# 國 立 交 通 大 學

## 電信工程研究所

## 博 士 論 文

# 多封包接收無線網路之上鏈媒體存取控制協定設計

# Medium Access Control Protocol Design for Uplink in Wireless Networks with Multipacket Reception Capability


研 究 生：楊 雯 芳

指導教授：李 大 嵩 博士

共同指導教授：吳 卓 諭 博士


中 華 民 國 九 十 九 年 一 月

# 多封包接收無線網路之上鏈媒體存取控制協定設計

# Medium Access Control Protocol Design for Uplink in Wireless Networks with Multipacket Reception Capability

研 究 生：楊雯芳　Student: Wen-Fang Yang
指導教授：李大嵩　博士　Advisor: Dr. Ta-Sung Lee
共同指導教授：吳卓諭　博士　Co-Advisor: Dr. Jwo-Yuh Wu

國立交通大學
電信工程研究所
博士論文

A Dissertation
Submitted to Institute of Communication Engineering
College of Electrical and Computer Engineering
National Chiao Tung University
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in
Communication Engineering
Hsinchu, Taiwan
January 2010

中　華　民　國　九 十 九　年　一　月

# 多封包接收無線網路之上鏈媒體存取控制協定設計

學生：楊雯芳　　　　　　　　　指導教授：李大嵩 博士

共同指導教授：吳卓諭 博士

國立交通大學電信工程研究所

## 摘要

本論文主要探討多封包接收（MPR）無線網路之上鏈媒體存取控制（MAC）協定設計，藉由一個簡單的旗標位元機制，吾人提出適用於多封包接收無線網路之多群優先佇列（MGPQ）媒體存取控制協定。多群優先佇列協定能夠克服現今多封包接收媒體存取控制協定設計的兩大瓶頸。首先，此法避免使用複雜的使用者狀態估測演算法，而依據封包接收狀況自動排序出使用者的可能活躍程度，進而大幅降低演算複雜度；其次，還就使用者狀態估測演算法所加諸於使用者的封包阻絕（blocking）限制也隨之解除。因此，多群優先佇列協定不僅可以適用於異質使用者的環境，同時性能也優於現今的多封包接收媒體存取控制協定。模擬數據顯示，相對於常見的動態佇列（DQ）媒體存取控制協定，多群優先佇列協定最多可以提昇 40%的系統吞吐量，平均而言，也有 14%的改善。

本論文接著將同質（homogeneous）通道的假設推廣為異質（heterogeneous）通道環境。協力式的媒體存取控制協定在多封包接收無線網路的設計上為一具挑戰性的議題，也尚未見諸於文獻上；吾人提出協力式多群優先佇列（CMGP），以利用空間多樣性（diversity）來提昇系統吞吐量，並利用使用者空閒（idle）的時間作封包的中繼傳輸，因此沒有一般中繼方式造成部分使用者吞吐量下降的缺點。此外，吾人也以馬可夫鍊（Markov Chain）針對最差情況作分析，推導出直接傳輸受到中繼傳輸干擾所引起的吞吐量損失上界，及中繼傳輸對失敗傳輸所提供的吞吐量增益下界。藉由上述推導的封閉解，吾人將可以直接經由實體層的多封包接收矩陣，計算協力式多群優先佇列的吞吐量性能。

無線通道不可避免地受到各種衰落（fading）而惡化，儘管吾人可利用以機率密度函數為基礎的統計量，例如蜂巢邊緣可靠度、蜂巢區域可靠度等來量測其影響，但實際上由於傳統的多封包接收媒體存取控制協定必須分配通道資源給每一使用者，因此單一個具有較差通道狀況的使用者都可造成整個系統吞吐量的惡化。本論文最後從系統吞吐量最佳化的觀點，提出基於流量的動態使用者集合（DUST）演算法，進一步改善整體系統吞吐量並已模擬加以驗證。

# Medium Access Control Protocol Design for Uplink in Wireless Networks with Multipacket Reception Capability

**Student: Wen-Fang Yang** **Advisor: Dr. Ta-Sung Lee**

**Co-Advisor: Dr. Jwo-Yuh Wu**

**Institute of Communication Engineering**
**National Chiao Tung University**

## Abstract

This dissertation focuses on the medium access control (MAC) protocol design for the uplink of wireless networks with multi-packet reception (MPR) capability. Relying on a simple flag-assisted mechanism, a multi-group priority queueing (MGPQ) MAC protocol is proposed. The proposed MGPQ scheme is capable of overcoming two major performance bottlenecks inherent in the existing MPR MAC protocols. 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. As a result, the proposed MGPQ is not only applicable to both homogeneous and heterogeneous (in traffic) cases, but also outperforms the existing MPR MAC protocols. Simulation results show that the network throughput can be improved by 40% maximum and 14% average as compared with the well-known dynamic queue (DQ) MAC protocol.

Subsequently the homogeneous channel is generalized into heterogeneous channel. MAC protocol design for cooperative networks over MPR channels is a challenging topic, but has not been addressed in the literature yet. In this dissertation, we propose a cooperative multi-group priority (CMGP) based MAC protocol to exploit the cooperation diversity for throughput enhancement over MPR channels. The proposed approach can bypass the computationally-intensive active user identification process. Moreover, our method can efficiently utilize the idle periods for packet relaying, and can thus effectively limit the throughput loss resulting from the relay phase. 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 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. Simulation results confirm the system-wide throughput advantage achieved by the proposed scheme, and also validate the analytic results.

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 central controller (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. Numerical results show significant improvement in the network throughput.

# Acknowledgement

I would never have been able to complete this dissertation without the help from many people. Foremost, I would like to express my deep gratitude to my advisors Prof. Ta-Sung Lee and Prof. Jwo-Yuh Wu, because they provided me with the platform to investigate the advanced wireless technology at National Chiao Tung University. I learned much from them to improve my research and working attitude, especially the insight into complicated issues. Special thanks went to Prof. Li-Chun Wang, who led me into the MAC field and encouraged me while facing difficulty and frustration. Of course, the valued comments from oral defense committee were highly appreciated.

I particularly appreciated my bosses, president Ming-I Wong and vice president Dr. Frank Hwang, in Tellus. They gave me maximal working flexibility to balance between company and school at the first two years.

I also want to thank all the members of Communication System Design and Signal Processing (CSDSP) Lab: Dr. Chih-Yuan Lin, Dr. Fang-Shuo Tseng, Kuang-Ming Lin, Wen-Chang Yu, Chester Huang, Wei-Sheng Lai, Hsien-Lee Pan, Shi-Yuan Liu, Wen-Chin Ouyang, and so on, for team work and sharing these years.

This dissertation is dedicated to my family, my father, mother, elder sister, and wife, for their unwavering support and endless love. I am very grateful to my lovely wife Candy Liao for her understanding and cheering.

Finally, "Glory to God in the highest, and on earth peace to men on whom his favor rests." (Luke 2:14)

# Contents

# List of Figures

# List of Tables

# List of Notations

| | |
|---|---|
| $\otimes$ | matrix Kronecker product |
| $E[y]$ | expected value of the random variable $y$ |
| $\Pr\{\ \}$ | probability |
| $X_{m \times n}$ | $m \times n$ matrix |
| $\mathbf{C}$ | matrix |
| $\lfloor\ \rfloor$ | floor function |
| $\lceil\ \rceil$ | ceiling function |

# List of Acronyms

| | |
|---|---|
| AF | Amplify-and-Forward |
| ALLIANCES | ALLow Improved Access in the Network via Cooperation and Energy Savings |
| AMC | Adaptive Modulation and Coding |
| BMDQ | Bit-Map assisted Dynamic Queue |
| CC | Central Controller |
| CDMA | Code-Division Multiple-Access |
| CMA | Cooperative Multiple Access |
| CMGP | Cooperative Multi-Group Priority |
| CoopMAC | Cooperative MAC |
| DF | Decode-and-Forward |
| DQ | Dynamic Queue |
| DUST | Dynamic User Set based on Traffic |
| FCFS | First-Come First-Served |
| FDMA | Frequency-Division Multiple-Access |
| MAC | Medium Access Control |
| MGP | Multi-Group Priority |
| MGPQ | Multi-Group Priority Queueing |
| MPR | Multi-Packet Reception |
| MQSR | Multi-Queue Service Room |
| OFDMA | Orthogonal FDMA |
| PHY | PHYsical |
| PLR | Packet Loss Ratio |
| PMP | Predictive Multicast Polling |
| PREM | PRe-EMptive |
| SPR | Single-Packet Reception |

| | |
|---|---|
| TDMA | Time-Division Multiple-Access |
| TP | Transmission Periods |

# Chapter 1

# Introduction

In this introductory chapter, some background materials about medium access control (MAC) in uplink/downlink transmissions, and multi-packet reception (MPR) are presented. What follow up are the literature survey, contributions and an overview of this dissertation.

## 1.1 Basics of MAC

Multiple access is a technique used to make best use of the transmission medium. In multiple access, multiple terminals or users share the bandwidth of the transmission medium. An efficient MAC mechanism is characterized by high throughput and low delay. A major concern in a MAC protocol is to decide which users are *allowed* to participate in each *simultaneous* transmission. Specifically, the MAC protocol may need to restrict the number of simultaneous transmissions in order to provide service to each user with acceptable quality.

A centralized network typically involves two-side communications, namely, downlink and uplink. The former is the transmission from the central controller (CC) to users, and the latter is the transmission from users to the CC. As all the packets of downlink are stored at the buffer of the CC, MAC can easily exploit the MPR capability of physical (PHY) layer due to the full knowledge about the packet status for all users. Nevertheless, there must be some specially designed mechanism for scheduling the uplink transmission due to the lack of full knowledge about the status of users' buffers in which the packets are stored as shown in Fig. 1.1. We will focus on the uplink in this dissertation.

Fig. 1.1 Schematic diagram of uplink transmission.

## 1.2 Basics of MPR

MAC is responsible for allocating communication bandwidth resources to multiple users. An essential requirement is the “separation” of users at the receiver in order to achieve effective multipoint-to-point communication. In practice, we want to allow users to transmit data simultaneously such that their transmissions can be separated at the receiver. However, such transmission simultaneity can be manifested in time, in space, in frequency, or in all of these domains. Which form of simultaneity is preferable depends on the cost and the application of the system. Different choices of transmission simultaneity lead to different user separation schemes (i.e., different methods to provide orthogonality). For example, in a frequency-division multiple-access (FDMA) system, users transmit data simultaneously from the time domain perspective but are separated in the frequency domain. In a code-division multiple-access (CDMA) system, users transmit data simultaneously in both time and frequency domains, but are separated in the "code" domain. Traditionally, the design of MAC protocols is based on the so-called collision channel model, that is, a transmitted packet is successfully received only when no concurrent transmission occurs. Such a paradigm, however, ignores the MPR capability at the PHY layer, for example, FDMA, orthogonal FDMA (OFDMA), CDMA, and multiuser detection [18].

## 1.3 Related Literature Review

Recently MAC protocols with the MPR capability draw increasing attention. Several proposals have been reported in the literatures. An initial attempt to reflect the MPR facility is the channel model with capture effect characterized via the probability of successful reception [17]. The impact of capture effects on various existing MAC protocols such as slotted ALOHA, and FCFS has been addressed in [8][29][30]. However, the capture model overall remains a simplified representation of the actual channel characteristics and does not explicitly account for the MPR capability. This thus motivates the development of more realistic MPR channel model [7], based on which several MAC protocols have been proposed for realizing various system-wide performance requirements. The multiqueue service room (MQSR) protocol [27] is, to the best of our knowledge, the first proposal which relies on the MPR model [7] for user scheduling. It calls for active user prediction via an exhaustive search over all the available network-traffic and PHY layer channel capacity information up to the current slot. However, as the total number of users increases, the number of search states grows exponentially thereby incurring high-computational complexity. Moreover, the transmission of the newly generated packets of selected users is not allowed in order to maintain the active user prediction determined via the previous network traffic, inevitably resulting in throughput degradation. The dynamic queue (DQ) protocol introduced in [28] delivers a large portion of performance gain attained by MQSR solution but at reduced complexity. By viewing the traffic as a flow of transmission periods (TP), the DQ protocol otherwise aims for minimization of the expected

TP duration by exploiting the MPR property. To further reduce the idle period of users with empty buffer, a modification of DQ scheme that includes active user identification at the receiver is subsequently introduced in [15]. In [6], a predictive multicast polling (PMP) scheme was proposed for the general finite buffer size. This approach relies on active user prediction slot by slot, and can significantly improve system throughput since packet blocking is no longer necessary. However, the computational complexity is still a concern. The bit-map assisted dynamic queue (BMDQ) protocol [22], which is essentially a modified DQ scheme, inserts an extra time-division multiple-access (TDMA) slot at the head of each TP for channel access/reservation request. However, such an overhead will reduce the bandwidth efficiency, especially when the number of users is large. The two major performance bottlenecks inherent in the existing MPR MAC protocols are the computational complexity and the packet blocking constraints. In order to optimize the number of concurrent transmissions, the CC may rely on an exhaustive search to estimate the buffer status of each user, thus resulting in a high-computational load. Second, the newly generated packets are not allowed to enter the buffer (hence blocked) for maintaining a static buffer status during each processing round.

Cooperative MAC protocol design can exploit multi-user diversity for network-wide performance enhancement, and has attracted considerable attention in the recent years [5][12]. The cooperation diversity can be exploited to improve system performance in both PHY and MAC layers. In PHY layer, many variant technologies based on amplify-and-forward (AF) and decode-and-forward (DF) are proposed. As in MAC layer, the special cooperative MACs such as CMA [16], CoopMAC [13], and ALLIANCES [26] are proposed. As shown in Fig. 1.2, the packet reception capability and cooperation diversity are never jointed together to design the MAC protocol. On the one hand it is difficult to take MPR capability into cooperative single-packet reception (SPR) MAC unless certain assumption, such as separate channels in [26], is assumed. On the other the existing non-cooperative MPR MACs are too complicated to further include cooperation into analysis. Most of the existing works, however, are devised exclusively for the collision channel model and do not

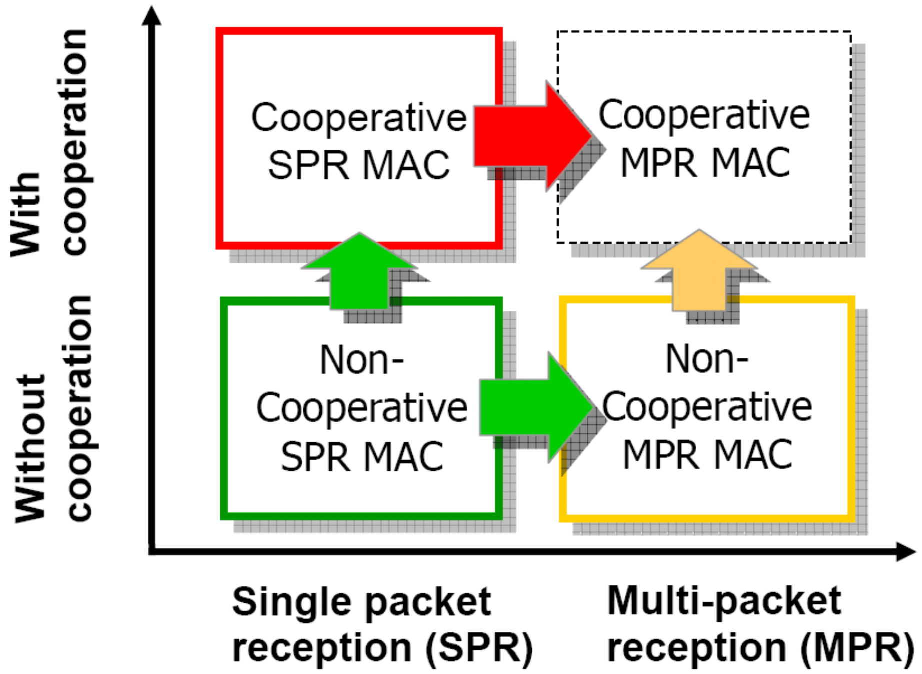



Fig. 1.2 Category of MAC.

exploit the MPR capability at the PHY layer [7][8][17][19][20][29]. Toward more efficient solutions, one promising approach is thus to further take the MPR advantage into consideration so as to gain full benefits from the PHY-layer processing.

## 1.4 Main Contributions

The contributions of this dissertation are summarized as three parts:

A. MPR MAC in homogeneous channels

1. A single flag-bit is appended on the tail of the transmitted packet for indicating the existence of the following packet in the buffer. This scheme provides the CC with the certain partial knowledge about the subsequent network traffic in a deterministic fashion. The flag-assisted information can greatly simplify the channel access which can be reserved directly for the users with packets ready to transmit. Note that the deterministic knowledge is only available for those users whose packets are successfully received by the base station. Although the

mechanism similar to the flag-bit may be available in the existing network protocol such as IEEE 802.11 [2], it is never exploited for facilitating the MPR MAC protocol design.

2. By exploiting the on-off flag signature, we propose to classify the users into three groups with different service priorities: the ACTIVE group consisting of the users with packets to send, the STANDBY group consisting of those with empty buffers, and the PRe-EMptive (PREM) group accommodating those who have stayed in the STANDBY or the ACTIVE group longer than certain waiting period. The users in the ACTIVE group are guaranteed to have packets waiting for transmission. However, those users in the STANDBY group are NOT guaranteed to have no packets waiting for transmission, because there may be packets generated after last successful transmission (note that the successful transmission is the only way for the users to convey the flag-bit information to the CC). The inclusion of the complementary PREM group is to avoid unfair scheduling that can occur in a binary grouping strategy. (If there are merely two groups, users in the STANDBY group would suffer an unlimited service delay since the channels could be constantly reserved for some ACTIVE links with heavy traffic.) With the trigroup user classification scheme, the priorities of service (from high to low, respectively) are PREM, ACTIVE, and STANDBY. The proposed method integrates the deterministic knowledge of those users in the ACTIVE group and the estimated states of those users in the STANDBY group to derive the optimal waiting period for the PREM group.

3. Through a Markov chain model of the proposed protocol and an associated analysis of the steady-state transition probabilities, we propose a method for determining the optimal waiting period, subject to the constraint that a uniform mean delay requirement among all users must be met.

4. In the proposed scheme, the number of users permitted for channel access is deterministically set to be that attaining the MPR channel capacity. This prevents the channel from being overloaded and hence avoids irrecoverable packet collision in a heavy traffic environment.

B. MPR MAC in heterogeneous channels

1. The proposed protocol is, to our best knowledge, the first cooperative MPR MAC scheme. It is free from any assumptions on the channel and is applicable to the general heterogeneous environment [26].

2. The number of users permitted for channel access is deterministically set to attain the MPR channel capacity. This prevents the channel from being over-loaded, thereby avoiding irrecoverable packet failure due to collisions.

3. Based on the Markov chain model, the throughput performance in the worst-case scenario is analytically characterized. Specifically, we derive 1) a closed-form upper bound for the throughput penalty of the direct-link user that is incurred by the interference of relay packet transmission; 2) a closed-form lower bound for 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 cooperative multi-group priority (CMGP) protocol directly in terms of the MPR channel coefficients. Also, simulation study evidences that the proposed CMGP protocol results in a system-wide throughput advantage.

4. In the proposed CMGP protocol there is a threshold for the waiting time slots above which the idle users are permitted for channel access. Again based on the Markov chain model of the proposed protocol and an associated analysis of the state transition probabilities, we propose a method for determining the optimal period threshold, subject to the requirement that a uniform average delay of all users must be met.

C. Throughput Optimization

1. A theoretical channel capacity bound for a user set is derived, which reveals the importance of selection on user set.

2. A dynamic user set based on traffic (DUST) algorithm is proposed to optimize the system performance from throughput viewpoint.

## 1.5 Organization of Dissertation

The remaining of this thesis is organized as follows.

In Chapter 2, relying on a simple flag-assisted mechanism, a multi-group priority queueing (MGPQ) MAC protocol is proposed for the wireless networks with MPR. The proposed MGPQ scheme is capable of overcoming two major performance bottlenecks inherent in the existing MPR MAC protocols. 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. As a result, the proposed MGPQ is not only applicable to both homogeneous and heterogeneous (in packet generating probabilities) cases, but also outperforms the existing MPR MAC protocols. Simulation results show that the network throughput can be improved by 40% maximum and 14% average as compared with the well-known DQ MAC protocol.

