcome the above problem, we propose a dynamic user set based on traffic (DUST) algorithm aiming for uplink throughput optimization in wireless networks with multi-packet reception in the second year. Specifi-

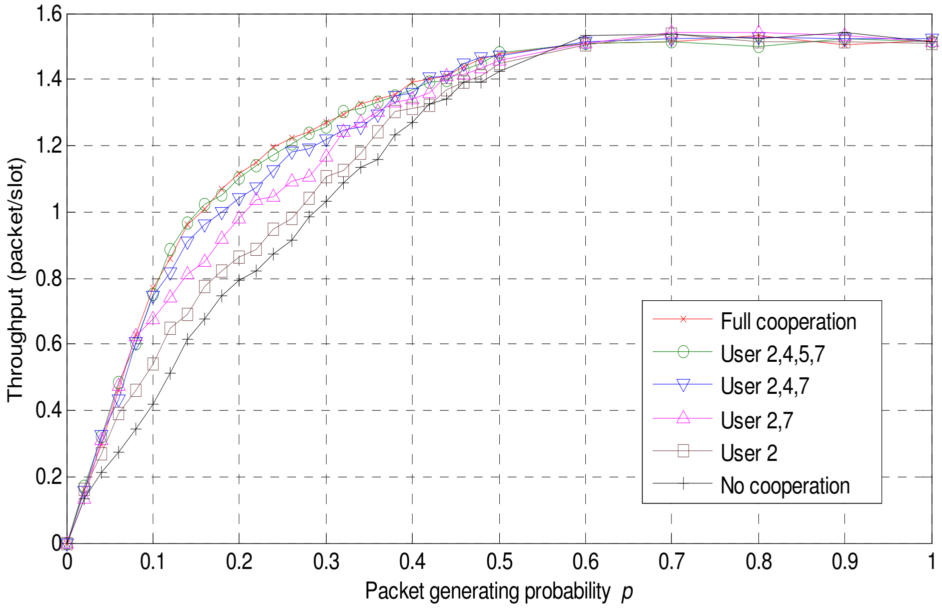

Figure 3.4: Throughput performance for different number of users participating in co-operation.

cally, when the traffic is light, CC will include more users into the set for channel access, and request the users in idle state to help relaying the packets from users with poor links. When the traffic becomes heavier, CC will remove the users, in order from the poorest link to the best link, out of user set to increase the overall system capacity.

Again, we consider a CDMA network with random spreading. The packetlength, spreading gain, and number of correctable errors in a packet are, respectively, 200, 6, and 2. 48 users are deployed in a grid distribution. Fig. 3.5 shows that by adapting the user set, the significant improvement in the network throughput is obtained.

In the final year, it is found that the traditional MPR matrices cannot reflect the channel dynamics in modern wireless communication networks when adaptive modulation and coding (AMC) mechanisms are adopted to improve the system performance. If AMC mechanisms are directly incorporated into MPR environments, the selected users and the associated transmission modes may not be optimal for the medium access control