Chapter 3 generalizes the homogeneous channel into heterogeneous channel. MAC protocol design for cooperative networks over MPR channels is a challenging topic, but has not been addressed in the literature yet. In this chapter, we propose a CMGP based MAC protocol to exploit the cooperation diversity for throughput enhancement over MPR channels. The proposed approach can bypass the computationally-intensive active user identification process. Moreover, our method can efficiently utilize the idle periods for packet relaying, and can thus effectively limit the throughput loss resulting from the relay phase. By means of a Markov chain model, the worst-case throughput analysis is conducted. Specifically, we derive 1) a closed-form upper bound for the throughput penalty of the direct link that is caused by the interference of concurrent packet relay transmission; 2) 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. Simulation results confirm the system-wide throughput advantage achieved by the proposed scheme, and also validate the analytic results.

In Chapter 4, a pre-processing algorithm is proposed to further improve the system throughput. As we know that wireless channel is degraded with three major factors: quasi-deterministic attenuation, shadow fading, and multipath 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 DUST algorithm aiming for uplink throughput optimization in wireless networks with MPR. Numerical results show significant improvement in the network throughput.

Finally, Chapter 5 concludes this thesis and discusses future extensions of this research.

# Chapter 2

# Multipacket Reception MAC Design in Homogeneous Channels

## 2.1 Overview

In this chapter, we propose a new approach to design the MAC protocol for wireless networks with MPR capability. The proposed approach relies on the flag-bit assisted knowledge about the presence of buffered packets as well as a priority user grouping strategy. The distinctive advantage of the proposed method is three-fold: 1) it is applicable to both the homogeneous and heterogeneous environments (in traffic), whereas almost all existing protocols developed for the MPR channel are exclusively tailored for the former case; 2) the insertion of a single bit facilitates the acquisition of network traffic condition with minimal bandwidth expansion; 3) the adopted user grouping policy avoids computationally-intensive search for the active user set as required in the existing protocols. To prevent an infinitely long service delay the waiting period of those yet-to-be-served users can be determined subject to a specified delay requirement. Simulation results show that, compared with the DQ protocol, the proposed scheme yields improved throughput, reduces the average delay penalty when the traffic condition is light, and yields a smaller packet loss ratio (PLR).

## 2.2 System Model

### 2.2.1 System Description

In the proposed system model, all accesses to the common wireless channel are controlled by the CC. At the beginning of each slot, the CC broadcasts an access set to inform the users who are allowed to access the channel in the current slot. Upon reception, the CC acknowledges the users whose packets are successfully received. Users who transmit packets but do not receive the acknowledgments assume their packets are lost, and will retransmit whenever they are enabled. At the end of this slot, the CC updates the access set by the proposed multi-priority grouping strategy. In this dissertation, it is assumed that feedback acknowledgement channel (from the CC to the users) is error free and the incurred time delay is negligible. As in [28], we assume that each user has a buffer of size two. We propose to append one flag-bit on the tail of the transmitted packet for indicating if there is a following packet in the buffer. The extra flag-bit has the advantage to provide explicit information about the incoming traffic condition, as discussed next.

### 2.2.2 MPR Channel

Following [28], the MPR channel matrix for $M$ users is described as

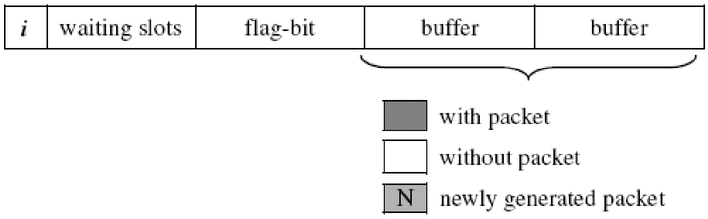
$$\mathbf{C} = \begin{bmatrix} C_{1,0} & C_{1,1} & & & \\ C_{2,0} & C_{2,1} & C_{2,2} & & \\ \vdots & \vdots & \vdots & \ddots & \\ C_{M,0} & C_{M,1} & C_{M,2} & \cdots & C_{M,M} \end{bmatrix}, \tag{2.1}$$

where

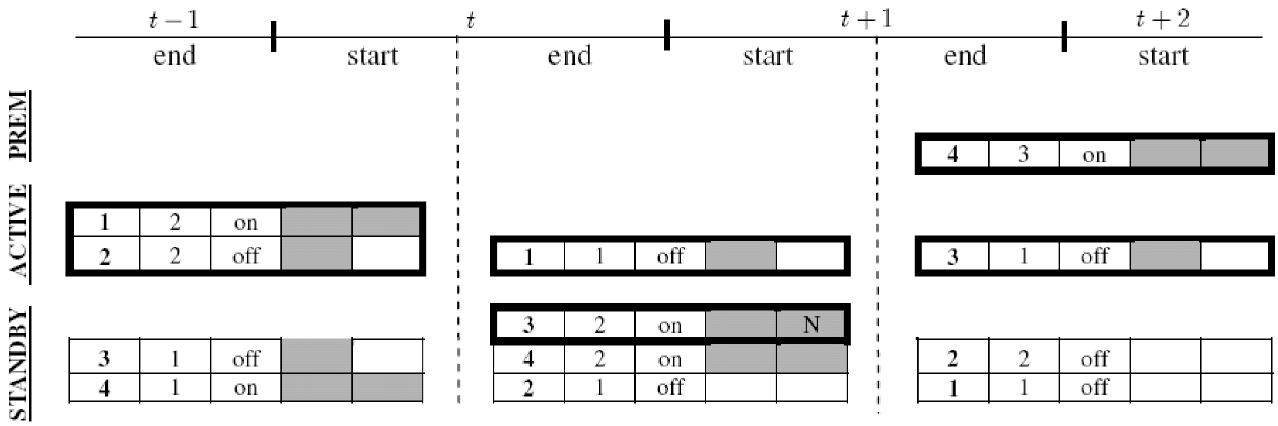
$$C_{n,k} = \Pr\{ k \text{ packets correctly received} \mid n \text{ packets transmitted} \}, \tag{2.2}$$

for $1 \le n \le M$ and $0 \le k \le n$. Denote $C_n = \sum_{k=1}^{n} kC_{n,k}$ the expected number of the correctly received packets when $n$ packets are concurrently transmitted. The capacity of an MPR channel is defined as $\eta = \max_{1 \le n \le M} C_n$. Note that the numbers of simultaneously transmitted packets to achieve the channel capacity may not be unique. Let

$$n_0 = \min\left\{ \arg\max_{1 \le n \le M} C_n \right\} \tag{2.3}$$




(a) The tag designating the status of the $i$th user, $1 \le i \le 4$.




(b) The priority grouping process within three consecutive time slots.

Fig. 2.1 An illustrative example of MGPQ with four users.

be the minimum amount of capacity-achieving packets. Hence the maximal number of users permitted to access the channel should be $n_0$, since there will be no further improvement in system capacity if more than $n_0$ users are simultaneously served. Note that the MPR matrix (1) can be determined via the physical layer performance metric such as bit error rate; an illustrative example based on CDMA communication can be found in [28].

## 2.3 Multi-Group Priority Queueing Protocol

### 2.3.1 An Illustrative Example

Fig. 2.1 shows an illustrative example for the proposed MGPQ protocol, where the total number of users is $M = 4$ and $n_0 = 2$ users are selected to simultaneously access the channel. In MGPQ, all users are classified into three different priority groups (PREM, ACTIVE, and STANDBY). The condition of the user $i$ is summarized in a tag as shown in Fig. 2.1(a), in which the first field represents user ID, second field is the count of waiting slots, third field marks the on/off status of the flag-bit, fourth and fifth fields represent the contents of the buffer. Fig. 2.1(b) depicts the operation of the proposed protocol during three consecutive time slots. At the end phase of slot $t-1$, there is no user in the PREM group, user 1 with two packets and user 2 with one packet are in the ACTIVE group, and user 3 with one packet and user 4 with two packets are in the STANDBY group. The detailed operations of the proposed MGPQ are described as follows.

1) At the start phase of slot $t$, with empty PREM group, users 1 and 2 in the ACTIVE group are selected for transmitting packets.

2) At the end phase of slot $t$,

   (i) upon successful packet reception, user 1 with flag-bit on in the start phase is retained in the ACTIVE group; the flag-bit is then switched off since there is no packet in the second buffer. User 2 is moved to the tail of the STANDBY group since the flag-bit is off;

   (ii) the waiting slots of both users 1 and 2 are reset to 1, and the waiting slots of the yet-to-be-served users 3 and 4 are increased to 2;

   (iii) user 3 has a newly generated packet in the second buffer, and the associated flag-bit is switched on.

3) At the start phase of slot $t+1$, there is no user in the PREM group and there is only one user in the ACTIVE group, so users 1 and 3 are selected.

4) At the end phase of slot $t+1$,

   (i) upon successful packet reception, user 1 is moved to the tail of the STANDBY group (flag-bit off). User 3 is moved into the ACTIVE group, and then flag-bit is switched off;

   (ii) both the waiting slots of users 1 and 3 are reset to 1, and the waiting slots of the yet-to-be-served users 2 and 4 are increased to 2 and 3 respectively;

   (iii) because user 4 has stayed in the STANDBY group for a certain waiting period $S=3$ (to be specified later), it is moved into the PREM group.

5) At the start phase of slot $t+2$, there is one user in the PREM group and one user in the ACTIVE group, so users 4 and 3 will be selected.

Table 2.1 Transition conditions among three different priority groups.

| From \ To | PREM (1st priority) | ACTIVE (2nd priority) | STANDBY (3rd priority) |
|---|---|---|---|
| **PREM (1st priority)** | • without getting permission to access the channel | • transmitted packet (flag-bit = 1) being successfully received<br>• transmitted packet not being successfully received, and previous flag-bit = 1 | • transmitted packet (flag-bit = 0) being successfully received<br>• transmitted packet not being successfully received, and previous flag-bit = 0<br>• no packet for transmission |
| **ACTIVE (2nd priority)** | • without getting permission to access the channel for $S$ slots | • transmitted packet (flag-bit = 1) being successfully received<br>• transmitted packet not being successfully received<br>• without getting permission to access the channel for less than $S$ slots | • transmitted packet (flag-bit = 0) being successfully received |
| **STANDBY (3rd priority)** | • without getting permission to access the channel for $S$ slots | • transmitted packet (flag-bit = 1) being successfully received | • transmitted packet (flag-bit = 0) being successfully received<br>• transmitted packet not being successfully received<br>• no packet for transmission<br>• without getting permission to access the channel for less than $S$ slots |

## 2.3.2 Proposed MGPQ Algorithm

The proposed MGPQ protocol is now stated as follows, and the resulting state transition conditions are summarized in Table 2.1.

(I) Put all users into the PREM group.

(II) Select first $n_0$ users (by the order of PREM, ACTIVE, and then STANDBY group) to access the channel.

(a) If the packet of a certain user is received successfully, then put the user to the tail of the ACTIVE (if the flag-bit is on) or STANDBY group (if the flag-bit is off). And reset its count of waiting slots to zero.

(b) If, for a certain user, the buffer is empty (no packet sent) or there is packet transmitted but not successfully received, and then put the user back to the tail of the STANDBY or ACTIVE group in which the user originally stayed.

(III) Increase waiting slots of all users by one.

(IV) Move those users with waiting slots equal to $S$ to the PREM group.

(V) Repeat steps (II) to (IV).

We note that, in the initial step, all users should be put in the PREM group rather than the STANDBY group. The rationale behind this choice is to avoid unfair scheduling when the packet generating probability is high. Indeed, if the protocol starts with all users in the STANDBY group, the first-selected $n_0$ users are likely to stay ACTIVE for a long time. The channel will thus be reserved for such ACTIVE users (with higher service priority), and those in the STANDBY group will then suffer a long delay.

### 2.3.3 Stability

System stability in the MAC design is extremely important since it guarantees all users with acceptable delays. A fixed packet arrival rate vector is stable if a transmission probability vector can be found to make all the queues in the corresponding system are stable [3]. However, it is difficult to derive the stability region for MPR protocols due to the complicated interactive queue behavior. Another approach to characterize the stability in the systems with finite buffer size is the absence of deadlock [4], or equivalently, all packets will be successfully received with finite delay. In this section, instead of finding the stability region, we will prove that the MGPQ MAC protocol is stable in terms of the finite delay criterion. According to the proposed protocol, the worst case occurs when a certain user is assigned with the lowest service priority in the STANDBY group while having two packets in the buffer. In this case, the second buffered packet will experience the longest service delay $d_{\max}$. To prove that the average of $d_{\max}$ is finite, we need the following two lemmas (the detailed proofs can be found in Appendices A and B, respectively).

**Lemma 2.1** Let $p_{ms}$ be the minimal probability that a packet can be successfully received. Then $p_{ms}$ is bounded away from zero. That is, there exists $\delta > 0$ such that $p_{ms} \geq \delta > 0$. □

**Lemma 2.2** Let $t_k$ be the total time slots elapsed after $k$ rounds of channel access ($k \geq 1$), and let $t_{\max}$ denote the maximal waiting slots for each access. Then we have

$$t_k \le k t_{\max}, \tag{2.4}$$

$$\text{where } t_{\max} = \begin{cases} \left\lceil \dfrac{M}{n_0} \right\rceil, \text{ if } 1 \le S \le \dfrac{M}{n_0} \\ S, \text{ if } \dfrac{M}{n_0} < S < \infty \end{cases}, \tag{2.5}$$

and $S$ is the waiting period. □

Based on the above two lemmas, the following theorem can be sustained.

**Theorem 2.1** The mean worst-case delay $E[d_{\max}]$ satisfies

$$E[d_{\max}] \le t_{\max}\delta^{-1} + \frac{M}{n_0}\delta^{-1} < \infty. \tag{2.6}$$

□

Proof: The mean worst-case delay can be expressed as $E[d_{\max}] = E[d_1] + E[d_2]$, where $E[d_1]$ and $E[d_2]$ are the averaged delays upon which the first and the second packets associated with the last-to-be-served user are successfully received, respectively. We first observe that

$$\begin{aligned} E[d_1] &= \sum_{k=1}^{\infty} t_k \Pr\{\text{1st packet successfully received in the } k\text{th round}\} \\ &\le t_{\max} \sum_{k=1}^{\infty} k \Pr\{\text{1st packet successfully received in the } k\text{th round}\} \\ &\le t_{\max}\left\{p_{ms} + 2p_{ms}(1-p_{ms}) + 3p_{ms}(1-p_{ms})^2 + \cdots\right\} \\ &= t_{\max}\sum_{k=1}^{\infty} k p_{ms}(1-p_{ms})^{k-1} \\ &= t_{\max} p_{ms}^{-1}. \end{aligned} \tag{2.7}$$

We note that the considered user will be moved to the ACTIVE group when the first packet is successfully received. In the worst-case, $d_2$ will incur when all the $M$ users are in the ACTIVE group. Therefore, the CC will assign users to access the channel in a round-robin way, and the average time slots elapsed per service round is thus $\frac{M}{n_0}$. Thus, it is implied that

$$
\begin{aligned}
E[d_2] &\le \binom{M}{n_0} p_{ms} + 2\binom{M}{n_0} p_{ms}(1-p_{ms}) + 3\binom{M}{n_0} p_{ms}(1-p_{ms})^2 + \cdots \\
&= \frac{M}{n_0}\sum_{k=1}^{\infty} k p_{ms}(1-p_{ms})^{k-1} \\
&= \frac{M}{n_0} p_{ms}^{-1}.
\end{aligned} \tag{2.8}
$$

Combining (2.7) and (2.8), we obtain

$$
\begin{aligned}
E[d_{\max}] &= E[d_1] + E[d_2] \\
&\le t_{\max} p_{ms}^{-1} + \frac{M}{n_0} p_{ms}^{-1} \\
&\le t_{\max} \delta^{-1} + \frac{M}{n_0} \delta^{-1} \\
&< \infty.
\end{aligned} \tag{2.9}
$$

□

Note that for those protocols with more than $n_0$ users allowed to access the channel simultaneously, deadlock may occur if $C_{n_0+i,0} = 1$ for $i \ge 1$. With the benefit from the fixed $n_0$ accesses, MGPQ is more robust in such a channel environment.

## 2.4 Optimal Waiting Period Selection

In the proposed protocol, the number of users permitted for channel access is fixed to be $n_0$, namely, the one attaining the MPR channel capacity. A natural criterion for determining the waiting period $S$ is to maximize the probability that each of the selected $n_0$ users has a packet to send. We first note the probability of the user $i$ (selected from PREM) with a packet to transmit after waiting a period of $S$ is at least [14]

$$
\tilde{p}_i := 1-(1-p_i)^S, \quad i \in \{1,2,\cdots,M\}, \tag{2.10}
$$

where $p_i$ denotes the packet generating probability of the user $i$. This implies that the larger the waiting period $S$, the more likely the users in the PREM group have packets to send. As a result, $S$ should be kept as large as possible. However, the unlimited increase in $S$ may incur severe delay penalty. Particularly if $S \to \infty$, the transition from STANDBY to PREM is prevented and the proposed trigroup priority queuing protocol degenerates into a bigroup scheme. To determine an $S$ for striking a balance between large $\tilde{p}_i$ and small delay, we propose to seek the optimal $S_{opt}$ with which the following set of constraints on the mean delay per user is satisfied:

$$D_i(S) \le D_r, \ 1 \le i \le M, \tag{2.11}$$

where $D_i(S)$ stands for the mean delay of the user $i$ and $D_r$ is a uniform delay requirement.

To find the desired $S$ from (2.11), one crucial step is to determine an explicit expression of $D_i(S)$ in terms of $S$. Toward this end, we shall determine all the possible transitions of states (an exact definition of a "state" will be specified later) in the proposed protocol. This can be solved by applying Markov chain analysis shown below.

### 2.4.1 Markov Chain

Associated with the user $i$ ($1 \le i \le M$), we define $x_i(t)$, $y_i(t)$, and $z_i(t)$ to be the assumed value of the waiting slots, the indication of the flag, and the number of packets in the buffer at the $t$th time slot, respectively. Hence we have $x_i(t) \in \{1, 2, \cdots, S\}$, $y_i(t) \in \{0, 1\}$, and $z_i(t) \in \{0, 1, 2\}$. (The waiting period $S \ge \left\lceil \frac{M}{n_0} \right\rceil$ and the buffer of size two are assumed hereafter if not specified otherwise.) Let us further collect $x_i(t)$, $y_i(t)$, and $z_i(t)$ for all users to form $X(t) = (x_1(t), x_2(t), \cdots, x_M(t))$, $Y(t) = (y_1(t), y_2(t), \cdots, y_M(t))$, and $Z(t) = (z_1(t), z_2(t), \cdots, z_M(t))$. The proposed protocol can be modeled by a Markov chain with state space

$$\Omega := \{E(t) | E(t) = (X(t), Y(t), Z(t)),\ t \geq 1\}. \tag{2.12}$$

We note that the number of states is at most $(S \cdot 2 \cdot 3)^M$. However, since in each time slot, exact $n_0$ users can simultaneously access the channel, it follows that (i) the number of "1" in $X(t)$ must be equal to $n_0$; (ii) no more than $n_0$ entries in $X(t)$ will assume the same value. Taking the above constraints into account and using the permutation and combination theory, the number of distinct outcomes of $X(t)$ is (see Appendix C for proof)

$$N_C = \frac{M!}{n_0!(M-n_0)!} \cdot \sum_{m_i} \frac{(S-1)!}{\prod_{i=0}^{n_0}(m_i!)} \cdot \frac{(M-n_0)!}{\prod_{i=0}^{n_0}(i!)^{m_i}}, \tag{2.13}$$

where the integers $m_i$'s are found as the solutions to the following equations:

$$\begin{cases} \sum_{i=0}^{n_0} i \cdot m_i = M - n_0 \\ \sum_{i=0}^{n_0} m_i = S - 1 \end{cases}. \tag{2.14}$$

With (2.13) and the constraint that there must be packet(s) in the buffer for the users in the ACTIVE group (i.e., $(y_i, z_i) \neq (1,0)$), the total number of possible states in the system can be reduced to

$$N_S = N_C \cdot 5^M. \tag{2.15}$$

If there exists some $p_i$ = 0 or 1, the total number of states will be further reduced.