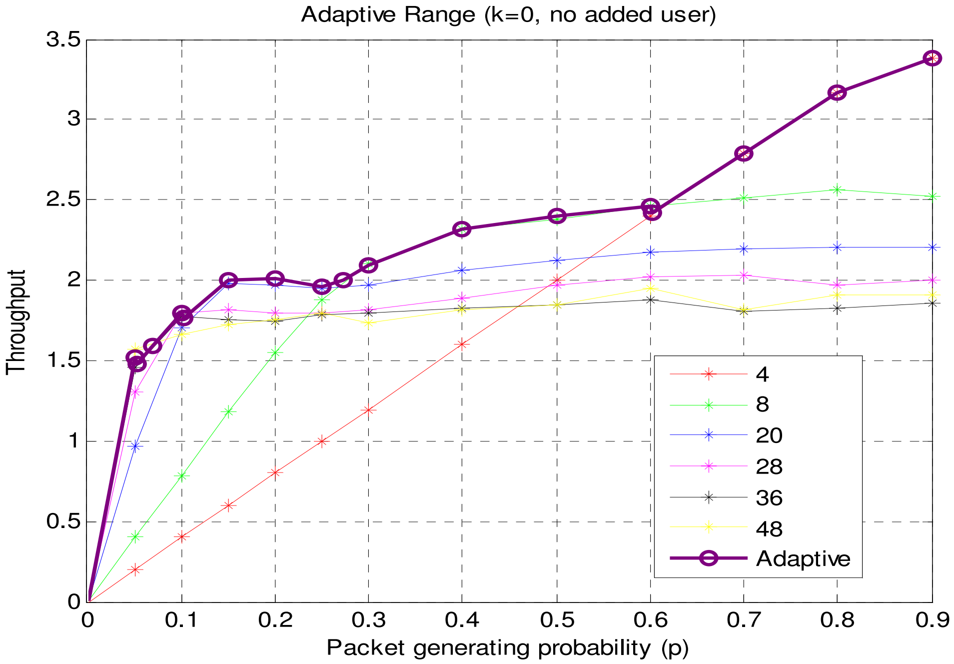

Figure 3.5: Throughput performance of the proposed DUST.

(MAC) layer to fully exploit the MPR capabilities of the physical layer, as illustrated in Fig. 3.6. Here, we consider two mode shown in Table 3.1. It can be observed that if the signal to interference ratio (SINR) is higher than the cross point (about 6.7 dB), the suitable mode is mode 2. On the contrast, if the SINR is smaller than the cross point, the suitable mode is mode 1, which shows that the optimal performance is not obtained by directly incorporating AMC into MPR networks.

Mode	1	2
Modulation	QPSK	16QAM
Coding rate	1/2	3/4

Table 3.1: Adopted modes

In this project, we propose a cross-layer design to jointly optimize the user selection and the corresponding modes, which can fully exploit the MPR capabilities while MAC layer performing the scheduling procedure. The basic idea of the proposed method is a reverse design from MAC to PHY. We try to find the optimal accessing user set selection

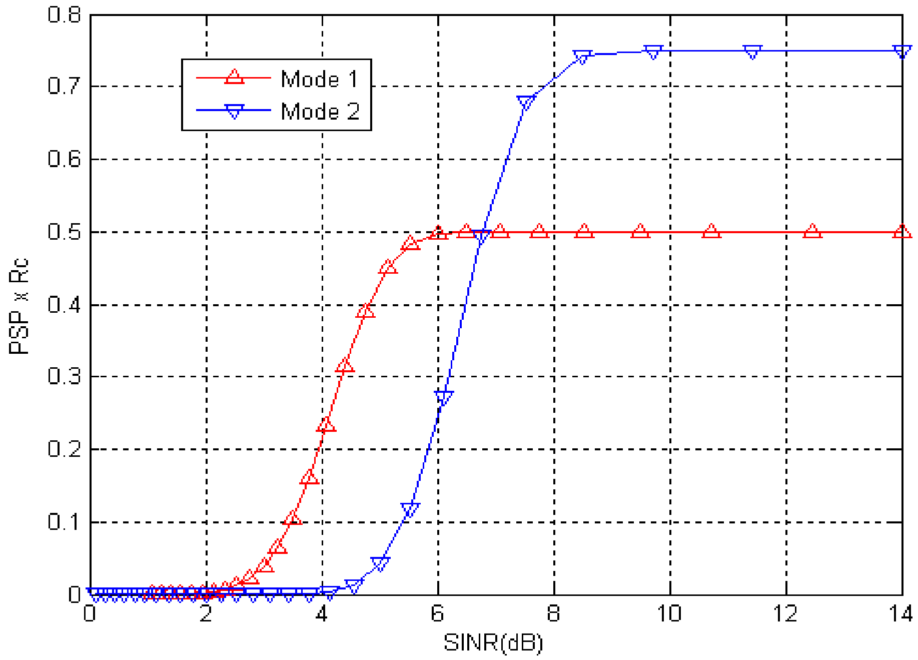

Figure 3.6: Throughput of adopted modes corresponding to different SINR.

and the corresponding transmission modes, and then the MAC layer reversely tells the physical layer which transmission mode should be adopted to fully exploit the MPR capabilities. Basically, the proposed method is a simple iterative method which tries every possible combination of user set and modes to find the user-mode combination that maximizes the average system throughput. Then, the scheduling procedure with the selected users and the corresponding modes is performed.

Similar to the previous simulation environment, we consider a CDMA network with eight users. For more consideration, please refer to the chapter 5 in the report of the project 2. The SNR level of the nearest and farthest user from the CC are 20 and 16, respectively. We compare the performance between the proposed method (joint AMC) and suboptimal methods (suboptimal AMC (k)). The suboptimal AMC k means that the MPR matrix is formed based on the parameters of mode k and the AMC is directly incorporated into MPR environment. From Fig. 3.6, the proposed method outperforms the other two suboptimal methods in the region $p > 0.45$ (p is the packet generating probability).

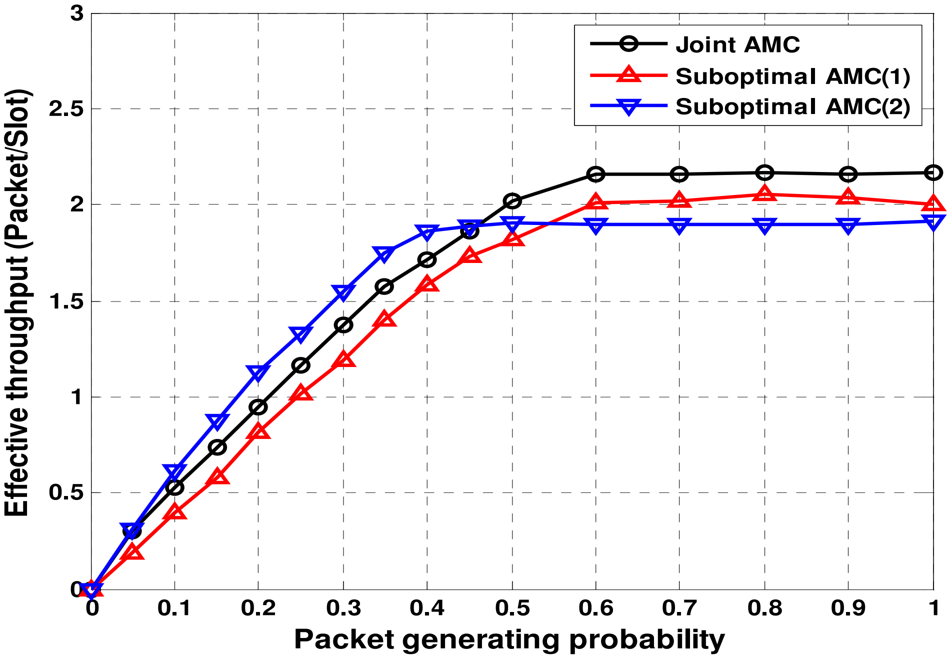

Figure 3.7: Throughput comparison between the proposed method (joint AMC) and suboptimal methods.

Chapter 4

Cooperative Routing Protocols and QoS Control in Cognitive Wireless Mobile Networks

The contribution of this project can be divided into two parts. In the first part, the spectrum handoff is investigated. In cognitive radio network, the second users need to sense the spectrum holes, which are not exploited by primary users, and transmit the information in these spectrum holes. In previous literature, the spectrum sensing is assumed to be perfect known and, in practice, the sensing time may be too long such that the throughput of primary user is reduced significantly. Hence, a partially observable markov decision process (POMDP)-based spectrum handoff scheme is proposed in this subproject. This scheme only require the partial observation and, therefore, the waiting time can be reduced significantly.

Specifically, the POMDP framework contains three parts, as shown in Fig. 4.1. The first component is the observation. Since not all the states are directly observable, a set of observations is essential to provide an indication about which state the environment should be located. This observation is usually related with actions and resulting states. The belief state is the second component, which comprises a sufficient statistical information for the past history, including all the actions and observations that can provide a basis for decision-making under environment uncertainties. Moreover, the belief state is updated after each corresponding action in order to incorporate one additional step of information into the history. The final component is the reward and value functions. It provides a measurement to evaluate the cost or to reward the update from each state such that the optimal decision is made. That is, the decision policy by exploiting the POMDP is determined by optimizing the reward and value functions. In general, the solution for the POMDP-based problem is obtained via optimization techniques.