### 2.4.2 State Transition Probability

We proceed to compute the state transition probabilities as follows. Assuming that the events of packet generation among users are independent, we have

$$\Pr\left\{E(t+1)=\left(\tilde{X},\tilde{Y},\tilde{Z}\right)\middle|E(t)=(X,Y,Z)\right\}=\prod_{i=1}^{M}P_x\left(\triangle x_i\right)P_y\left(\triangle y_i\right)P_z\left(\triangle z_i\right), \qquad (2.16)$$

where $\tilde{X}-X=\left(\triangle x_1,\triangle x_2,\cdots,\triangle x_M\right)$, $\tilde{Y}-X=\left(\triangle y_1,\triangle y_2,\cdots,\triangle y_M\right)$, and $\tilde{Z}-Z=\left(\triangle z_1,\triangle z_2,\cdots,\triangle z_M\right)$; $P_x\left(\triangle x_i\right)$, $P_y\left(\triangle y_i\right)$, and $P_z\left(\triangle z_i\right)$ are the probabilities of the increment of state components given $(X,Y,Z)$ (see Appendix D for details). Based on the state transition probabilities (2.16), we can immediately construct the transition matrix $\mathbf{T}_{N_S\times N_S}$, with which the steady-state probability $\pi_j$, $1\le j\le N_S$ can be readily obtained by

$$\lim_{t\to\infty}\mathbf{T}^t=\begin{bmatrix}\pi_1 & \pi_2 & \cdots & \pi_{N_S}\\ \pi_1 & \pi_2 & \cdots & \pi_{N_S}\\ \vdots & \vdots & \ddots & \vdots\\ \pi_1 & \pi_2 & \cdots & \pi_{N_S}\end{bmatrix}. \qquad (2.17)$$

In this dissertation, we assume that the above limit exists, and the assumption is justified by numerical results. The mean delay $D_i(S)$ can be then determined as follows.

### 2.4.3 Computation of Mean Delay

According to Little's law [11], we have

$$D_i(S)=\frac{N_i(S)}{\lambda_i(S)}, \qquad (2.18)$$

where $N_i(S)$ is the average number of packets in the buffer of the user $i$, and $\lambda_i(S)$ is the packet departure rate (i.e., throughput) of the user $i$. Let $z_{i,j}$ be the number of buffered packets of the user $i$ in the $j$th state, then we have

$$N_i(S) = \sum_{j=1}^{N_S} \pi_j z_{i,j} . \quad (2.19)$$

Also, denoted by $p_{B,i}(S)$ the packet blocking probability of user $i$, therefore

$$p_{B,i}(S) = \sum_{1 \le j' \le N_S, z_{i,j'}=2, i \notin A} \pi_{j'} + \sum_{1 \le j' \le N_S, z_{i,j'}=2, i \in A} \pi_{j'} (1 - P_S), \quad (2.20)$$

where access set $A$ and success probability $P_S$ are defined in Appendix D. Then it follows that

$$\lambda_i(S) = p_i (1 - p_{B,i}(S)). \quad (2.21)$$

Substituting (2.19) and (2.21) into (2.18), we can obtain a functional relation of $D_i(S)$ in terms of $S$. The solution to (2.11) can then be computed via numerical search.

### 2.4.4 Homogeneous Case

In the homogeneous environment, that is, the packet generating probabilities of all users are identical; it can be shown that the mean delay in (2.18) is independent of waiting period $S$ (the detailed proof is referred to Appendix E). An intuitive explanation of this phenomenon is that, when subject to the same packet generating probability, all users tend to share the same service priority, and hence experience the same average service delay irrespective of the choice of $S$.

### 2.4.5 Extension to Finite Buffer Case

Although the previous derivation is obtained under the assumption that each user has a buffer of size two, it can be easily extended to the case with finite buffer size $B$ by allowing $z_i(t) \in \{0,1,2,\cdots,B\}$. The $N_S$ in (2.15) must also be increased to $N_C(2B+1)^M$ accordingly. This case will be simulated and compared with other MPR MACs in the next section.

## 2.5 Numerical Results

In this section, simulations are carried out by Matlab and we first compare the results with the theoretical analysis for a simple scenario to validate the derivation in Section 2.4. In this dissertation, throughput is defined as the average of successful packet transmissions per slot; delay is defined as the average elapsed time slots for a packet to be successfully received by CC; PLR is defined as the average ratio of the number of blocked packets to the number of generated packets. Then in the heterogeneous case, the individual delay curves with increasing $S$ are plotted to show the effect of $S$ on system performance. In the homogeneous case, throughput, delay, and PLR of MGPQ are further compared with those of DQ. Finally, the throughput performance with more users and finite buffer size of MGPQ, PMP [6], and DQ [28] are compared to verify their scalability.

### 2.5.1 Validation of Analytical Results

This simulation aims at validating the analytical performance results in Section 2.4. The test system is a CDMA network with random spreading; the packet length, spreading gain, number of correctable errors in a packet, and noise variance are, respectively, 200, 6, 2, and 10 dB as adopted in [28]. The capacity of such an MPR channel in this scenario is 1.7925, which is attained by $n_0 = 2$ concurrent transmissions in each time slot. The total number of users is set to be $M = 3$. We note that the incurred overhead due to the insertion of a flag-bit is 1/201 < 0.005, which is rather small and is thus neglected in the performance evaluation. Figures 2.2 and 2.3, respectively, show the mean throughput and mean delay curves for the two scenarios: (i) the heterogeneous case with packet generating probabilities $[p_1, p_2, p_3] = [0.1, 0.1, 0.9]$, and (ii) the homogeneous case with an equal packet generating probability $p_1 = p_2 = p_3 = 0.5$. As we can see from the figures, in both cases the theoretical results well predict the corresponding simulated outcomes. It can also be seen that, in the homogeneous environment, the mean throughput and mean delays remain unchanged as the waiting period increases: this confirms the assertion in Section 2.4.4. For the heterogeneous case, we impose the mean delay requirement of each user to be less than 4 time slots;

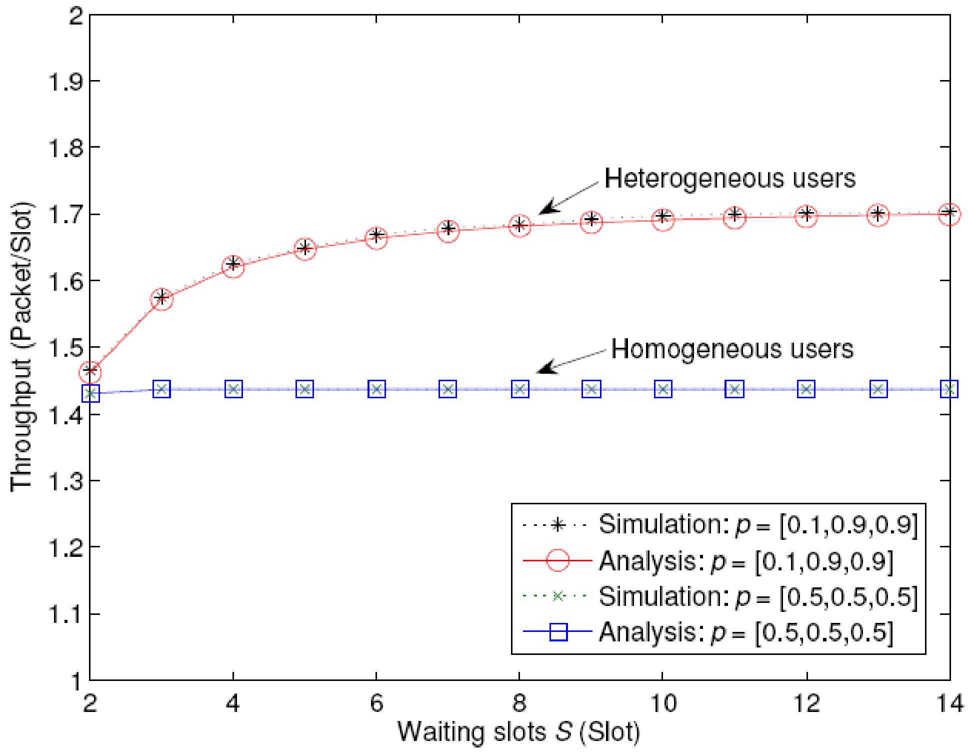



Fig. 2.2 Mean throughput performance of the proposed MGPQ.

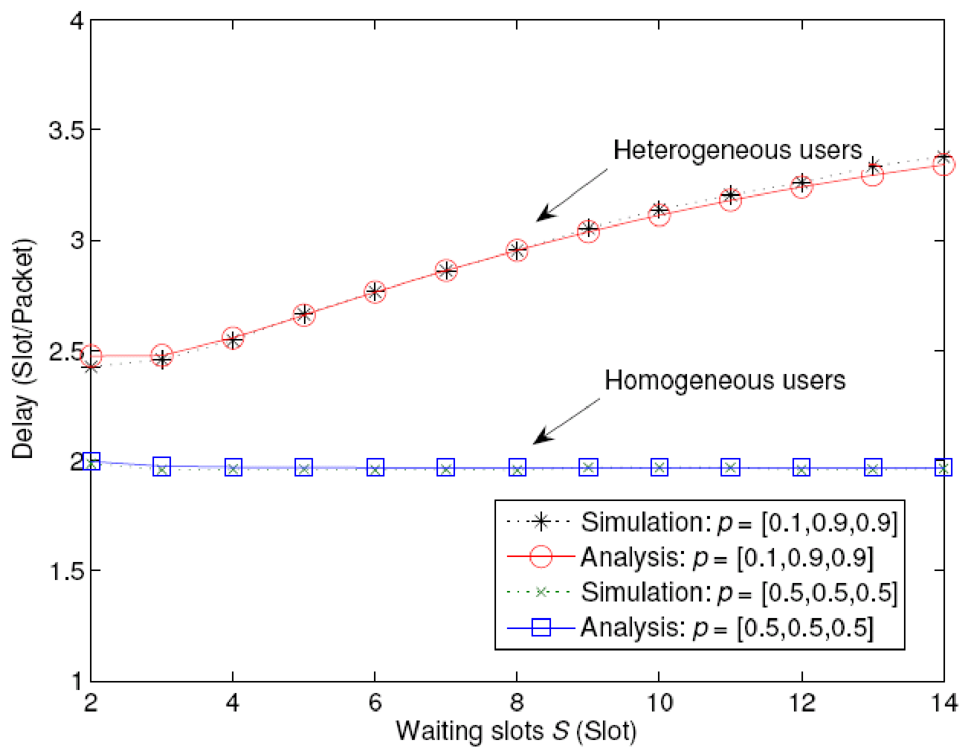



Fig. 2.3 Mean delay performance of the proposed MGPQ.

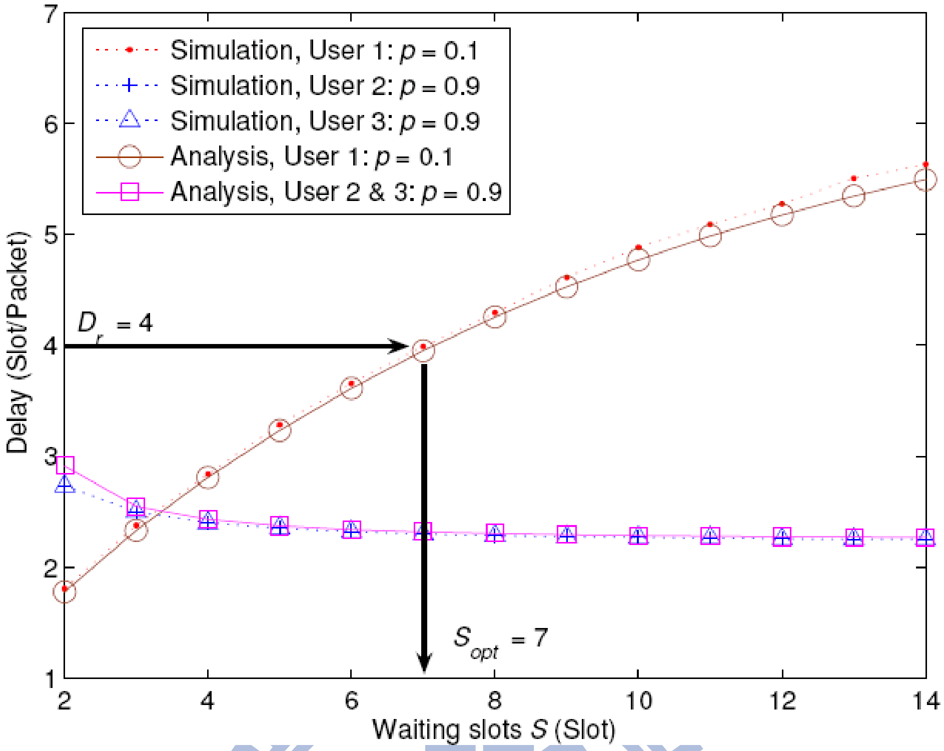



Fig. 2.4 Delay performance of individual users.

by using the results in Section 2.4.3, the optimal waiting period is computed to be $S_{opt} = 7$. Fig. 2.4 depicts the mean delay of each user. It can be seen that the delays of all the three users are indeed kept below 4 when $S = S_{opt} = 7$. We also note from Fig. 2.4 that users with large (or small, respectively) packet generating probabilities $p_i$ experience less (or more) delay. This is not unexpected since, if $p_i$ is large, the flag-bit will be on with a high probability and the user will be allowed for accessing the channel more frequently.

### 2.5.2 Comparison with Previous Work [28]

This simulation further compares the proposed MGPQ scheme with the DQ protocol [28]. We will consider the homogeneous case since the DQ protocol is exclusively tailored for this scenario. The respective throughput curves, including the slotted ALOHA with optimal retransmission probability [28], are plotted in Fig. 2.5. As we can see, the proposed solution can outperform the

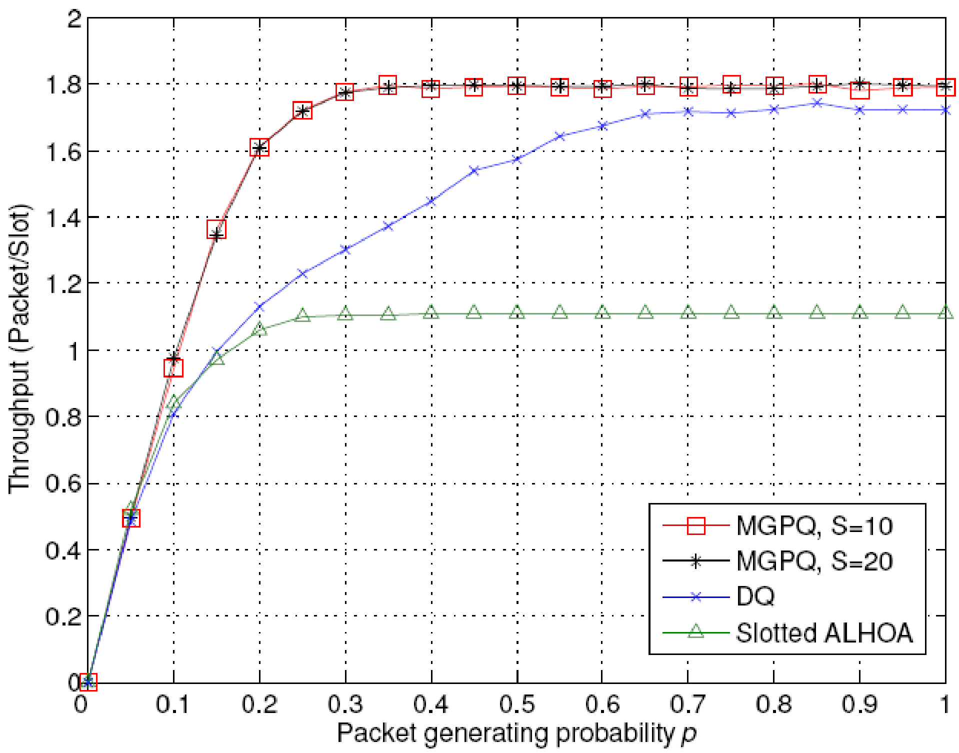



Fig. 2.5 Throughput performance comparison between MGPQ and DQ.

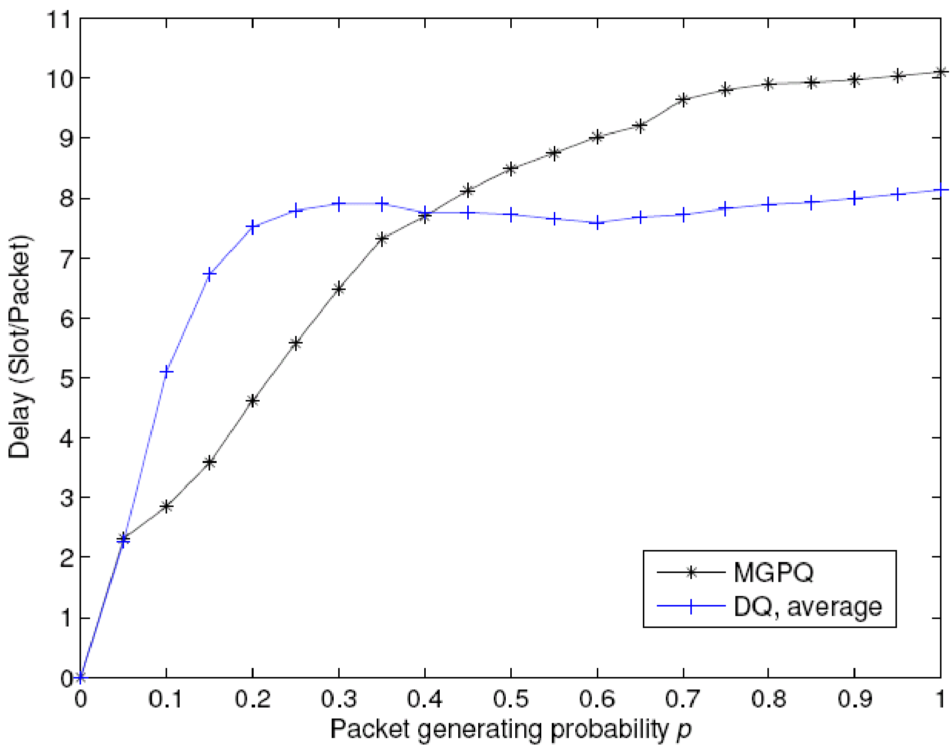



Fig. 2.6 Delay performance comparison between MGPQ and DQ.

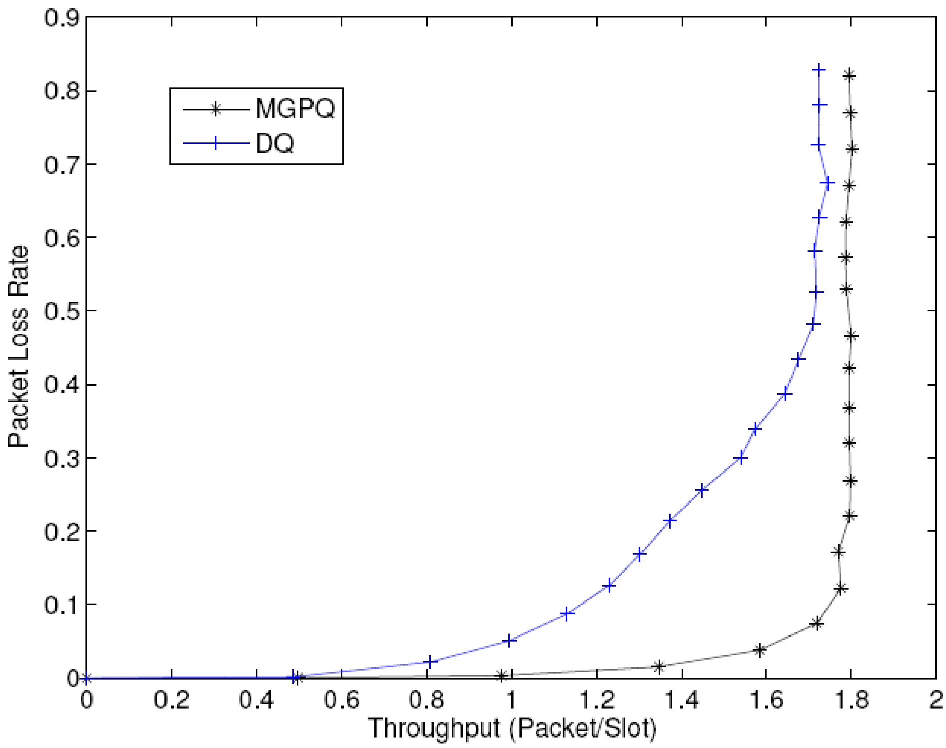



Fig. 2.7 Packet loss ratio performance comparison between MGPQ and DQ.

DQ protocol over a wide range of the packet generating probabilities. The maximal achievable throughput improvement is about 40% for $p = 0.25$. Also, the proposed approach almost achieves the channel capacity 1.7925 whenever $p \geq 0.3$, whereas the DQ protocol can attain at most 96% of the capacity for $p \geq 0.8$. Fig. 2.6 shows the delay performances (measured via time slots per packet) of the two schemes. As shown, the proposed method yields a smaller mean delay with light traffic ($p \leq 0.4$). This is because 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 a heavy-traffic environment, the DQ protocol will block the incoming packets, thereby reduce the mean delay. However, this comes at the expense of a larger PLR, as evidenced in Fig. 2.7.