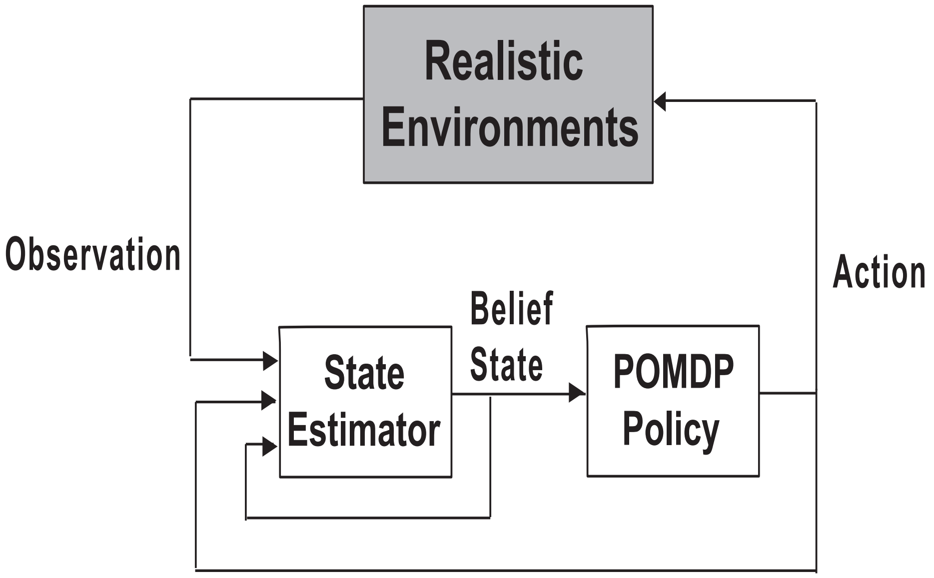

Figure 4.1: The schematic diagram of the POMDP framework.

For the spectrum handoff problem, the state of the ith spectrum in time slot k is either busy or idle state, according to the usage of primary users and the state of the whole spectrums comprises the state space in POMDP. An action at a time instant is to appropriately choose the target handoff spectrum from the entire spectrum. Since the purpose of the proposed POSH scheme is to reduce the waiting time, it is natural to define the waiting time as the cost function within the POMDP framework. Note that the time required for spectrum handoff of a CR (cognitive radio) user is defined as the time duration from the termination of packet transmission in one spectrum to the stating time of retransmission in another spectrum. To show the advantage of the proposed POSH scheme, we compare the POSH scheme with non-spectrum handoff (NSH) scheme and the randomly choose strategy (RCS). Fig. 4.2 shows the performance comparison of the number of waiting time slots versus the total number of spectrum handoff for the POSH and the RCS with three channels (spectrums). Two different channel conditions are considered. A better channel means that the transition probability from idle/busy to idle state is high such that the CR user can transmission with high probability. The NSH scheme is not included in this case since the CR user can always stay at the channel with better condition. As shown in Fig. 4.2, the total waiting time slots acquired from the proposed POSH scheme is smaller than that from the RCS scheme under both channel conditions and the POSH scheme can provide better performance as the the number of spectrum handoff is increased.

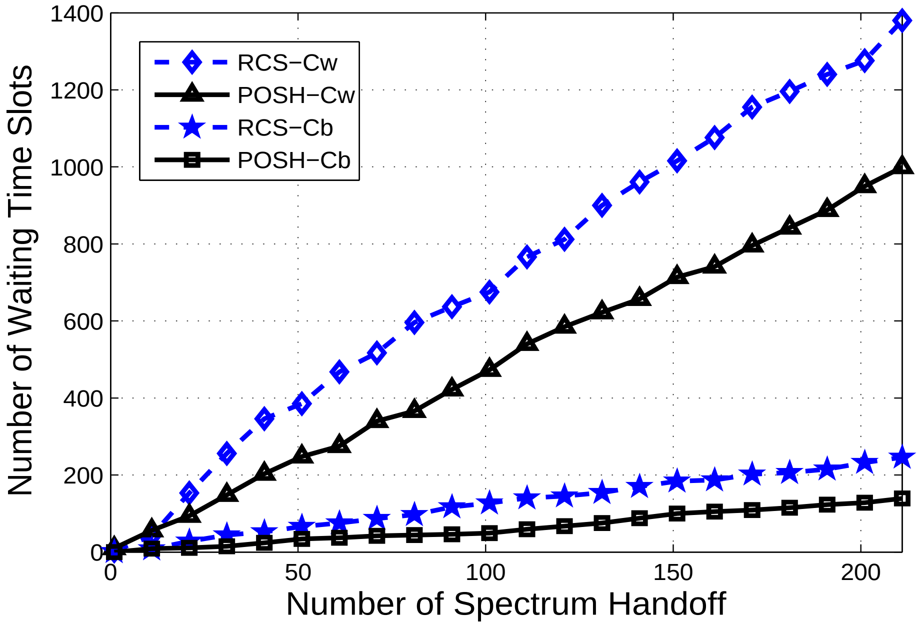

Figure 4.2: Performance comparison: number of waiting time slots versus number of spectrum handoff.

Fig. 4.3 shows the performance comparison among the POSH, the RCS, and the NSH schemes under different values of packet arrival rate of the primary user and 100 transmission time slots. It is obvious that the POSH scheme outperforms the other two methods under different packet arrival rates. The benefits from the POSH scheme is especially revealed at smaller packet arrival rates since there can be more opportunity for the POSH scheme to select a feasible target channel to conduct spectrum.

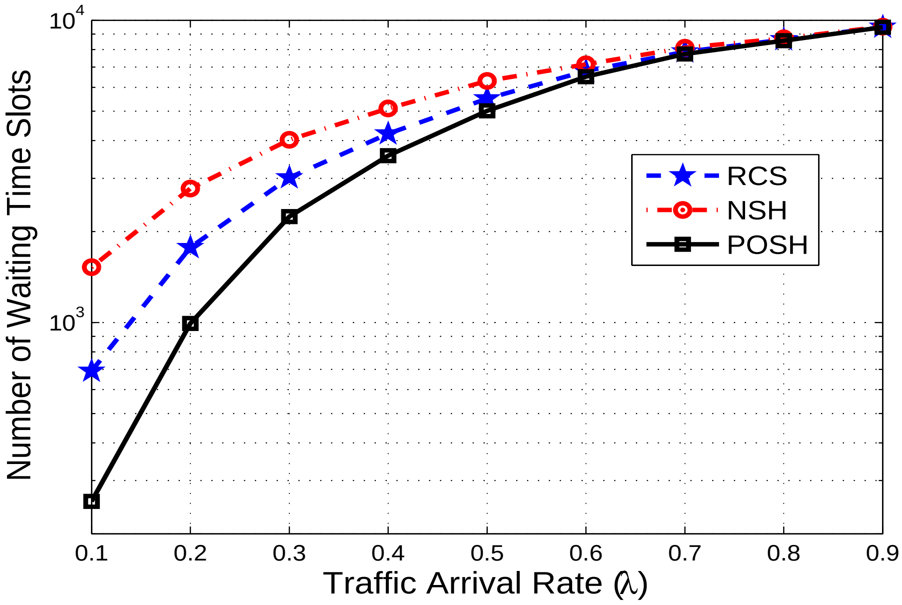

Figure 4.3: Performance comparison: number of waiting time slots versus traffic arrival rate of primary user under number of transmission time slots = 1200.

For more practical consideration and results about the POSH scheme, please refer to the report of this subproject.

In the POSH scheme, it is assumed that there is only one CR user in the network. It may, however, not be true and several CR users in a network is a more practical assumption. In this case, it is possible that more than one CR user will select an identical spectrum for spectrum handoff. Therefore, the packet collisions among the users will appear if the POSH scheme is applied directly in multi-user network. To alleviate this problem, a multi-user POSH (M-POSH) protocol is also proposed. The main purpose of the M-POSH protocol is to reduce the waiting time of network by ensuring that every possible spectrum hold can be fully exploited, whereas the fairness for channel access among all CR users can still be maintained. Specifically, the M-POSH protocol not only needs to consider the traffic of primary user but also requires to coordinate the channel access among the CR users. Instead of exchanging message among the CR users in distributed, a common control channel is exploited to exchange required information between the CR users. Fig. 4.4 shows the performance comparison with two CR users under different numbers of available channels. It is apparently to observe that the NSH scheme results in the same performance under different numbers of channels since it does not perform any spectrum handoff activity. On the other hand, regarding the RCS and M-POSH, the expected number of waiting time slot is decreased as the number of available channel is augmented. It is clear that the M-POSH scheme has the smallest number of waiting time slots for every number of channels since it adaptively select the channel based on the available of network channels. Moreover, it is also shown in the report of this subproject that the M-POSH scheme also has the smallest number of waiting time slots for every number of users (compared with RCS and NSH scheme).