### 2.5.3 General Case

In this simulation, we test the proposed protocol with finite buffer size, and compare the

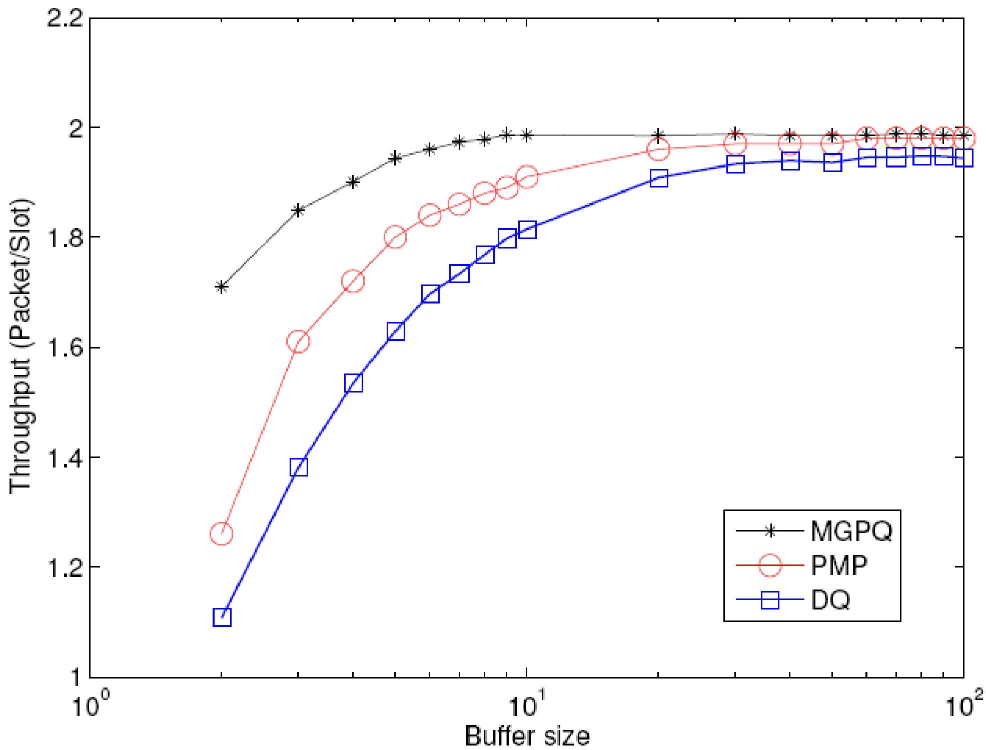



Fig. 2.8 Throughput comparison between MGPQ, PMP, and DQ for different buffer size.

performance with the DQ [28] and PMP [6] methods (the latter is specifically devised for the case with finite buffer size).We consider the system setup as in [6] which is described in terms of the MPR matrix as

$$\mathbf{C} = \begin{bmatrix} 0 & 1 & & & \\ 0 & 0 & 1 & & \\ 1 & 0 & 0 & & \\ \vdots & \vdots & \vdots & \ddots & \\ 1 & 0 & 0 & \cdots & 0 \end{bmatrix}, \tag{2.22}$$

thus with $n_0 = 2$, $\eta = 2$, and set the total traffic load to be the same with channel capacity. Fig. 2.8 shows the throughput curves of the three methods as the buffer size increases from 2 to 100. It is seen that the DQ scheme results in the lowest throughput, mainly due to the packet blocking constraint. The proposed MGPQ protocol outperforms the PMP solution, thanks to the benefits from the priority mechanism which can reduce the blocking rate especially when the buffer size is

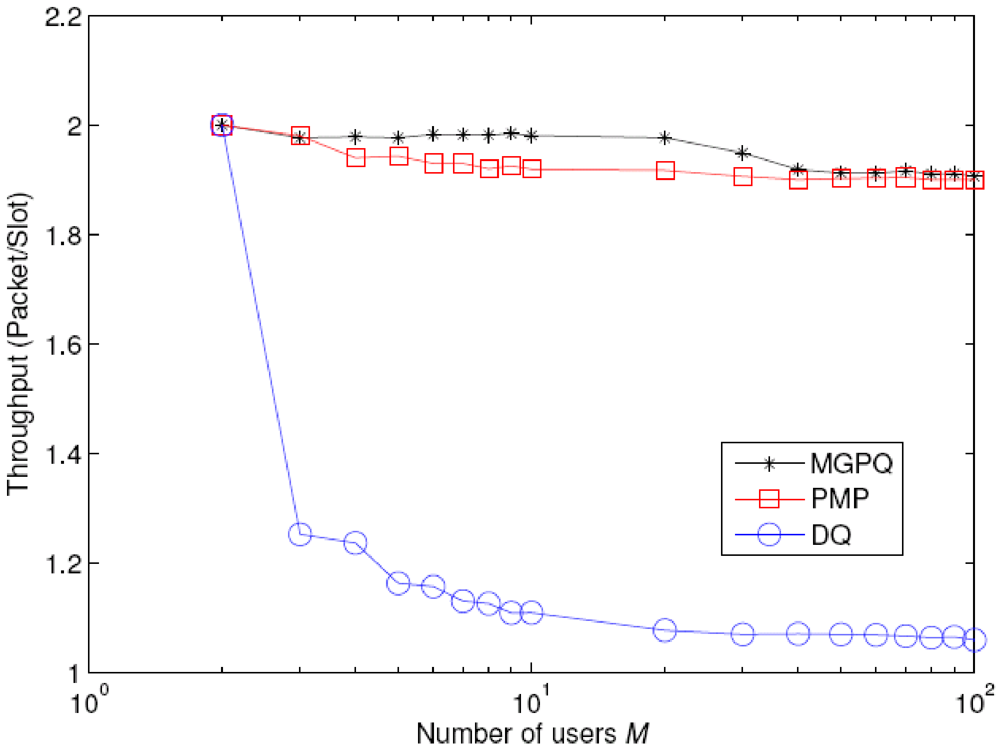



Fig. 2.9 Throughput comparison between MGPQ, PMP, and DQ for different number of users.

small. Fig. 2.9 further depicts the respective throughput performance as the number of user increases from 2 to 100. The result shows that the DQ protocol degrades the performance severely when there are more than two users. This is mainly because in the DQ protocol all users, no matter with packet or not, will be served continually until their packets are received successfully or empty slot occurs. With more than $n_0$ users in the system, the probability of serving idle users is definitely increased.

## 2.6 Summary

In this chapter, we proposed a new approach to design the MAC protocol for wireless networks with MPR capability. The proposed approach relies on the flag-bit-assisted knowledge about the presence of buffered packets as well as a multi-priority user grouping strategy. The advantages of the proposed method are three folds: 1) it is applicable to both the heterogeneous and homogeneous environments, whereas almost all existing protocols developed for the MPR channel are exclusively tailored for the latter case; 2) the insertion of a single bit facilitates the acquisition of network traffic condition with minimal bandwidth expansion; 3) the adopted user grouping policy avoids computationally intensive search for the active users as required in the existing protocols. To prevent an infinitely long service delay in the heterogeneous environment, the waiting period of those yet-to-be-served users can be determined subject to a specified delay requirement. Simulation results show that, compared with the DQ protocol, the proposed scheme achieves higher throughput, reduces the mean delay penalty in light traffic condition, and yields a smaller PLR. Also, the proposed MGPQ protocol outperforms the PMP protocol for the general case with finite buffer size. Next chapter will focus on generalizing the result in this chapter to the more realistic generalized MPR channel model [1].

# Chapter 3

# Multipacket Reception MAC Design in Heterogeneous Channels

## 3.1 Overview

Cooperative MAC protocol design aimed for MPR channels is typically subject to the following challenges. Firstly, 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. However, this will call for extra communication overheads, and will degrade the system-wide throughput, especially in a large-scale mobile network. Secondly, 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 protocols for cooperative user scheduling, there would be a large throughput penalty incurred by the latent of packet relaying phase. To the farthest of our knowledge, cooperative MAC protocol designs for MPR channels have not been found in the literature yet.

MGPQ scheme proposed in Chapter 2 has several distinctive features that make it a potential candidate for cooperative MPR MAC protocol designs. Firstly, in the MGPQ 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. Secondly, 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. To realize the aforesaid advantages, in this chapter we subsequently extend the MGPQ scheme and propose a cooperative MAC protocol for MPR channels.

## 3.2 Preliminary

### 3.2.1 System Scenario

We consider the uplink transmission of a centralized cooperative wireless network, in which the CC and the user terminals are equipped with the MPR capability. We assume that the transmission is slotted, and the CC controls the user's access to a common wireless channel. At the beginning of each time slot the CC determines an access set according to some user scheduling rule to be specified later, and broadcasts this message to initialize data transmission. Due to the broadcast nature of the wireless medium, the CC and all the inactive users can receive the transmitted packets at the end of the data transmission phase. Depending on whether or not the packet of a particular user is successfully received at the CC, an associated ACK or NAK is sent by the CC over the wireless channel and will be received by all users. When the packet reception failure occurs, one of the inactive users who successfully decode the packet may serve as the relay during some future channel access period.

### 3.2.2 MPR Matrix

This section reviews the MPR channel model matrix [28] which specifies the MPR capability at the receiver. Assume that the total number of users is $M$. Let $U$ be a permutation of the index set $\{1,2,\cdots,M\}$ that represents a particular order of the user service schedule. Then the MPR matrix associated with $U$ is described as

$$\mathbf{C}(U) \triangleq \begin{bmatrix} C_{1,0}(U) & C_{1,1}(U) & & & \\ C_{2,0}(U) & C_{2,1}(U) & C_{2,2}(U) & & \\ \vdots & \vdots & \vdots & & \\ C_{M,0}(U) & C_{M,1}(U) & C_{M,2}(U) & \cdots & C_{M,M}(U) \end{bmatrix}, \qquad (3.1)$$

where $C_{n,k}(U) = \Pr\{k$ packets are correctly received | $n$ packets from first $n$ users in $U$ are transmitted$\}$ for $1 \le n \le M$ and $0 \le k \le n$. We note that, according to the setting (3.1), different permutation index sets $U$ in general result in different MPR matrices. Let

$$C_n(U) \triangleq \sum_{k=1}^{n} kC_{n,k}(U) \tag{3.2}$$

be the expected number of correctly received packets when $n$ packets are concurrently transmitted. The capacity of an MPR channel for the particular service sequence $U$ is defined as

$$\eta(U) \triangleq \max_{n=1,\cdots,M} C_n(U). \tag{3.3}$$

Note that the numbers of simultaneously transmitted packets for achieving the channel capacity may not be unique. Let

$$n_0(U) \triangleq \min\left\{\arg \max_{n=1,\cdots,M} C_n(U)\right\} \tag{3.4}$$

be the minimum amount of capacity-achieving packets. Hence the maximal number of users permitted to access the channel should be $n_0(U)$, since there will be no further improvement in system capacity if more than $n_0(U)$ users are simultaneously served. Note that the MPR matrix (3.1) can be determined via the PHY layer performance metric such as bit error rate; an illustrative example based on CDMA communication can be found in [28].

### 3.2.3 Highlight of the MGP Protocol [24]

The proposed cooperative MPR MAC scheme is based on the MGP method [24], which is highlighted below. As in [28] it is assumed that each user has a buffer of size two for storing two

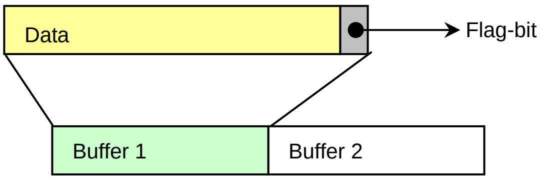



Fig. 3.1 Packet formats.

data packets. The central idea behind the MGP scheme is to append a flag-bit at the tail of the transmitted packet to inform the CC about the next buffer status (see Fig. 3.1 for a schematic description). The flag will be set ON if there is a packet in the next buffer, and is set OFF when otherwise. By exploiting such an on-off flag signature, the MGP scheme classifies the users into three groups with different service priorities: the ACTIVE group consisting of the users with flag-bit ON, the STANDBY group consisting of those with flag-bit OFF, and the PREM group accommodating those who have stayed in the STANDBY or the ACTIVE group for longer than a certain waiting period $S$. The inclusion of the complementary PREM group is to avoid unfair service scheduling that can occur in a binary grouping strategy: Without the PREM mechanism, users in the STANDBY group would suffer an unlimited service delay since the channels could be constantly reserved for some ACTIVE links with heavy traffic. Based on the tri-group user classification scheme, the channel access priority (from high to low, respectively) is PREM, ACTIVE, and STANDBY. According to such a service strategy, at the beginning of each time slot a total number of $n_0(U)$ users (for some $U$) are selected for data transmission, where $n_0(U)$ is the minimal number of users that achieves the capacity of the MPR channel. In case that the CC successfully receives the packet sent from, say, user $i$, the service priority of this user is determined by the decoded flag information from the current packet. If, instead, packet reception failure occurs, the CC schedules the service priority of user $i$ according to the previous flag record. We shall note the followings:

a) In the MGP scheme the number of users permitted for channel access is deterministically set to attain the MPR channel capacity. This prevents the channel from being overloaded, thereby avoiding irrecoverable packet reception failure due to collisions.

b) Under light traffic environments, a significant portion of the users could be in the idle phase (i.e., no data packets to send). If packet reception failure occurs, the idle periods can then be exploited for packet relaying to reduce the possible throughput loss. This can be effectively accomplished via a natural extension of the MGP protocol, as discussed next.

## 3.3 Cooperative Multi-Group Priority Protocol

The flag-bit is the instrumental mechanism for facilitating the multi-group priority based user service in the MGP protocol. The central idea of the proposed CMGP scheme is to exploit the flag-bit message for distinguishing the direct links from the relay ones. By assigning different service priority to different types of links, the throughput degradation due to the packet relaying overheads can be limited, and an increase in the network-wide throughput can be achieved.

### 3.3.1 Operation of the Proposed CMGP Protocol

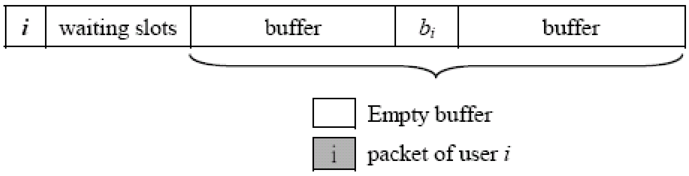
If user $i$ is permitted to access the channel, as in the MGP scheme a flag-bit $b_i$ is appended at the tail of the packet upon transmission. The flag signature is ON ($b_i = 1$) only if the second buffer is non-empty and contains a data packet also of user $i$. The flag signature is instead OFF ($b_i = 0$) when either one of the following cases is true: i) the second buffer is empty, ii) the second buffer is nonempty but the packet therein is received from some other user $j(\neq i)$. Upon successful packet reception, the CC decodes the flag-bit message and then schedules the user access according to the MGP protocol. If packet reception failure occurs at the CC and user $k$, who is not in the access set and has empty second buffer, successfully decodes the transmitted packet from user $i$, user $k$ can serve as the relay in some upcoming channel access period[1]. If none of the users can serve as the relay, which happens when all other users' buffers are non-empty or none of the users can successfully receive the packet, user $i$ then re-transmits this packet during the next channel access. We note the following key features regarding the proposed protocol:

1) The adoption of the flag-bit provides an in-built mechanism for the CC to dintinguish between the direct and relay-or-idle links for service scheduling. Users with flag-bits ON for direct data transmission will be arranged into either the ACTIVE or the PREM group, and thus enjoy potentially higher channel access priority. This prevents possibly frequent data relaying when collision occurs, thereby reducing the throughput penalty incurred by the packet relaying overheads.
2) Thanks to the PREM mechanism, users who are not permitted to access the channel over a time period longer than the threshold $S$ will be granted with the highest service priority. This can limit the service delay of the relay links, and can thus maintain the overall QoS requirement.
3) In the proposed protocol, each user takes his/her turn to access the channel according to the prescribed service priority. There is no need for active user identification, and the protocol complexity can be substantially reduced.

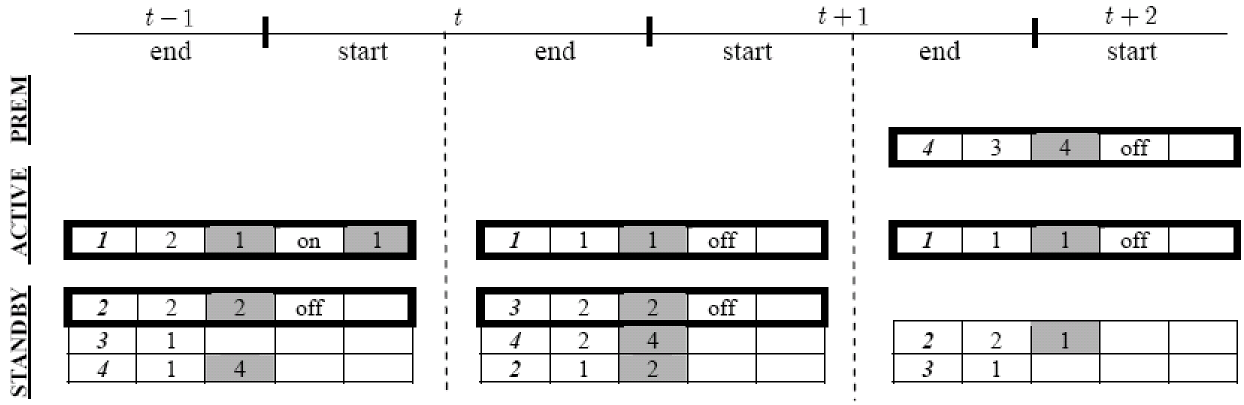
### 3.3.2 An Illustrative Example

This subsection uses an example to demonstrate the proposed CMGP protocol. We consider a network of $M = 4$ users, and assume for simplicity that i) $n_0(U) = 2$ attains the MPR channel capacity irrespective of the index set, and ii) the time slot threshold above which the STANDBY or

[1] The newly generated packets of user $k$ always enjoy the highest processing priority and, due to limited buffer size, may cause the dropping of the buffered packet from user *i*.




(a) The tag designating the status of the $i$th user, $1 \le i \le 4$.




(b) The priority grouping process within three consecutive time slots.

Fig. 3.2 An illustrative example.

ACTIVE users will be promoted into the PREM group is $S = 3$. The traffic status of user $i$ is summarized in a tag shown in Fig. 3.2 (a), in which the first field represents the user ID, second field is the counts of waiting slots, third and fifth fields represent the content of the two buffers, and forth field marks the status of the flag-bit. Fig. 3.2 (b) depicts the operation of the proposed protocol during three consecutive time slots, and is also explained in detail as below.

- At the end phase of slot $t-1$:

The PREM group is empty; user 1 is in the ACTIVE group, users 2, 3, 4, are in the STANDBY group.

- At the start phase of slot $t$:

User 1 (with $b_1 = 1$) and user 2 (with $b_2 = 0$) are allowed for channel access.

- At the end phase of slot $t$:

(i) The packet of user 1 is successfully received by CC; user 1 remains ACTIVE but the flag is updated to $b_1 = 0$ since its second buffer is empty.

(ii) The packet of user 2 is not successfully received by CC; user 2 is put into the bottom of the STANDBY group.

(iii) User 3 successfully decodes the packet of user 2 and will serve as the relay.

- At the start phase of slot $t+1$:

  User 1 (with $b_1 = 0$) and user 3 (with $b_3 = 0$) are allowed for channel access.

- At the end phase of slot $t+1$:

  (i) User 3 successfully relays the packet of user 2 to CC, and is then put to the STANDBY group since $b_3 = 0$.

  (ii) The CC fails to successfully receive the packet of user 1, and thus does not correctly decode the current bit message. User 1 remains ACTIVE since the latest flag message available to the CC is the previous setting $b_1 = 1$.

  (iii) User 2 successfully received the packet of user 1 and will serve as the relay.

  (iv) User 4 (with $b_4 = 0$) has not been allowed to access the channel for more than $S = 3$ time slots, and is moved into the PREM group.

- At the start phase of slot $t+2$:

  User 1 (with $b_1 = 0$) and user 4 access the channel.

### 3.3.3 Algorithm Summary

The proposed CMGP protocol is summarized as below.

CC-end:

I. Put all users into the PREM group.

II. Select first $n_0(U)$ users (by the order of PREM, ACTIVE, and then STANDBY group) to access the channel.

  a) If the packet of a certain user is received successfully, then put the user to the tail of the ACTIVE (if the flag-bit is on) or STANDBY group (if the flag-bit is off). And reset its

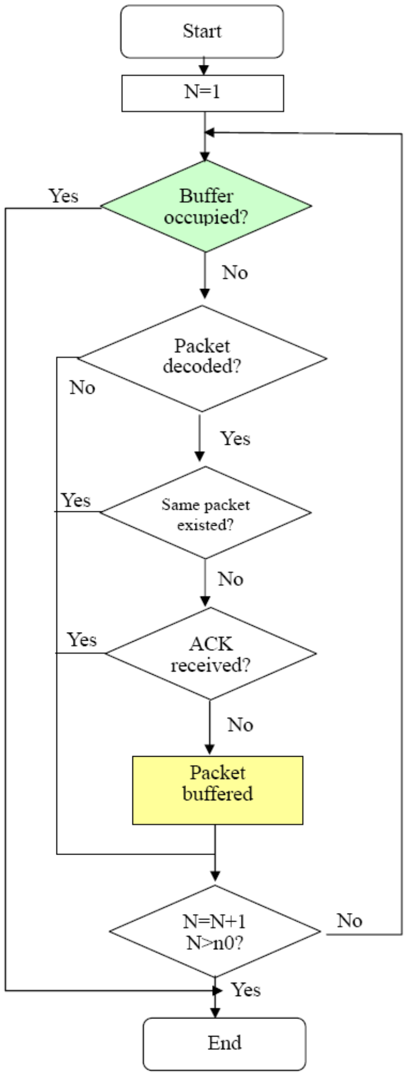



Fig. 3.3 Flow chart of user acting as a relay.

count of waiting slots to zero.

b) If, for a certain user, the buffer is empty (no packet sent) or there is a packet transmitted but not successfully received, and then put the user back to the tail of the STANDBY or ACTIVE group in which the user originally stayed. Reset its count of waiting slots to zero.

III. Increase waiting slots of all users by one.

IV. Move those users with waiting slots equal to $S$ to the PREM group.

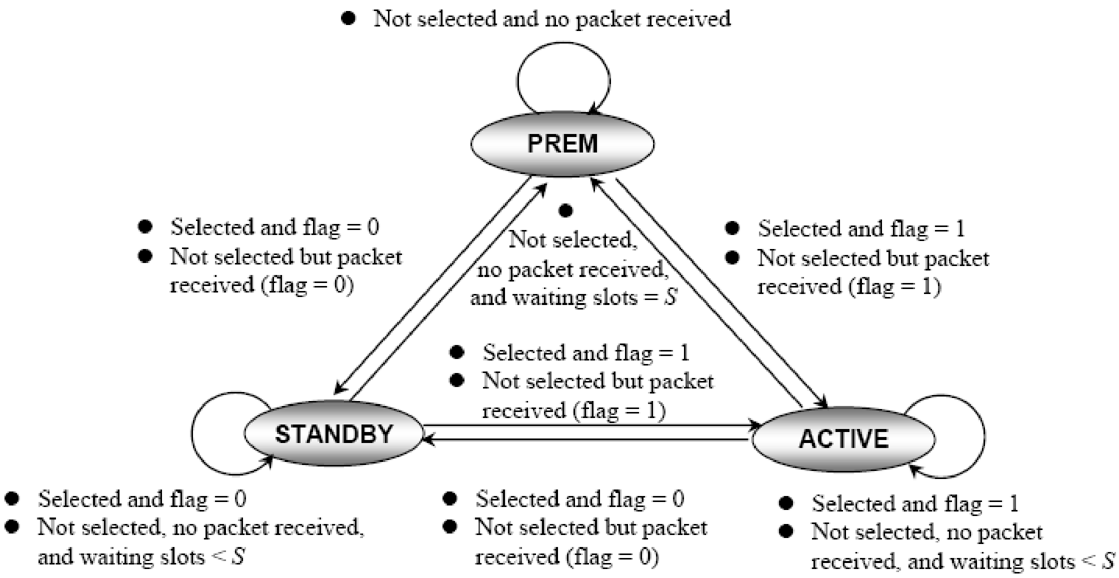



Fig. 3.4 Centrally controlled state transition diagram of an individual user.

V. Repeat steps II to IV.

User-end:

I. If the packet of user $i$ is received successfully by some other user $j$, and then user $j$ will store this packet if it has at least one buffer empty.

II. If an ACK for user $i$'s packet is received by user $j$, then user $j$ will remove user $i$'s packet from his/her buffer.

The detail flow chart of client-end protocol is shown in Fig. 3.3, and the group transition diagram of users is shown in Fig. 3.4.

## 3.4 Throughput Analysis

Recall that the proposed CMGP protocol exploits the idle periods of the MGP scheme for packet relaying. Hence, during each time slot there are in general more concurrently transmitted packets as compared with the MGP method. Even though packet relying can compensate for the throughput loss due to packet reception failure, the increase in the number of active relay links, however, will introduce stronger interference toward direct data transmissions. The throughput loss caused by the relay-induced interference is thus one major limiting factor for the overall system performance. By regarding the achievable throughput of the MGP scheme as a benchmark, this section aims to characterize the throughput performance of the proposed CMGP protocol. We shall note that the exact analysis for the general case, however, is quite difficult. In this section we will focus on the interference-limited worst case, in which *there is only one direct link, and the other* $n_0(U)-1$ *users serve as the relay*. Although the performance evaluation based on such a worst-case scenario could be conservative, our analyses are quite appealing in that the problem formulation becomes tractable. As will be shown below, we can derive a closed-form upper bound for the throughput penalty incurred by the relay interference, as well as a closed-form lower bound for the throughput gain benefiting from user cooperation, directly in terms of the MPR matrix coefficients. This allows us to deduce several interesting features regarding the proposed CMGP protocol.

### 3.4.1 Upper Bound for Worst-Case Throughput Penalty

We shall note that the *effective* relay candidates are those users with a good link condition and low packet generating probability (or, low packet blocking probability). Based on this observation, we can derive a closed-form upper bound for the worst-case throughput penalty suffered by the direct-link user in terms of the MPR matrix coefficients in (3.1); the result allows us to further analyze the throughput results under various direct-link channel conditions. In the sequel we let $\{u_1, \cdots, u_{n_0}\}$ be the index set for the active users; without lose of generality we assume that $u_1$ denotes the direct-link user.

To proceed, we resort to the Markov chain based analysis. A reasonable model for the evolution of the buffer status is the birth-and-death process with a finite number of states [23]. With the aid of this model, we have the following theorems (see appendix F and G for the proofs).

**Theorem 3.1** Assume that, without user cooperation, the packet blocking probability $p_{u_1}^B$ of user $u_1$ is smaller than some positive $\delta$, i.e., $p_{u_1}^B \le \delta$. Then the throughput penalty $\Delta_{u_1}^p$ of the direct-link user $u_1$ in the CMGP protocol is upper bounded by

$$\Delta_{u_1}^p \le \Delta_{u_1} + \frac{\delta\left(A_{u_1} + B_{u_1}\right)}{A_{u_1} + \delta B_{u_1}}, \tag{3.5}$$

where

$$\Delta_{u_1} = C_1\left(\{u_1\}\right) - C_{n_0(U)}\left(U\right) + C_{n_0(U)-1}\left(U \setminus \{u_1\}\right), \tag{3.6}$$

and $A_{u_1}$ and $B_{u_1}$ are some constants which depend on the packet generating probability and the successful packet transmission probability. □

The upper bound in (3.5) splits into a sum of two terms: the first term $\Delta_{u_1}$ is completely characterized by the PHY-layer signal separation capability in terms of the MPR matrix, whereas the second term $\frac{\delta\left(A_{u_1} + B_{u_1}\right)}{A_{u_1} + \delta B_{u_1}}$ depends also on the MAC traffic condition. In the extreme case that $\delta \to 0$ (or $p_{u_1}^B \to 0$), the throughput penalty upper bound (3.5) is entirely determined by the MPR channel quality as

$$\Delta_{u_1}^p \le \Delta_{u_1} = C_1\left(\{u_1\}\right) - C_{n_0(U)}\left(U\right) + C_{n_0(U)-1}\left(U \setminus \{u_1\}\right). \tag{3.7}$$

Inequality (3.7) allows us to investigate the impact of the direct-link channel condition on the throughput penalty. We consider the following two cases.

***<u>Case 1:</u>*** Consider the situation that the MPR capability is strong enough so that concurrent transmission of any number of packets (not greater than the channel capacity along good communication links) can be perfectly recovered. The resultant MPR matrix admits the form [16][17]

$$\mathbf{C} = \begin{bmatrix} 0 & 1 & & & & & \\ 0 & 0 & 1 & & & & \\ 0 & 0 & 0 & 1 & & & \\ 1 & 0 & 0 & 0 & 0 & & \\ \vdots & \vdots & \vdots & \vdots & \cdots & \ddots & \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}, \text{ for some index set } U_1. \tag{3.8}$$

From (3.8) and by definitions (3.3) and (3.4), we have $\eta(U_1) = n_0(U_1) = 3$, $C_1(\{u_1\}) = 1$, $C_{n_0(U_1)}(U_1) = \eta(U_1) = 3$, and $C_{n_0(U_1)-1}(U_1 \setminus \{u_1\}) = 2$. Hence the throughput penalty upper bound (3.7) is identically zero:

$$\Delta_{u_1}^p \leq \Delta_{u_1} = 1 - 3 + 2 = 0. \tag{3.9}$$

Since $\Delta_{u_1}^p \geq 0$, (3.9) then implies $\Delta_{u_1}^p = 0$, i.e., there is no throughput penalty for the direct link. This is intuitively reasonable since, with strong packet separation capability, the interference caused by the relay links toward direct data transmissions can be kept negligible.

***Case 2:*** Consider the situation in which $k$ relay users $u_2, u_3, \cdots, u_{k+1}$ are located far away from the CC and suffer poor channel conditions so that the corresponding MPR matrix reads

$$\mathbf{C} = \begin{bmatrix} 0 & 1 & & & & & \\ 0 & 1 & 0 & & & & \\ \vdots & \vdots & \vdots & \ddots & & & \\ 0 & 1 & 0 & 0 & 0 & & \\ 0 & 0 & 1 & 0 & 0 & 0 & \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \begin{matrix} \\ \left.\begin{matrix} \\ \\ \\ \end{matrix}\right\} k \\ \\ \\ \end{matrix}, \text{ for some index set } U_2. \tag{3.10}$$

From (3.10) and by definitions (3.3) and (3.4), we have $\eta(U_2)=3$ and $n_0(U_2)=k+3$, $C_1(\{u_1\})=1$, $C_{n_0(U_2)}(U_2)=\eta(U_2)=3$, and $C_{n_0(U_2)-1}(U_2\setminus\{u_1\})=2$. Hence the throughput penalty upper bound (3.7) is still zero:

$$\Delta_{u_1}^p \le \Delta_{u_1} = 1-3+2=0. \tag{3.11}$$

Since $\Delta_{u_1}^p \ge 0$, (3.11) also implies $\Delta_{u_1}^p = 0$. This accounts for the fact that the far-end relay links only induce negligible interference which results in zero throughput penalty in the direct link.

### 3.4.2 Lower Bound for Worst-Case Throughput Gain

In the considered worst-case scenario, we can also specify a lower bound for the throughput gain that a user with packet transmission failure can benefit owing to cooperative packet relaying. More specifically, we have the following theorem.

**Theorem 3.2** Suppose that the user $u_j$, where $u_j \in U\setminus\{u_2,\cdots,u_{n_0(U)}\}$, suffers from the packet transmission failure. Then, due to cooperative packet relay from some other user $u_k \in \{u_2,\cdots,u_{n_0(U)}\}$, at least the user $u_j$ can enjoy a throughput gain $\Delta_{u_j}^g$:

$$\Delta_{u_j}^g \ge p\left(C_{n_0(U)}(U) - \min_{u_k\in\{u_2,\cdots,u_{n_0}\}} C_{n_0(U)-1}(U\setminus\{u_k\})\right), \tag{3.12}$$

where $p$ is the packet generating probability. □

Consider the two cases in Section 3.4.1 again. Note that $\min_{u_k\in\{u_2,\cdots,u_{n_0}\}} C_{n_0(U_1)-1}(U_1\setminus\{u_k\})=\eta(U_1)-1=2$ in case 1 and $\min_{u_k\in\{u_2,\cdots,u_{n_0}\}} C_{n_0(U_2)-1}(U_2\setminus\{u_k\})=\eta(U_2)-1=2$ in case 2. Hence, in both cases, the lower bound (3.12) becomes

$$\Delta_{u_j}^{g} \geq p(3-2) = p. \tag{3.13}$$

Since $\Delta_{u_j}^{g} \leq p$, we must have $\Delta_{u_j}^{g} = p$. This implies that, even in the interference-limited worst case, the proposed CMGP protocol can still retrieve the maximal achievable throughput advantage.

## 3.5 Optimal Waiting Period Selection

### 3.5.1 Markov Chain

In the proposed protocol, the number of users permitted for channel access is $n_0(U)$, namely, the one attaining the MPR channel capacity. A natural criterion for determining the waiting period $S$ is to maximize the probability that each of the selected $n_0(U)$ users has a packet to send. We first note that the probability of the user $i$ (selected from PREM) with a packet to transmit after waiting a period of $S$ is at least [24]

$$\tilde{p}_i = 1-(1-p_i)^S,\ i \in \{1,2,\cdots,M\}, \tag{3.14}$$

where $p_i$ denotes the packet generating probability of the user $i$. This implies that the larger the waiting period $S$ is, the more likely the users in the PREM group have packets to send. As a result, $S$ should be kept as large as possible. However, the unlimited increase in $S$ may incur severe delay penalty. Particularly if $S \to \infty$, the transition from STANDBY group to PREM group is prevented and the proposed tri-group priority queuing protocol degenerates into a bi-group scheme. To determine an $S$ for striking a balance between large $\tilde{p}_i$ and small delay, we propose to seek the optimal $S_{opt}$ with which the following set of constraints on the mean delay per user is satisfied:

$$D_i(S) \le D_i^r,\ 1 \le i \le M, \tag{3.15}$$

where $D_i(S)$ stands for the mean delay of the user $i$ and $D_i^r$ is the delay requirement for user $i$. To find the desired $S$ from (3.15), one crucial step is to determine an explicit expression of $D_i(S)$ in terms of $S$. Toward this end, we shall determine all the possible transitions of states (an exact definition of a "state" will be specified later) in the proposed protocol. This can be solved by applying Markov chain analysis shown below.

Associated with user $i$ ($1 \le i \le M$) we define $x_i(t)$, $y_i(t)$, $z_{i,0}(t)$, $z_{i,1}(t)$ to be the assumed value of the waiting slots, the indication of the flag-bit, and the buffer contents (0 stands for no packet) in the primary buffer and the additional buffer at the $t$th time slot respectively. Hence we have $x_i(t) \in \{1,\cdots,S\}$ [2], $y_i(t) \in \{0,1\}$, $z_{i,0}(t) \in \{0,1,\cdots,M\}$, and $z_{i,1}(t) \in \{0,1,\cdots,M\}$. Let us further collect $x_i(t)$, $y_i(t)$, $z_{i,0}(t)$ and $z_{i,1}(t)$ for all users to form $X(t) = (x_1(t),\cdots,x_M(t))$, $Y(t) = (y_1(t),\cdots,y_M(t))$, and $Z(t) = (z_{1,0}(t), z_{1,1}(t),\cdots,z_{M,0}(t),,z_{M,1}(t))$. The proposed protocol can be described by a Markov chain with state space

$$\Omega := \{E(t) \mid E(t) = (X(t), Y(t), Z(t)), t \ge 0\}. \tag{3.16}$$

We note that the number of states is at most $(S \cdot 2 \cdot (M+1) \cdot (M+1))^M$. However, since in each time slot, exact $n_0(U)$ users can simultaneously access the channel, it follows that (i) the number

[2] $S$ is assumed to be larger than $\lceil M / n_0(U) \rceil$ for simplicity [24].

Table 3.1

COMBINATIONS OF $y_i(t)$, $z_{i,0}(t)$ AND $z_{i,1}(t)$

| $y_i(t)$ | $z_{i,0}(t)$ | $z_{i,1}(t)$ | Amount |
|---|---|---|---|
| 0 | 0 | 0 | 1 |
| | $i$ | $j \in \{0,1,\cdots,M\}$ | $M+1$ |
| | $j \in \{1,\cdots,M\} \setminus \{i\}$ | $k \in \{0,\cdots,M\} \setminus \{i,j\}$ | $(M-1)^2$ |
| 1 | $i$ | $j \in \{0,1,\cdots,M\}$ | $M+1$ |

of "1" in $X(t)$ must equal $n_0(U)$; (ii) no more than $n_0(U)$ entries in $X(t)$ will assume the same value. Taking the above constraints into account and using the permutation and combination theory, the number of distinct outcomes of $X(t)$ is [24]

$$N_C = \frac{M!}{n_0(U)!\left(M-n_0(U)\right)!} \cdot \sum_{m_i} \frac{(S-1)!}{\prod_{i=0}^{n_0(U)} (m_i!)} \cdot \frac{\left(M-n_0(U)\right)!}{\prod_{i=0}^{n_0(U)} (i!)^{m_i}}, \tag{3.17}$$

where the integers $m_i$'s are found as the solutions to the following constraints

$$\sum_{i=0}^{n_0(U)} i \cdot m_i = M - n_0(U), \text{ and } \sum_{i=0}^{n_0(U)} m_i = S-1. \tag{3.18}$$

Because (i) there must be own packet in the buffer for each user in the ACTIVE group, (ii) own packet has higher priority than relayed packet, and (iii) flag-bit only indicates own buffered packet, the total number of possible states in the system can be reduced to $N_S = \left(N_C \cdot \left(M^2+4\right)\right)^M$ (see Table 3.1 for possible combinations of $y_i(t)$, $z_{i,0}(t)$ and $z_{i,1}(t)$). If there exists some $p_i = 0$ or 1, the total number of states will be further reduced.

### 3.5.2 State Transition Probability

We proceed to compute the state transition probabilities as follows, assuming that the events of packet generation among users are independent, we have

$$\Pr\left\{E(t+1)=(\tilde{X},\tilde{Y},\tilde{Z})\,|\,E(t)=(X,Y,Z)\right\}$$

$$=\prod_{i=1}^{M}P_x\left(\triangle x_i\middle|X,Y,Z\right)P_y\left(\triangle y_i\middle|X,Y,Z\right)P_{z_0}\left(\triangle z_{i,0}\middle|X,Y,Z\right)P_{z_1}\left(\triangle z_{i,1}\middle|X,Y,Z\right), \qquad (3.19)$$

where $\tilde{X}-X=\left(\triangle x_1,\cdots,\triangle x_M\right)$, $\tilde{Y}-Y=\left(\triangle y_1,\cdots,\triangle y_M\right)$, $\tilde{Z}-Z=\left(\triangle z_{1,0},\triangle z_{1,1},\cdots,\triangle z_{M,0},\triangle z_{M,1}\right)$. $P_x\left(\triangle x_i\middle|X,Y,Z\right)$, $P_y\left(\triangle y_i\middle|X,Y,Z\right)$, $P_{z_0}\left(\triangle z_{i,0}\middle|X,Y,Z\right)$, and $P_{z_1}\left(\triangle z_{i,1}\middle|X,Y,Z\right)$ are the conditional probabilities of the increment of state components given $(X,Y,Z)$. These conditional probabilities $P_x\left(\triangle x_i\middle|X,Y,Z\right)$, $P_y\left(\triangle y_i\middle|X,Y,Z\right)$, $P_{z_0}\left(\triangle z_{i,0}\middle|X,Y,Z\right)$, and $P_{z_1}\left(\triangle z_{i,1}\middle|X,Y,Z\right)$ can be calculated according to current state ($X$, $Y$, $Z$). Based on the state transition probabilities (3.19), we can immediately construct the transition matrix $\boldsymbol{T}$, with which the steady-state probability $\pi_j$, $1\le j\le N_S$, can be readily obtained by

$$\lim_{t\to\infty}\boldsymbol{T}^t=\begin{bmatrix}\pi_1 & \pi_2 & \cdots & \pi_{N_S}\\ \pi_1 & \pi_2 & \cdots & \pi_{N_S}\\ \vdots & \vdots & \vdots & \vdots\end{bmatrix}. \qquad (3.20)$$

In this chapter, we assume that the above limit exists. The mean delay $D_i(S)$ can be then determined as follows.