The second part of the contribution is the investigation of the cooperative strategies. In previous researches (e.g. [32]-[34]), it has been shown that the cooperative communication can provides the cooperative diversity to enhance the diversity order. However, most of researches focus on cooperative communication from the viewpoint of information theory and physical layer design. In practical, the half-duplex antennas are adopted and it takes two phases to relay the signals for relay-based communication. Due to the additional phase, even the diversity is enhanced, the throughput may not be improved. This motivates us to investigate when to cooperate. Here, the backoff model (Markov model) of IEEE 80.11 MAC extended from [35], [36] is adopted to analyze the saturation throughput of cooperative techniques. It is assumed that there are one destination, one fixed relay, and N user nodes in the network considered in this project. The users in the network are adaptively categorized into non-cooperative and cooperative groups

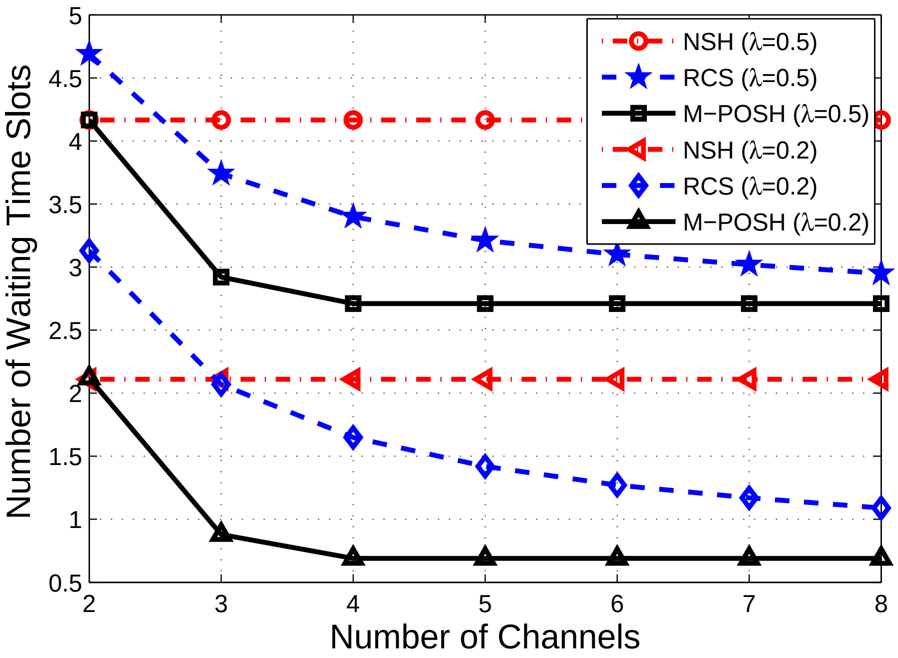

Figure 4.4: Performance comparison: number of waiting time slots versus number of channels (with two CR users).

depending on the transmission requirements.

Through the analysis and simulations, it is found that as the channel quality of direct link is good enough, transmission from the source directly to the destination is considered as a better choice since the decreased frame error rate (FER) resulted from cooperative communication may not be significant and the prolonged transmission due to cooperation can cause negative effect on the throughput. Hence, to design a cooperative MAC protocol with the consideration of delay is indeed important and practical topic. Moreover, it is found that as the source is suffering from severe fading channel and noises to the destination, a better source-relay channel is considered more important compared to the relay-destination channel in order to allow the destination to acquire the diversity. These results will further be explored in the design of cooperative MAC protocol.

In realistic situation, how to select an appropriate relay node among the available network nodes is also crucial for the improvement of network throughput. To optimize the throughput of the network, this factor should also be taken into account. Therefore, the objectives for the design of proposed cooperative MAC protocols consist of the following: (a) to determine if cooperative communication should be employed, and (b) to select a feasible relay node based on available relays within the network. According to the analytical study in this project, to determine the relay node and cooperation or not depends on the channel information at destination. Hence, an additional period (called CSI-acquiring period) should be inserted in order to acquire the channel state information (CSI) at destination. Then, as a source requires a relay node to help transmit signals, the destination will make a decision based on the CSI and make a response to source node. The decision rule can be obtained according to the analytical results in this project.

In the CSI-acquiring period, a control frame named relay ready-to-send (rRTS) is created to carry the channel information of source-relay link from the relays to destination, as shown in Fig. 4.5. It is designed to have the same structures as the CTS frame except that additional one-byte is added to store the channel information between source and relay and rRTS will be transmitted sequentially in a pre-determined order. Because the CSI of all links are available at destination node, this proposed protocol is called Full CSI based Cooperative (FCC) MAC protocol. However, the overhead caused by the FCC scheme can degrade the throughput performance as the number of available relays is significantly increased. To overcome this problem, making the CSI-acquiring period small is a possible way but this may result in the incompleteness of CSI at destination. Hence, a pre-specified length of CSI-acquiring period is provided for all the relays in the network to conduct relay contention process and only the winner, who has the best channel condition, will be the only relay to transmit its rRTS frame to the destination. It is possible that there are more than one relays has the best channel condition and 2-bit relay identifier is inserted to avoid potential collision under the situations that two relays may have the same channel information sequence. Since the relays contend in bit level

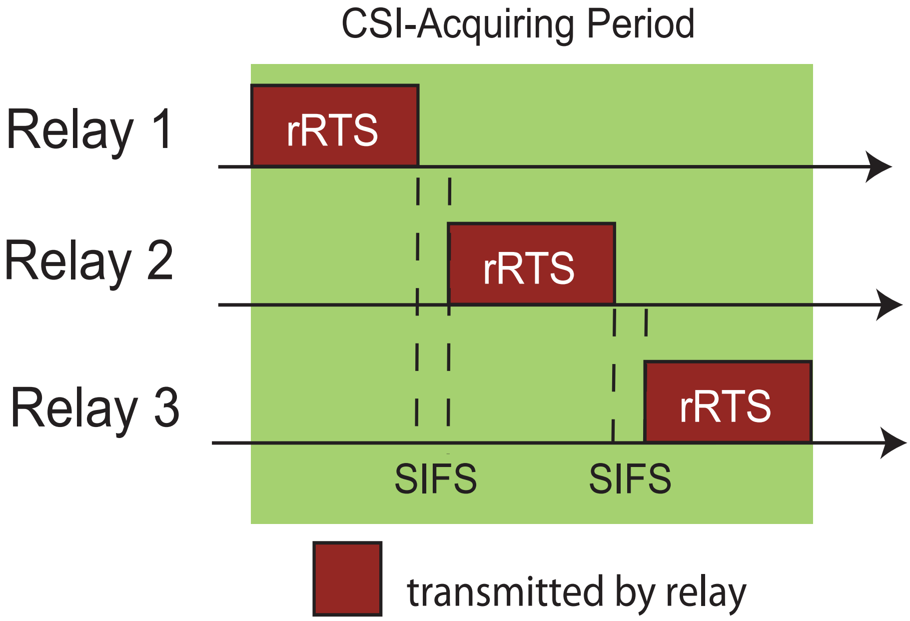

Figure 4.5: The schematic diagram of process in CSI-acquiring period with FCC protocol.

(every bit occupies one time slot), the proposed protocol is called bitwise competition based cooperative (BCC) MAC protocol. Simulation results show that both the proposed MAC protocols (FCC and BCC) can provide enhanced throughput performance compared to direct communication, especially under poor channel conditions.

Chapter 5

Cooperative MAC Protocol Design and User/Base Station Selection in Cognitive Wireless Mobile Networks

In this project, we investigate spectrum management techniques in cognitive radio (CR) networks with quality of service (QoS) provisioning. One fundamental issue in enhancing QoS performance for the secondary users is the multiple interruptions from the primary users during each secondary user's connection. These interruptions from the primary users result in the phenomenon of multiple spectrum handoffs within one secondary user's connection. Thus, a set of target channels for spectrum handoffs are needed to be selected sequentially.

In order to overcome the performance degradation issue due to multiple spectrum handoffs for the secondary users, various spectrum management techniques in CR networks are re-examined from a link connection quality perspective. There are four spectrum management functionalities in CR networks:

- Spectrum sensing: The secondary users should monitor all channels in order to capture channel characteristic and detect spectrum holes. Based on sensing results, the secondary users can find some candidate channels to transmit data. In this dissertation, we consider a fully-connected CR network. Hence, the transmitter and receiver of a secondary connection can have the same consensus on sensing results.

- Spectrum decision: The secondary users can select the best channel from many candidate channels to transmit data. This decision should take the traffic statistics of the primary users as well as the secondary users into account.

- Spectrum mobility: The secondary users must vacate the occupied channel when the primary user appears because the primary users have the preemptive priority to access channels. In order to return the occupied channel to the primary users and resume the unfinished transmission at the suitable channel, the *spectrum handoff* procedures are initiated for the interrupted secondary user.