### 3.5.3 Computation of Mean Delay

According to Little's law, we have

$$D_i(S)=N_i(S)/\lambda_i(S), \qquad (3.21)$$

where $N_i(S)$ is the average number of *own* packets in the buffer of user $i$, and $\lambda_i(S)$ is the packet departure rate of user $i$. Then we have

$$N_i(S) = \sum_{j=1}^{N_S} \sum_{l=0}^{1} \pi_j \delta\left(z_{i,l}^{(j)} - i\right), \tag{3.22}$$

where $z_{i,l}^{(j)}$ is the $z_{i,l}$ value at the state $j$, and $\delta(\bullet)$ is the delta function. Also, denote by $P_i^B(S)$ the packet blocking probability of user $i$, therefore

$$P_i^B(S) = \sum_{j=1}^{N_S} \delta\left(z_{i,1}^{(j)} - i\right) \pi_j \prod_{u \in U_A} \delta\left(z_{u,0}^{(j)} - i\right)\left[1 - P_u^S(U_A)\right]; \tag{3.23}$$

where $P_u^S(U_A)$ is the successful packet transmission probability of the user $u$ in access set $U_A$. Then it follows that

$$\lambda_i(S) = p_i(1 - P_i^B(S)). \tag{3.24}$$

Substituting (3.22) and (3.24) into (3.21), we can obtain a functional relation of $D_i(S)$ in terms of $S$. The solution to (3.15) can then be computed via numerical search.

## 3.6 Simulation Results

We consider a CDMA network with randomly generated spreading codes. The packet length, spreading gain, and number of correctable errors in each packet are, respectively, 200, 6, and 2. We assume that there are a total number of $M = 8$ users in the network, among which users 2, 4, 5, and 7 are nearby the CC and users 1, 3, 6, and 8 are located far away from the CC. The MPR matrix of the considered system scenario can be derived in an analogue way as in [28].

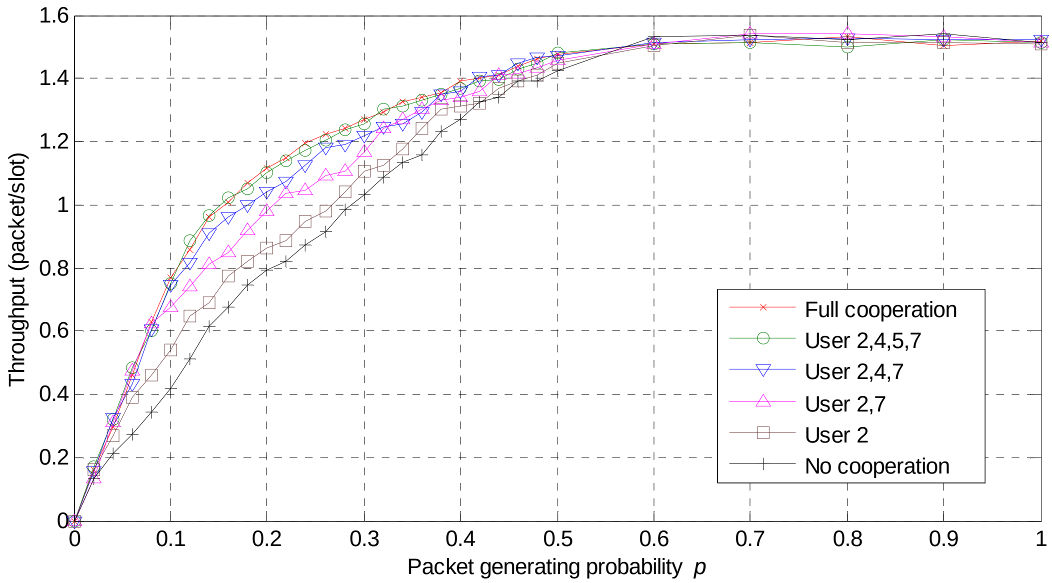



Fig. 3.5 Throughput performance for different number of users participating in cooperation.

### 3.6.1 Throughput Enhancement due to Cooperation

Fig. 3.5 compares the throughput performance when the number of the near-end users participating in cooperative communication increases from one to four. The throughput curve when all the eight users are involved for full cooperation is also included. In this example the waiting period is determined to be $S = 4$ (assuming that the delay requirement is $D_i^r = 80,\ i = 2,4,5,7$ in (3.15)). The figure shows that, as the number of near-end user increases, the throughput performance is improved. This benefits from the increase in the multi-user diversity (or cooperation gain). However, further throughput enhancement is hardly seen if full cooperation is allowed. This is because the inclusion of far-end users can not increase the effective cooperation gain, since they are typically subject to worse channel conditions. We can also see from the figure that cooperation can improve the performance only when the packet generating probability is small (in our case $p < 0.6$). That is because, in a heavy traffic environment (large $p$), the channel access phase will be fully reserved for direct data transmission, and idle periods are seldom available for cooperative packet relaying.

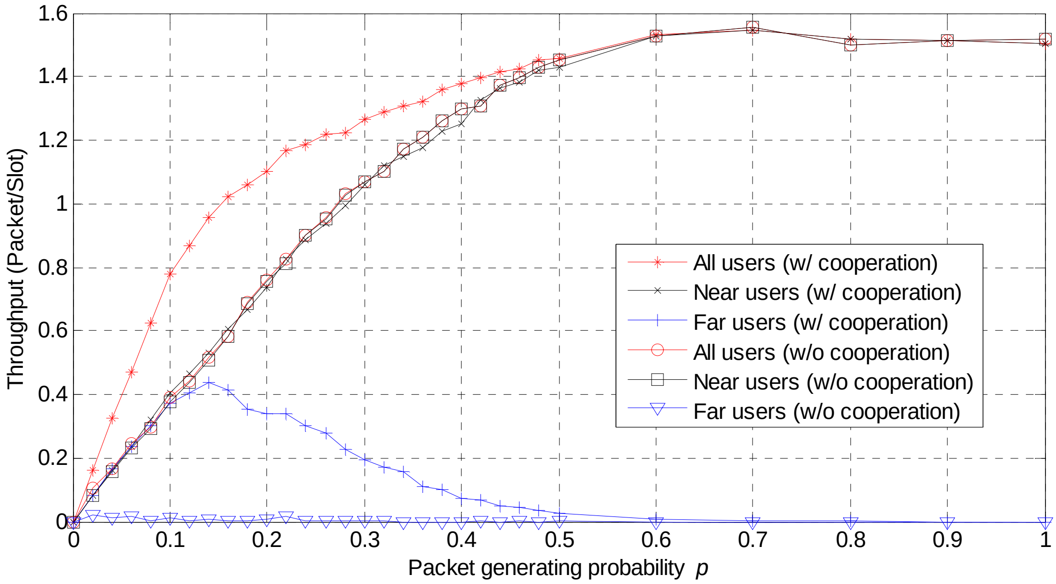



Fig. 3.6 Average throughput of near, far and all users.

### 3.6.2 Throughput Results for Near- and Far-End Users

We go on to investigate the throughput results for near-end and far-end users in both cooperative and non-cooperative environments. The results are depicted in Fig. 3.6. As we can see, due to poor channel conditions the average throughput of the far-end users is almost zero without cooperation. However, when cooperation with near-end users is allowed, throughput up to about 0.4 for the far-end users can be achieved when the packet generating probability $p$ is not large. Also, there is a significant increase in the overall throughput when compared with the non-cooperative case. For the near-end users, it is important to see that the throughput penalty is almost zero even though a certain portion of the channel access will be dedicated to packet relaying. This is mainly because, in the proposed CMGP protocol, only the idle periods are exploited for the relay phase, and the service priority of the relay users are potentially lower than the direct data transmission links. Fig. 3.7 compares the simulated average throughput gain (per direct link user) with the theoretical lower bound (3.12). As we can see, the analytic result shows close agreement with the simulated outcome

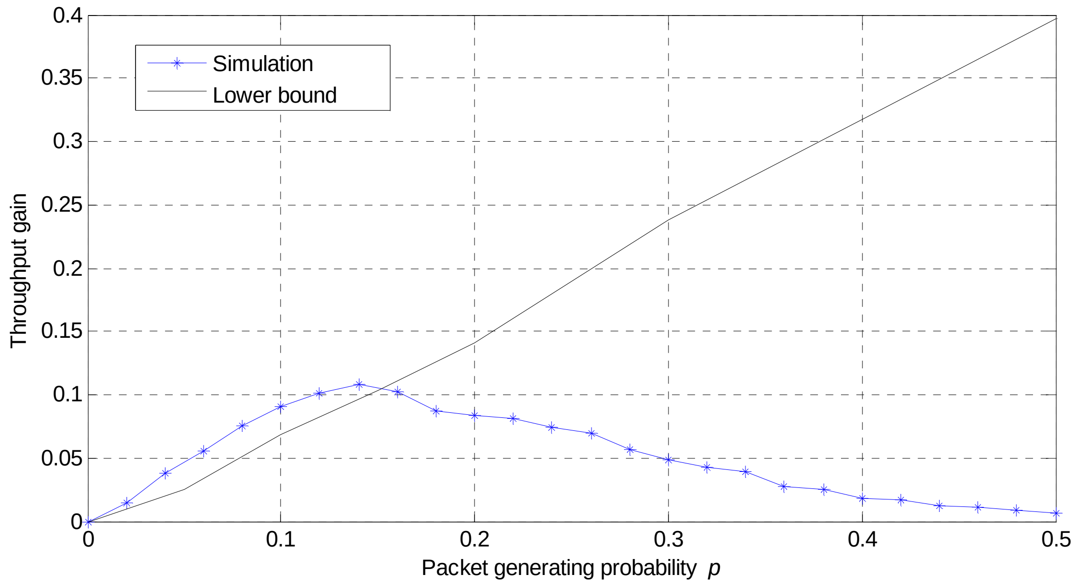



Fig. 3.7 Lower bound of throughput gain derived from Theorem 3.2.

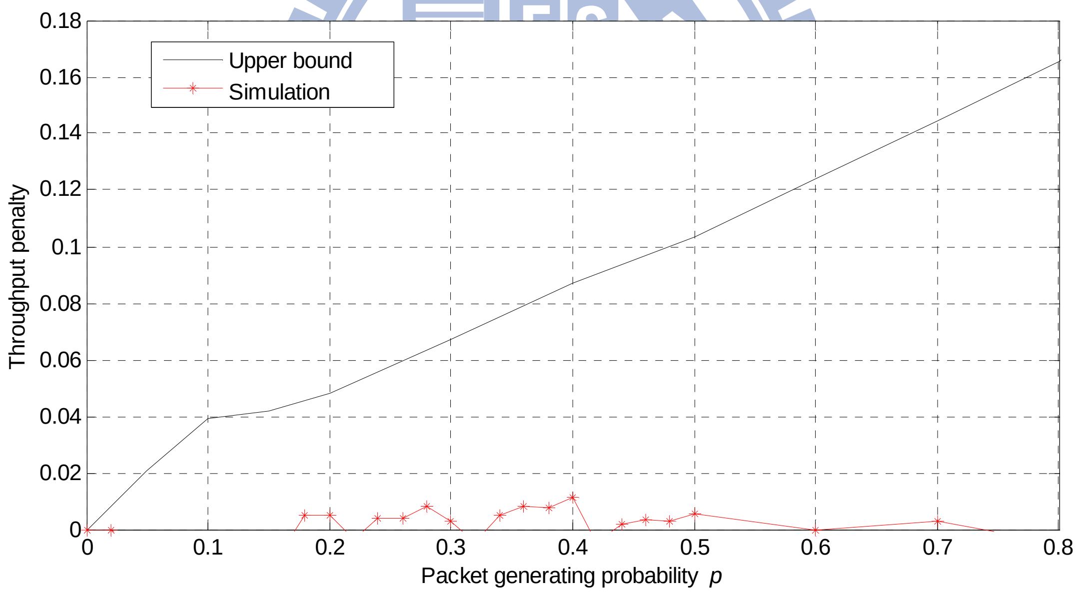



Fig. 3.8 Upper bound of throughput penalty derived from Theorem 3.1.

in a low traffic scenario ($p \leq 0.15$). However, there is a large discrepancy as the traffic load becomes heavy. This is reasonable since the lower bound (3.12) is derived specifically for the low traffic environment, in which idle periods are available and can be exploited for packet relaying.

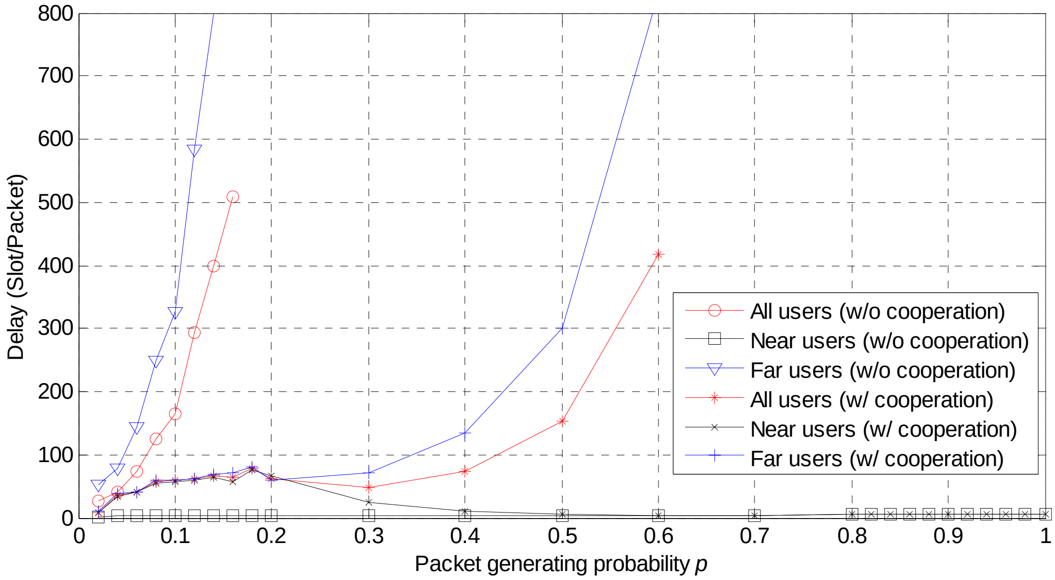



Fig. 3.9 Average delay of near, far and all users.

Fig. 3.8 further compares the simulated throughput penalty (per direct link user) with the theoretical upper bound (3.7). The result shows that the upper bound (3.7) tends to be conservative. Actually, the throughput loss due to packet-relaying interference is pretty small (<0.02) in the proposed CMGP protocol.

### 3.6.3 Delay and Packet Blocking Performances

Fig. 3.9 further shows the resultant average delay performance. It can be seen that, without cooperation, even a small packet generating probability ($p \approx 0.1$) results in severe delay penalty. However, if cooperation is allowed, the delay performance becomes more robust against the increase in $p$. Finally, Fig. 3.10 depicts the packet blocking probability curves. It can be seen that, for small $p$ (hence small packet blocking probability), the blocking probability associated with the near-end users almost diminishes. This reflects the fact that the near-end users typically enjoy good channel conditions, and the MPR capability of these links is strong so that throughput penalty can be kept very small (as evidenced by the analysis in Sec. 3.4.1).

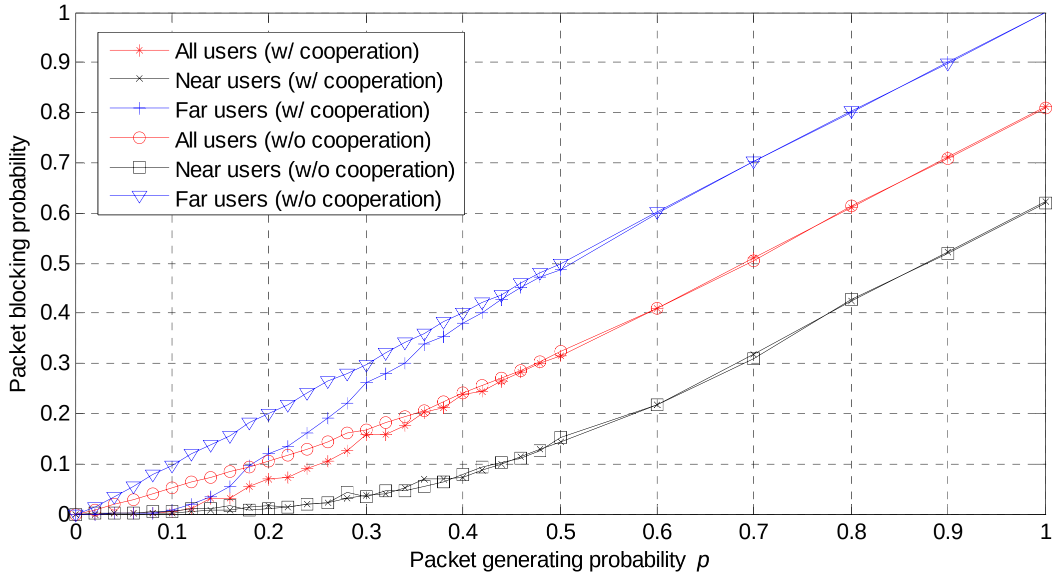



Fig. 3.10 Average packet blocking probability of near, far and all users.

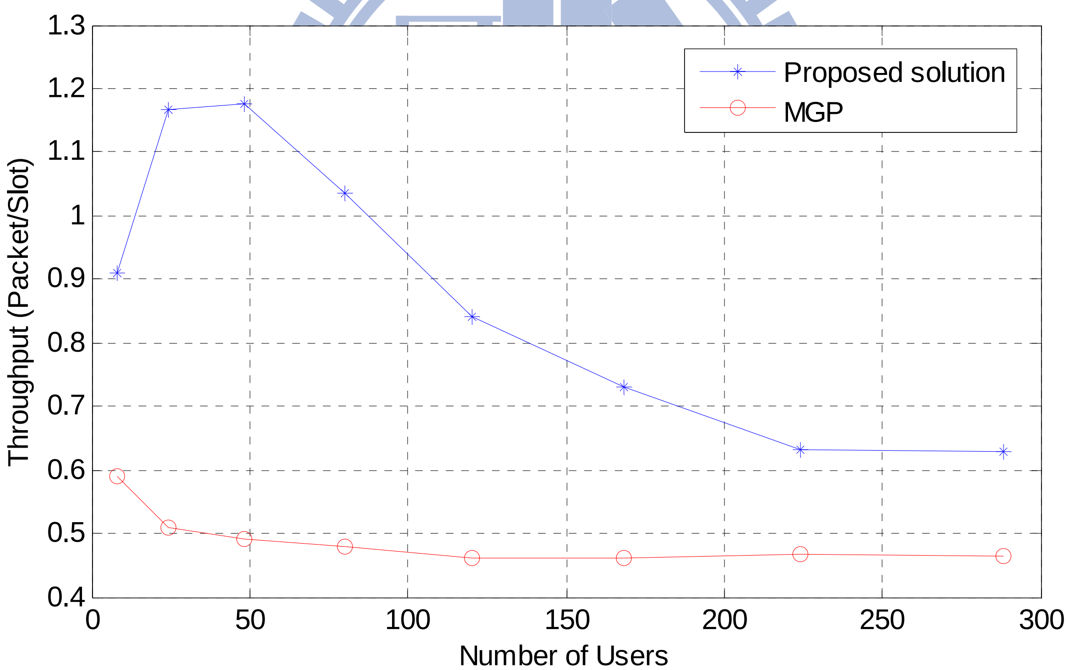



Fig. 3.11 Average throughput in a dense environment.

### 3.6.4 Throughput Results in a Dense Environment

Fig. 3.11 further illustrates the throughput performance as the total number of users increases;

the aggregate traffic load is set to be 80% of the channel capacity, i.e., 1.2 packets per slot. The proposed CMGP method is seen to achieve the maximal throughput of 1.18 when the number of users equals 48; this yields about a 140% throughout gain as compared with the MGP. As the number of users increases, both methods are subject to throughput floors, but the CMGP still results in a 34% gain as compared with the MGP.

## 3.7 Summary

Motivated by [24] this chapter proposes a cooperative MAC protocol for MPR channels. As far as we know, our scheme is the first proposal which integrates the user cooperation facility and the PHY-layer MPR advantage for MAC protocol designs. The proposed method relies on a priority-based scheduling mechanism, and does not need active user identification: It is thus a promising candidate for the low-complexity protocol implementation in dense cooperative networks. Based on Markov chain models we provide throughput analysis for the proposed protocol. We derive closed-form throughput bounds for the worst case that allow us to investigate the impact of the MPR capability on the system performance. Simulation results confirm the throughput advantage achieved by the proposed method, and validate the presented analytical results.

# Chapter 4

# Dynamic User Set Based Uplink Throughput Optimization for Wireless Networks

## 4.1 Overview

Traditionally, the design of MAC protocols is based on the so-called collision channel model, in which a transmitted packet is successfully received only when there is no concurrent transmission. Such a paradigm, however, ignores the MPR capability at the PHY layer. As the improvement in throughput performance, MAC protocol designs which exploit the MPR facility draw increasing attention, and several proposals have been found in the literature recently [10][21][25]. Nevertheless, the throughput performance is still bounded by the channel capacity of *fixed* user set. In other words, all users with very diversity of channel links are assigned a portion of bandwidth to access the channel [9]. As a result, the channel resources allocated to the users with poor channel conditions are wasted in most cases.

To save the waste in invalid channel allocation to users with poor channel condition, we propose a DUST algorithm, in which the user set is dynamically adjusted by the CC based on the traffic load. More specifically, 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 [25]. When the traffic becomes heavier, CC will remove the users, in the order from poorest link to best link, out of user set to increase the overall system capacity. The reason behind is the opportunity of relaying becomes smaller, and the transmissions from users with poor links are wasted.

## 4.2 Preliminary

Consider the *uplink* of a centralized wireless network and there are total *M* users within this network.

### 4.2.1 Generalized MPR Channel

Let *1* ~ *M* denote the users' IDs respectively. Thus, the generalized MPR matrix can be expressed as

$$\mathbf{C}(U(t)) \triangleq \begin{bmatrix} C_{1,0}(U(t)) & C_{1,1}(U(t)) & & & \\ C_{2,0}(U(t)) & C_{2,1}(U(t)) & C_{2,2}(U(t)) & & \\ \vdots & \vdots & \vdots & & \\ C_{M,0}(U(t)) & C_{M,1}(U(t)) & C_{M,2}(U(t)) & \cdots & C_{M,M}(U(t)) \end{bmatrix}, \tag{4.1}$$

in which the user set $U(t) = \{u_1(t), u_2(t), \cdots, u_M(t)\}$, $u_i(t) \in U = \{1, 2, \cdots, M\}$, is the index set of users after certain permutation such as priority sorting [25]. For $1 \le n \le M$ and $0 \le k \le n$, $C_{n,k}(U(t)) \triangleq$ Pr{ $k$ packets correctly received | $n$ packets from first $n$ users in $U(t)$ transmitted}. Denotes

$$C_n(U(t)) \triangleq \sum_{k=1}^{n} kC_{n,k}(U(t)) \tag{4.2}$$

the expected number of correctly received packets when total $n$ packets from $U_n(t) = \{u_1(t), u_2(t), \cdots, u_n(t)\}$ are transmitted. The *instantaneous* channel capacity is defined as

$$\eta(U(t)) \triangleq \max_{n=1,\cdots,M} C_n(U(t)). \tag{4.3}$$

Let

$$n_0(U(t)) \triangleq \min\left\{\arg\max_{n=1,\cdots,M} C_n(U(t))\right\} \tag{4.4}$$

be the minimum among those capacity-achieving packet numbers for power saving.

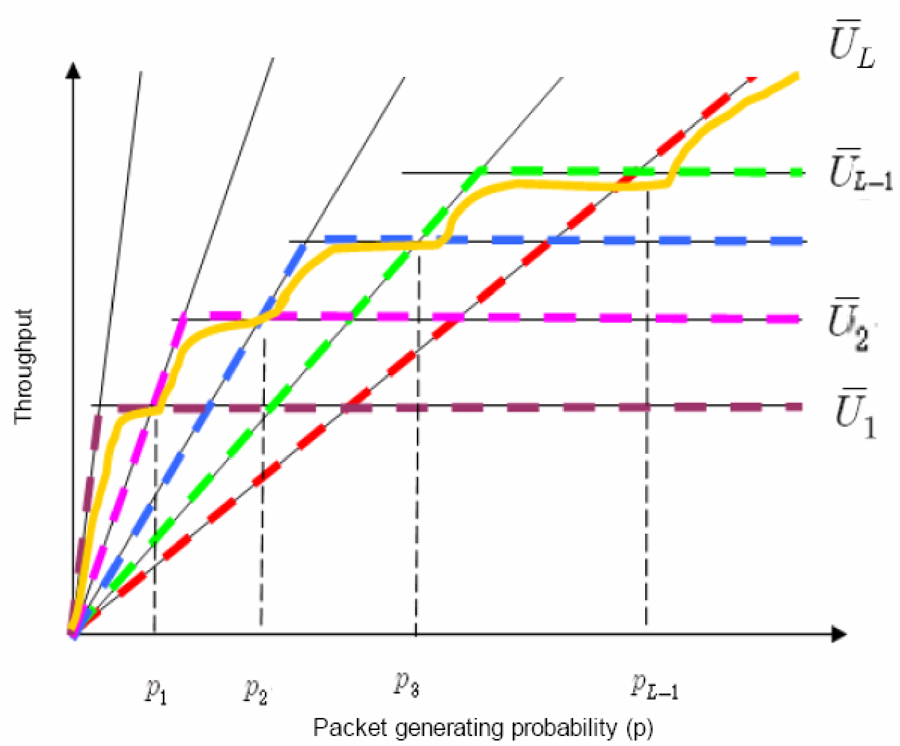



Fig. 4.1 Schematic throughput curves for different user sets.

### 4.2.2 Capacity Bound

As shown in [10][25] and depicted in Fig. 4.1, the *fair*[3] system capacity of MPR channel is bounded by one oblique line for unsaturated traffic and one horizontal line for saturated traffic. To utilize the observation for the proposed DUST algorithm, we derive the following theorem.

**Theorem 4.1** For a user set $\bar{U}$ with $m$ users, the fair system capacity is upper bounded by *mp* and $\frac{1}{m!}\sum_{\forall \bar{U}_i \in \mathbf{\bar{U}}} \eta\left(\bar{U}_i\right)$, where $p$ is the packet generating probability. □

Proof: Assume that the traffic is unsaturated; the throughput $T_p$ equals the number of transmitted packets. $T_p$ can be calculated as

[3] A fair system, i.e., all users in the specified user set sharing the same channel resources under full load, is considered.

$$
\begin{aligned}
T_p &= s \cdot p \\
&= \frac{T_1 - T_0}{p_1 - p_0} \cdot p,
\end{aligned}
\tag{4.5}
$$

where $s$ is the slope of the throughput curve, $p$ is the packet generating probability. It can be easily seen that $T_0 = 0$ and $T_1 = m$ under the assumption that the traffic is unsaturated. Hence the capacity for the unsaturated traffic can be represented by

$$
\begin{aligned}
T_p &= \frac{T_1 - T_0}{p_1 - p_0} \cdot p \\
&= \frac{m - 0}{1 - 0} \cdot p \\
&= mp.
\end{aligned}
\tag{4.6}
$$

If the traffic is saturated, the throughput $T_p$ equals to a constant value no matter how the traffic changes. For each permutation $\bar{U}_i(t)$, there exists an instantaneous channel capacity $\eta\left(\bar{U}_i(t)\right)$. In order to get an average channel capacity instead of an instantaneous channel capacity changing with time, an averaging method is proposed. There are total $m!$ permutations and $\bar{\mathbf{U}} = \left\{\bar{U}_1, \bar{U}_2, \cdots, \bar{U}_{m!}\right\}$ is the permutation set, where $\bar{U}_i$ is the index set of users under certain permutation. The average channel capacity can be calculated using the instantaneous channel capacity set above under the assumption that every permutation will have the same probability to appear in the long run if the network is a fair system. Therefore the average channel capacity under the fair system is

$$
\begin{aligned}
\sum_{i=1}^{m!} \eta\left(\bar{U}_i\right) p\left(\bar{U}_i\right) &= \sum_{i=1}^{m!} \eta\left(\bar{U}_i\right) \frac{1}{m!} \\
&= \frac{1}{m!} \sum_{\forall \bar{U}_i \in \bar{\mathbf{U}}} \eta\left(\bar{U}_i\right)
\end{aligned}
\tag{4.7}
$$

where $p\left(U_i\right)$ is the probability of permutation $U_i$. □

With above theorem, we propose to specify a dynamic user set for throughput optimization based on traffic load as shown in Fig. 4.1. $L$ user sets should be determined for $L$ traffic load sections, i.e., $[p_0, p_1]$, $[p_1, p_2]$, …, $[p_{L-1}, p_L]$, where $p_0 = 0$ and $p_L = 1$. $L$ is a parameter related to user distribution, $1 \le L \le M$.

## 4.3 Proposed DUST Algorithm

### 4.3.1 Initialization

In order to construct the GMPR matrix (4.1) and dynamically exclude user(s) from user set by channel condition as described in Section 4.2.2, CC will request a beacon signal from each $u_i \in U$ and form a vector $\mathrm{s} = [s_1, s_2, \cdots, s_M]$, where $s_i$ is the received signal power from user $i$. By sorting $\mathrm{s}$ in descending order as $\mathrm{s}' = [s_1', s_2', \cdots, s_M']$, CC can get a corresponding permutation of user set $U' = \{u_1', u_2', \cdots, u_M'\}$, and further decompose $U' = \bigcup_{1 \le i \le L} U_i'$, in which $\forall_{1 \le i,j \le L, i \ne j} U_i' \cap U_j' = \varnothing$, $s_i' = s_j'$ $\forall i, j \in U_k'$, and $s_i' > s_j'$ if and only if $s_i' \in U_a'$, $s_j' \in U_b'$, and $a < b$.

### 4.3.2 DUST Equations

$$p_i = \frac{1}{\left|\bar{U}_{i+1}\right|\left|\bar{U}_i\right|!} \sum_{\forall \bar{U}_i \text{ permutation}} \eta\left(\bar{U}_i\right), 1 \le i \le L-1, \tag{4.8}$$

where
$$\bar{U}_{i+1} = \bar{U}_i \setminus U_{L-i+1}', \quad \bar{U}_1 = U'. \tag{4.9}$$

### 4.3.3 DUST+CMGP Algorithm

1. Based on the traffic load, i.e. packet generating probability to define the user set. In other words, if $p_{i-1} \le p < p_i$, then chose $\bar{U}_i$ as user set.
2. Follow the CMGP in [25] (not duplicated here for saving space).

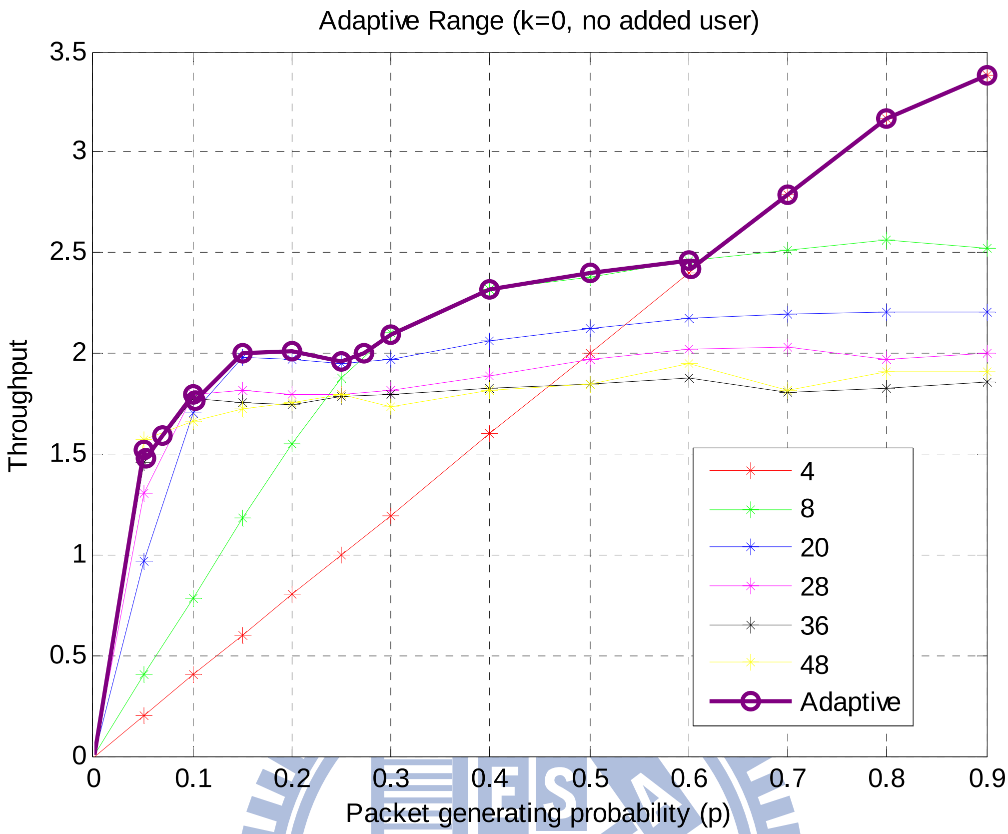



Fig. 4.2 Throughput performance of the proposed DUST.

## 4.4 Numerical Results

We consider a CDMA network with randomly generated spreading codes. The packet length, spreading gain, number of correctable errors in a packet are respectively, 200, 6, and 2, as in [25], and 48 users are deployed in a grid distribution. As we can see in Fig. 4.2, the simulated results comply with our initial observation in Fig. 4.1, thus validating the derived theorem. The associated packet generating probabilities for each user set are also correctly estimated by (4.8) and (4.9). Finally, the overall throughput is significantly improved by using DUST.

## 4.5 Summary

In this chapter we propose a DUST algorithm, where the user set is dynamically adjusted by the

CC based on the traffic load. More specifically, 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 the order from poorest link to best link, out of user set to increase the overall system capacity. Because the opportunity of relaying becomes smaller, the transmissions from users with poor links are wasted.

# Chapter 5

# Conclusions and Future Works

## 5.1 Summary of Dissertation

This dissertation mainly addresses the MAC protocol design for wireless networks with MPR capability. The main contribution lies in that we propose to utilize a simple flag-bit and multi-group priority queueing, which largely reduce the computational complexity for active user identification; moreover, the spatial diversity can be easily used for cooperation among users.

The introductory chapter includes the background overview, literature review, and contributions of this dissertation. In Chapter 2, we proposed a new approach to design the MAC protocol for wireless networks with MPR capability. The proposed approach relies on the flag-bit-assisted knowledge about the presence of buffered packets as well as a multi-priority user grouping strategy. The advantages of the proposed method are three folds: 1) it is applicable to both the heterogeneous and homogeneous environments, whereas almost all existing protocols developed for the MPR channel are exclusively tailored for the latter case; 2) the insertion of a single bit facilitates the acquisition of network traffic condition with minimal bandwidth expansion; 3) the adopted user grouping policy avoids computationally intensive search for the active users as required in the existing protocols. To prevent an infinitely long service delay in the heterogeneous environment, the waiting period of those yet-to-be-served users can be determined subject to a specified delay requirement. Simulation results show that, compared with the DQ protocol, the proposed scheme achieves higher throughput, reduces the mean delay penalty in light traffic condition, and yields a smaller PLR. Also, the proposed MGPQ protocol outperforms the PMP protocol for the general case with finite buffer size.

In Chapter 3, we extend the protocol proposed in Chapter 2 to develop a cooperative MPR

MAC. As far as we know, our scheme is the first proposal which integrates the user cooperation facility and the PHY-layer MPR advantage for MAC protocol designs. The proposed method relies on a priority based scheduling mechanism, and does not need active user identification. It is thus a promising candidate for the low-complexity protocol implementation in dense cooperative networks. Based on Markov chain models we provide throughput analysis for the proposed protocol. We derive closed-form throughput bounds for the worst case that allow us to investigate the impact of the MPR capability on the system performance. Simulation results confirm the throughput advantage achieved by the proposed method, and validate the presented analytical results.

In Chapter 4, we propose a DUST algorithm aiming for uplink throughput optimization in wireless networks with MPR. Numerical results show significant improvement in the network throughput.

## 5.2 Future Works

MPR matrix is actually an abstract form of PHY layer characteristics including modulation, coding, bit rate, antenna, and channel response. In other words, MPR matrix eases the design of MAC protocols by simplifying so many PHY individual complicated parameters as an integrated probability matrix. Comparing with traditional MAC designs, cross-layer concept has been utilized in such a PHY-to-MAC design approach. Therefore, how to obtain an accurate MPR matrix may be a crucial factor for a valid MAC protocol, and the associated sensitivity analysis is also a research topic not yet studied in the literature. The reverse direction, i.e., MAC-to-PHY design is another topic currently under investigation. The main idea is to use the channel capacity calculated by MPR matrix as a metric for adaptive modulation and coding (AMC).

# Appendix

## A. Proof of Lemma 2.1

According to the definition of $\eta$ in Section 2.2, we have

$$\begin{aligned}\eta &= \sum_{k-1}^{n_0} k \cdot C_{n_0,k} \\ &= \sum_{k-1}^{n_0-1} k \cdot C_{n_0,k} + n_0 \cdot C_{n_0,n_0}.\end{aligned} \tag{A.1}$$

If $C_{n_0,n_0} = 0$, then (A.1) becomes

$$\begin{aligned}\eta &= \sum_{k-1}^{n_0-1} k \cdot C_{n_0,k} \\ &\leq \sum_{k-1}^{n_0-1} k \cdot C_{n_0-1,k} \\ &= \eta',\end{aligned} \tag{A.2}$$

where $\eta'$ corresponds to a higher or equal channel capacity but achieved by sending $n_0 - 1$ packets simultaneously. Note that the inequality in (A.2) holds because the success probability of transmitting more packets simultaneously is less than or equal to that of transmitting less packets under the same channel condition, that is, $C_{n_0,k} \leq C_{n_0-1,k}$. Because (A.2) conflicts with the definition of channel capacity, we conclude that $C_{n_0,n_0} > 0$ > 0 with proof by contradiction. Thus, we have $p_{ms} \geq C_{n_0,n_0} = \delta > 0$. □

## B. Proof of Lemma 2.2

We first derive the $t_{\max}$ as follows.

For $1 \leq S \leq M / n_0$, do the following.

Let $n_{PREM}$, $n_{ACTIVE}$, and $n_{STANDBY}$ denote the number of users in the PREM, ACTIVE, and STANDBY groups, respectively, and then we have

$$n_{PREM} + n_{ACTIVE} + n_{STANDBY} = M. \tag{B.1}$$

Because the user with waiting slots equal to $S$ will be moved to the PREM group, the waiting slots of the users in the ACTIVE and STANDBY groups must be less than $S$, that is, equal to 1, 2, . . ., or $S-1$. Besides, as $n_0$ users are selected to access the channel in each slot, the maximal number of users with the same waiting slots must be less than or equal to $n_0$. Therefore, it can be seen that

$$\begin{aligned} n_{ACTIVE} + n_{STANDBY} &\leq (S-1)\,n_0 \\ &\leq \left(\frac{M}{n_0} - 1\right) n_0 \\ &= M - n_0. \end{aligned} \tag{B.2}$$

Combining (B.1) and (B.2), we have

$$\begin{aligned} n_{PREM} &= M - (n_{ACTIVE} + n_{STANDBY}) \\ &\geq M - (M - n_0) \\ &= n_0. \end{aligned} \tag{B.3}$$

Equation (B.3) shows that there will always be at least $n_0$ users in the PREM group waiting for channel access, which implies that all users will be selected ($n_0$ users per slot) to access the channel in turn in the PREM group, that is,

$$t_{\max} = \left\lceil \frac{M}{n_0} \right\rceil. \tag{B.4}$$

For $\frac{M}{n_0} < S < \infty$, the following hold.

According to the MGPQ protocol defined in Section 3.3, all users are in the PREM group initially. After $\left\lfloor \frac{M}{n_0} \right\rfloor$ slots, there will be less than $n_0$ users left in the PREM group because

$M - \left\lfloor \frac{M}{n_0} \right\rfloor n_0 < n_0$; and no user reenters the PREM group because $\left\lfloor \frac{M}{n_0} \right\rfloor \le \frac{M}{n_0} < S$. Hereafter, the input rate of the PREM group is less than or equal to the output rate ($n_0$/slot) of the PREM group, which implies that the users entering the PREM group will be immediately selected to access the channel, that is, $t_{\max} = S$. □

## C. Proof of $N_C$ in (2.13)

It is known from the multinomial theorem that [14]

$$\binom{n}{k_1, k_2, \cdots, k_m} = \frac{n!}{k_1! k_2! \cdots k_m!}, \text{ where } \sum_{i=1}^{m} k_i = n. \tag{C.1}$$

The above multinomial coefficient can be interpreted as the number of distinct ways to permute a multiset of $n$ elements, and $k_i$'s are the multiplicities of each distinct element. According to the MGPQ protocol defined in Section 3.3, there will be always exactly $n_0$ users whose waiting slots are one. However, there may be 0 to $n_0$ users with the same waiting slots ranging from 2 to $S$, because the users in the ACTIVE group may be selected with higher priority than those in the STANDBY group. Let $m_i$ stand for the number of distinct waiting slots which $i$ users have waited for, $0 \le i \le n_0$. Then we have

$$N_C = \underbrace{\frac{M!}{n_0!(M-n_0)!}}_{\text{(a)}} \cdot \underbrace{\sum_{m_i} \frac{(S-1)!}{\prod_{i=0}^{n_0}(m_i!)}}_{\text{(b)}} \cdot \underbrace{\frac{(M-n_0)!}{\prod_{i=0}^{n_0}(i!)^{m_i}}}_{\text{(c)}}, \tag{C.2}$$

where $\underbrace{\sum_{i=0}^{n_0} m_i = S-1}_{\text{(d)}}$ and $\underbrace{\sum_{i=0}^{n_0} i \cdot m_i = M - n_0}_{\text{(e)}}$.