- Spectrum sharing: The secondary users must coordinate their transmissions and avoid interfering with transmission of the primary users.

In this project, we focus on the spectrum decision, spectrum mobility, and spectrum sharing issues. In order to evaluate the system performance of the proposed spectrum management techniques, an analytical framework based on the preemptive resumption priority (PRP) M/G/1 queueing theory is developed to characterize the connection-based channel usage behaviors with multiple handoffs. We investigate the effects of multiple handoffs on the QoS performance and study the performance limitation of various spectrum management techniques in different traffic loads. Different from the traditional work which investigated the effects of multiple handoffs on the network throughput, this dissertation concentrates on the effects of latency performance of the secondary users. Based on the proposed analytical framework, some useful insights into the design of the spectrum management techniques can be provided and the traffic-adaptive spectrum management schemes can be developed according to traffic conditions such as traffic arrival rates and service time distributions.

In order to demonstrate the effectiveness of this analytical model, we discuss various spectrum management techniques, consisting of spectrum decision, spectrum sharing, and spectrum mobility. For the spectrum decision issue, we show how to determine which channels are required to probe and transmit. For the spectrum mobility issue, we illustrate how to characterize the effects of multiple handoffs, where the secondary users can have different operating channels before and after spectrum handoff. For the spectrum sharing issue, we explore how to determine the optimal admission probability to avoid the interference between primary and secondary users in the presence of false alarm and missed detection. From numerical results, we can develop traffic-adaptive spectrum management policies to enhance the QoS performance of the secondary users in CR networks with various traffic arrival rates and service distributions.

Chapter 6

Conclusion

In this report, we summary and show the main results of each subproject. In subproject 1, the impact of spectrum sensing error and the resource allocation problem for relay-based or MIMO-OFDMA systems are considered. In subproject 2, the MAC-protocol design for the uplink of wireless networks with multi-packet reception (MPR) capability are investigated under various physical layer structures. Spectrum handoff is also considered in subproject 3 and 4 via the different technologies. Partial observable Markov decision process (POMDP) is exploited in subproject 3 while Queuing theory is applied in subproject 4. Both of them aim to improve the throughput and spectrum efficiency. Moreover, in subproject 3, the opportunity to cooperate is studied and the associated protocols are proposed.

The results of this project are abundant and some of them have been either presented in a conference, published in a journal or under review. Here, we list these results below according to the order of subproject.

Subproject 1:

[37] J.-Y. Liu and Y.T. Su, "Performance Analysis of Transform Domain Communication Systems in the Presence of Spectral Mismatches" , in *Proc. Military Commun. Conf. (MILCOM),* Orlando, FL., USA, Oct. 28-31, 2007.

[38] Y.-S. Lu, Y.-B. Lin, and Y.T. Su, "Dynamic Resource Allocation for Relay-Based OFDMA Systems with Fairness Considerations," in *Proc. IEEE Wireless Commun. and*

Networking Conf. (WCNC), Sydney, NSW, Apr. 8-21, 2010.

[39] C.-L. Weng, Y.-B. Lin, and Y.T. Su, "Resource Allocation for MIMO-OFDMA Based Wireless Networks," in *Proc. IEEE Wireless Commun. and Networking Conf. (WCNC)*, Sydney, NSW, Apr. 8-21, 2010.

Subproject 2:

[40] W. F. Yang, J. Y. Wu, L. C. Wang, T. S. Lee, "A Multi-Group Priority Queueing MAC Protocol for Multipacket Reception Channel," *IEEE Wireless Commun. and Networking Conf. (WCNC 2008),* Las Vegas, USA, pp. 1673-1678, Apr. 2008

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Subproject 3:

[43] Rui-Ting Ma, Yu-Pin Hsu, Kai-Ten Feng, and Li-Chun Wang, "Stochastic Spectrum Handoff Protocols for Partially Observable Cognitive Radio Networks," major revision, *IEEE Trans. Veh. Tech.*

[44] Chun-Chieh Liao, Yu-Pin Hsu and Kai-Ten Feng, "Analysis and Determination of Cooperative MAC Strategies from Throughput Perspectives," major revision, *ACM Wireless Networks.*

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Subproject 4:

[47] L.-C. Wang, C.-W. Wang, and K.-T. Feng, "A Queueing-Theoretical Framework for QoS-Enhanced Spectrum Management in Cognitive Radio Networks," submitted to IEEE Wireless Communications Magazine.

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