In (C.2), (a) is the possible combinations for distinct $n_0$ users whose waiting slots equal 1; (b) accounts for possible combinations of $m_i$'s in the remaining $S-1$ waiting slots; (c) accounts for possible combinations of $i$'s in the remaining $M-n_0$ users; (d) is the constraint for multinomial coefficient (b), that is, summation of $m_i$'s must equal $S-1$; and (e) is the constraint for multinomial coefficients (c), that is, summation of users in each $m_i$'s must equal $M-n_0$. □

# D. Description of State Transition Probability in Section 2.4.2

Denoted by $A=\{a_1,a_2,\cdots,a_{n_0}\}$ the index set of the users who are allowed to access the channel. Also, let $n_a$ be the number of nonzero elements in $\{z_{a_1},z_{a_2},\cdots,z_{a_{n_0}}\}$, that is, the number of packets that will be sent simultaneously. Define $P_S$ as the success probability of selected user with packet to send in each slot, then

$$P_S=\sum_{k=1}^{n_a}\frac{k}{n_a}\cdot C_{n_a,k}\,. \tag{D.1}$$

Thus, the probabilities of the increment of state for $X$, $Y$, $Z$ components, that is, $P_x(\triangle x_i)$, $P_y(\triangle y_i)$, and $P_z(\triangle z_i)$ can be calculated by (D.2) according to current state $(X,Y,Z)$.

$$P_x(\triangle x_i=1-x_i)=1,\ \ i\in A$$

$$P_x(\triangle x_i=1)=1,\ \ i\notin A$$

$$P_y(\triangle y_i=0)=\begin{cases}1 & \begin{cases} i\in A,\ y_i=0,\ z_i<2\\ i\in A,\ y_i=1,\ z_i=2\\ i\notin A\end{cases}\\ 1-P_S,\ i\in A,\ y_i=0,\ z_i=2\end{cases}$$

$$P_y(\triangle y_i=1)=P_S,\ \ i\in A,\ y_i=0,\ z_i=2$$

$$P_y(\triangle y_i=-1)=1,\ \ i\in A,\ y_i=1,\ z_i=1$$

$$P_z(\triangle z_i = 0) = \begin{cases} p_i P_S + (1-p_i)(1-P_S),\ i \in A,\ z_i = 1 \\ p_i P_S + (1-P_S),\ i \in A,\ z_i = 2 \\ 1 - p_i \begin{cases} z_i = 0 \\ i \notin A,\ z_i = 1 \end{cases} \\ 1,\ i \notin A,\ z_i = 2 \end{cases}$$

$$P_z(\triangle z_i = 1) = \begin{cases} p_i(1-P_S),\ i \in A,\ z_i = 1 \\ p_i \begin{cases} i \notin A,\ z_i = 1 \\ z_i = 0 \end{cases} \end{cases}$$

$$P_z(\triangle z_i = -1) = (1-p_i)P_S,\ \ i \in A,\ z_i > 0. \tag{D.2}$$

□

## E. Proof of Statement in Section 2.4.4

If each user has equal packet generating probability, without loss of generality, we can write the transition matrix as **T**=**G** $\otimes$ **H** by appropriate ordering of states, where **G** is the $N_C \times N_C$ transition matrix of state $X(t)$, **H** is the $5^M \times 5^M$ transition matrix of state $(Y(t), Z(t))$, and $\otimes$ stands for Kronecker product. Note **G** (including size and contents) is the function of the waiting period selection $S$, and **H** is the function of packet generating probability.

To compute the steady-state probabilities, let

$$\mathbf{G} = \begin{bmatrix} g_{1,1} & g_{1,2} & \cdots & g_{1,N_C} \\ g_{2,1} & g_{2,2} & \cdots & g_{2,N_C} \\ \vdots & \vdots & \ddots & \vdots \\ g_{N_C,1} & g_{N_C,2} & \cdots & g_{N_C,N_C} \end{bmatrix},$$

$$\mathbf{H} = \begin{bmatrix} h_{1,1} & h_{1,2} & \cdots & h_{1,5^M} \\ h_{2,1} & h_{2,2} & \cdots & h_{2,5^M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{5^M,1} & h_{5^M,2} & \cdots & h_{5^M,5^M} \end{bmatrix}. \tag{E.1}$$

According to the property of Kronecker product, we have $\mathbf{T}^{\infty}=\mathbf{G}^{\infty} \otimes \mathbf{H}^{\infty}$, in which

$$\mathbf{G}^{\infty} = \begin{bmatrix} g_1 & g_2 & \cdots & g_{N_C} \\ g_1 & g_2 & \cdots & g_{N_C} \\ \vdots & \vdots & \ddots & \vdots \\ g_1 & g_2 & \cdots & g_{N_C} \end{bmatrix}, \text{ where } \sum_{\alpha=1}^{N_C} g_{\alpha} = 1;$$

$$\mathbf{H}^{\infty} = \begin{bmatrix} h_1 & h_2 & \cdots & h_{5^M} \\ h_1 & h_2 & \cdots & h_{5^M} \\ \vdots & \vdots & \ddots & \vdots \\ h_1 & h_2 & \cdots & h_{5^M} \end{bmatrix}, \text{ where } \sum_{\beta=1}^{5^M} h_{\beta} = 1. \tag{E.2}$$

Now, (17) can be written as

$$\begin{bmatrix} \pi_1 & \pi_2 & \cdots & \pi_{N_S} \\ \pi_1 & \pi_2 & \cdots & \pi_{N_S} \\ \vdots & \vdots & \ddots & \vdots \\ \pi_1 & \pi_2 & \cdots & \pi_{N_S} \end{bmatrix} = \begin{bmatrix} g_1 & g_2 & \cdots & g_{N_C} \\ g_1 & g_2 & \cdots & g_{N_C} \\ \vdots & \vdots & \ddots & \vdots \\ g_1 & g_2 & \cdots & g_{N_C} \end{bmatrix} \otimes \begin{bmatrix} h_1 & h_2 & \cdots & h_{5^M} \\ h_1 & h_2 & \cdots & h_{5^M} \\ \vdots & \vdots & \ddots & \vdots \\ h_1 & h_2 & \cdots & h_{5^M} \end{bmatrix}. \tag{E.3}$$

Substituting (E.3) into (2.19), we have

$$\begin{aligned} N_i(S) &= \sum_{j=1}^{N_S} \pi_j z_{i,j} \\ &= \sum_{\alpha=1}^{N_C} \sum_{\beta=1}^{5^M} \left( g_{\alpha} h_{\beta} z_{i,\beta} \right) \\ &= \sum_{\alpha=1}^{N_C} g_{\alpha} \left( \sum_{\beta=1}^{5^M} \left( h_{\beta} z_{i,\beta} \right) \right) \\ &= \sum_{\beta=1}^{5^M} \left( h_{\beta} z_{i,\beta} \right) \\ &\triangleq N_B. \end{aligned} \tag{E.4}$$

Substituting (E.3) into (20), we have

$$
\begin{aligned}
p_{B,i}(S) &= \sum_{1\le j'\le N_S, z_{i,j'}=2, i\notin A} \pi_{j'} + \sum_{1\le j'\le N_S, z_{i,j'}=2, i\in A} \pi_{j'}(1-P_S) \\
&= \sum_{\alpha=1}^{N_C} g_\alpha \left( \sum_{\beta=1, i\notin A}^{5^M} h_\beta \delta(z_{i,\beta}-2) + \sum_{\beta=1, i\in A}^{5^M} g_\alpha h_\beta \delta(z_{i,\beta}-2)(1-P_S) \right). \\
&= \sum_{\beta=1, i\notin A}^{5^M} h_\beta \delta(z_{i,\beta}-2) + \sum_{\beta=1, i\in A}^{5^M} g_\alpha h_\beta \delta(z_{i,\beta}-2)(1-P_S) \\
&\triangleq P_B.
\end{aligned}
\tag{E.5}
$$

Substituting (E.5) into (2.21), we have

$$
\begin{aligned}
\lambda_i(S) &= p_i\left(1-p_{B,i}(S)\right) \\
&= p(1-p_B) \\
&\triangleq \Lambda.
\end{aligned}
\tag{E.6}
$$

Note that the $z_{i,j}$ in (E.4) and (E.5) is replaced with $z_{i,\beta}$, because it is not related with $g_\alpha$. Substituting (E.4) and (E.6) into (18), we have

$$
\begin{aligned}
D_i(S) &= \frac{N_i(S)}{\lambda_i(S)} \\
&= \frac{N_B}{\Lambda} \\
&\triangleq D.
\end{aligned}
\tag{E.6}
$$

The above derivations prove the throughput (E.6), mean delay (E.7), and blocking probability (E.5) of the system with equal packet generating probability are the functions of packet generating probabilities, but independent of $S$. □

## F. Proof of Theorem 3.1

Without loss of generality, we assume that $u_1 = i$ for simplicity. To ease the derivation, we define the following notations. Note that the state $q$ is defined as the number of the packets in the user's buffer.

$p$ : packet generating probability

$T_i$ : throughput of user $i$

$p_i^B$ : packet blocking probability of user $i$

$\tilde{p}_i^B$ : packet blocking probability of user $i$ with cooperation

$p_i^a(q)$ : access probability of user $i$ at state $q$

$\tilde{p}_i^a(q)$ : access probability of user $i$ at state $q$ with cooperation

$p_i^s(q)$ : successful packet transmission probability of user $i$ at state $q$

$\tilde{p}_i^s(q)$ : successful packet transmission probability of user $i$ at state $q$ with cooperation

$s_i(q)$ : state probability of user $i$ at state $q$

$\tilde{s}_i(q)$ : state probability of user $i$ at state $q$ with cooperation

$\alpha_i(q)$ : birth probability of user $i$ at state $q$

$\beta_i(q)$ : death probability of user $i$ at state $q$

$\rho_i(q)$ : utilization factor of user $i$ between state $q-1$ and $q$

The state probability of the birth and death process can be derived by the birth probability and death probability as follows.

A birth event occurs when a new packet is generated and no existing packets in the buffer are successfully transmitted:

$$\begin{aligned}\alpha_i(q) &= pp_i^a(q)\left[1-p_i^s(q)\right]+p\left[1-p_i^a(q)\right] \\ &= p\left[1-p_i^a(q)\,p_i^s(q)\right],\ 0\le q<2.\end{aligned} \tag{F-1}$$

A death event occurs when a existing packet in the buffer is successfully transmitted but no new packets are generated:

$$\beta_i(q) = (1-p)\,p_i^a(q)\,p_i^s(q),\ \ 0 < q \le 2 \tag{F-2}$$

Thus, the utilization factor is obtained by definition [14],

$$\begin{aligned}\rho_i(q) &\triangleq \frac{\alpha_i(q-1)}{\beta_i(q)} \\ &= \frac{p\left[1-p_i^a(q-1)\,p_i^s(q-1)\right]}{(1-p)\,p_i^a(q)\,p_i^s(q)},\ 1 \le q \le 2.\end{aligned} \tag{F-3}$$

With the utilization factor in (F-3), we can proceed with the state probability of the state with occupied buffer, i.e., two packets in the buffer:

$$\begin{aligned}s_i(2) &= \frac{\rho_i(1)\,\rho_i(2)}{1+\rho_i(1)+\rho_i(1)\,\rho_i(2)} \\ &= \frac{\frac{\alpha_i(0)}{\beta_i(1)}\frac{\alpha_i(1)}{\beta_i(2)}}{1+\frac{\alpha_i(0)}{\beta_i(1)}+\frac{\alpha_i(0)}{\beta_i(1)}\frac{\alpha_i(1)}{\beta_i(2)}} \\ &= \frac{\frac{p[1-p_i^a(0)\,p_i^s(0)]}{(1-p)\,p_i^a(1)\,p_i^s(1)}\frac{p[1-p_i^a(1)\,p_i^s(1)]}{(1-p)\,p_i^a(2)\,p_i^s(2)}}{1+\frac{p[1-p_i^a(0)\,p_i^s(0)]}{(1-p)\,p_i^a(1)\,p_i^s(1)}+\frac{p[1-p_i^a(0)\,p_i^s(0)]}{(1-p)\,p_i^a(1)\,p_i^s(1)}\frac{p[1-p_i^a(1)\,p_i^s(1)]}{(1-p)\,p_i^a(2)\,p_i^s(2)}} \\ &= \frac{p[1-p_i^a(0)\,p_i^s(0)]\,p[1-p_i^a(1)\,p_i^s(1)]}{(1-p)\,p_i^a(1)\,p_i^s(1)(1-p)\,p_i^a(2)\,p_i^s(2)+p[1-p_i^a(0)\,p_i^s(0)](1-p)\,p_i^a(2)\,p_i^s(2)+p[1-p_i^a(0)\,p_i^s(0)]\,p[1-p_i^a(1)\,p_i^s(1)]}.\end{aligned} \tag{F-4}$$

A packet blocking occurs at the user who has no more buffer space and is neither being selected to access the channel nor transmitting successfully.

$$
\begin{aligned}
p_i^B &= s_i(2)[1-p_i^a(2)p_i^s(2)] \\
&= \frac{p[1-p_i^a(0)p_i^s(0)]p[1-p_i^a(1)p_i^s(1)][1-p_i^a(2)p_i^s(2)]}{(1-p)p_i^a(1)p_i^s(1)(1-p)p_i^a(2)p_i^s(2)+p[1-p_i^a(0)p_i^s(0)](1-p)p_i^a(2)p_i^s(2)+p[1-p_i^a(0)p_i^s(0)]p[1-p_i^a(1)p_i^s(1)]} \quad \text{(F-5)} \\
&= \frac{p^2[1-p_i^a(0)p_i^s(0)][1-p_i^a(1)p_i^s(1)][1-p_i^a(2)p_i^s(2)]}{(1-p)^2 p_i^a(1)p_i^s(1)p_i^a(2)p_i^s(2)+p(1-p)[1-p_i^a(0)p_i^s(0)]p_i^a(2)p_i^s(2)+p^2[1-p_i^a(0)p_i^s(0)][1-p_i^a(1)p_i^s(1)]} \\
&= \frac{p^2[1-p_i^a(0)p_i^s(0)][1-p_i^a(1)p_i^s(1)][1-p_i^a(2)p_i^s(2)]}{\left\{(1-p)^2 p_i^a(1)p_i^s(1)+p(1-p)[1-p_i^a(0)p_i^s(0)]\right\}p_i^a(2)p_i^s(2)+p^2[1-p_i^a(0)p_i^s(0)][1-p_i^a(1)p_i^s(1)]} \\
&= \frac{A_i[1-p_i^a(2)p_i^s(2)]}{B_i p_i^a(2)p_i^s(2)+A_i},
\end{aligned}
$$

where

$$A_i = p^2[1-p_i^a(0)p_i^s(0)][1-p_i^a(1)p_i^s(1)], \text{ and} \quad \text{(F-6)}$$

$$B_i = (1-p)^2 p_i^a(1)p_i^s(1)+p(1-p)[1-p_i^a(0)p_i^s(0)]. \quad \text{(F-7)}$$

For those users with packet blocking probability smaller than some positive number $\delta$, we can derive the following lower bound on $p_i^s(2)$. Substituting (F-5) into $p_i^B \le \delta$, we have

$$
\begin{aligned}
&\Rightarrow A_i[1-p_i^a(2)p_i^s(2)] \le \delta B_i p_i^a(2)p_i^s(2)+\delta A_i \\
&\Rightarrow p_i^a(2)p_i^s(2) \ge \frac{A_i-\delta A_i}{A_i+\delta B_i} \\
&\qquad = 1-\frac{\delta B_i+\delta A_i}{A_i+\delta B_i} \quad \text{(F-8)} \\
&\qquad = 1-\frac{\delta(A_i+B_i)}{A_i+\delta B_i} \\
&\Rightarrow p_i^s(2) \ge 1-\frac{\delta(A_i+B_i)}{A_i+\delta B_i}.
\end{aligned}
$$

Before stepping further, we need the respective successful packet transmission probability. Let $p_k^n(U)$ denote the successful packet transmission probability of user $k$ under concurrent transmissions from the first $n$ users in $U$. As the respective successful probability is a non-increasing function of the number of concurrent transmissions (interferences), it is evident that

$$p_k^n(U) \le p_k^{n-1}(U \setminus \{j\}), \tag{F-9}$$

where users $k$ and $j$ are two of the first $n$ users in $U$ and $k \ne j$.

Without loss of generality, we assume the user order and the designation of user are the same here, i.e., user $j$ is the $j$th user in $U$. By summing (F-9) for the first $n_0(U)$ users exclusive of user $j$ on both sides, we have

$$\sum_{k=1}^{j-1} p_k^{n_o(U)}(U) + \sum_{k=j+1}^{n_o(U)} p_k^{n_o(U)}(U) \le \sum_{k=1}^{j-1} p_k^{n_o(U)-1}(U \setminus \{j\}) + \sum_{k=j+1}^{n_o(U)} p_k^{n_o(U)-1}(U \setminus \{j\}). \tag{F-10}$$

Add $p_j^{n_o(U)}(U)$ on both sides of (F-10), and then

$$\begin{aligned} \sum_{k=1}^{j-1} p_k^{n_o(U)}(U) + \sum_{k=j+1}^{n_o(U)} p_k^{n_o(U)}(U) + p_j^{n_o(U)}(U) &\le \sum_{k=1}^{j-1} p_k^{n_o(U)-1}(U \setminus \{j\}) + \sum_{k=j+1}^{n_o(U)} p_k^{n_o(U)-1}(U \setminus \{j\}) + p_j^{n_o(U)}(U) \\ \sum_{k=1}^{n_o(U)} p_k^{n_o(U)}(U) &\le \sum_{k=1}^{j-1} p_k^{n_o(U)-1}(U \setminus \{j\}) + \sum_{k=j+1}^{n_o(U)} p_k^{n_o(U)-1}(U \setminus \{j\}) + p_j^{n_o(U)}(U) \\ p_j^{n_o(U)}(U) &\ge \sum_{k=1}^{n_o(U)} p_k^{n_o(U)}(U) - \left( \sum_{k=1}^{j-1} p_k^{n_o(U)-1}(U \setminus \{j\}) + \sum_{k=j+1}^{n_o(U)} p_k^{n_o(U)-1}(U \setminus \{j\}) \right). \end{aligned} \tag{F-11}$$

Note that $\sum_{k=1}^{n_o(U)} p_k^{n_o(U)}(U)$ equals $C_{n_0(U)}(U)$ in (2) and $\sum_{k=1}^{j-1} p_k^{n_o(U)-1}(U \setminus \{j\}) + \sum_{k=j+1}^{n_o(U)} p_k^{n_o(U)-1}(U \setminus \{j\})$ equals $C_{n_0(U)-1}(U \setminus \{j\})$.

Thus, we have

$$p_j^{n_o(U)}(U) \ge C_{n_0(U)}(U) - C_{n_0(U)-1}(U \setminus \{j\}). \tag{F-12}$$

We now consider the worst case where only the one direct link is user $i$, and the other concurrent transmissions are all relay links. In such a condition, the direct link will suffer from the most interference produced by relay links, which are not present in non-cooperative scenario.

Let $\tilde{p}_i^s(2) = p_i^s(2) - \Delta_i$, where $\Delta_i$ is the maximal degradation of the successful packet transmission probability of the user $i$ due to relay links. We have

$$\Delta_i = C_1(\{i\}) - C_{n_0(U)}(U) + C_{n_0(U)-1}(U \setminus \{i\}), \tag{F-13}$$

where $C_1(\{i\})$ is the successful packet transmission probability of only one user $i$'s packet transmitted, and $C_{n_0(U)}(U) - C_{n_0(U)-1}(U \setminus \{i\})$ is the *minimal* successful packet transmission probability of user $i$ with $n_0(U)-1$ relay links as shown in (F-12). Now, let us look at the packet blocking probability with cooperation:

$$\begin{aligned} \tilde{p}_i^B &= \tilde{s}_i(2)\left[1 - \tilde{p}_i^a(2)\tilde{p}_i^s(2)\right] \\ &= \tilde{s}_i(2)\left[1 - \tilde{p}_i^a(2)p_i^s(2) + \tilde{p}_i^a(2)\Delta_i\right] \\ &\le \tilde{s}_i(2)\left[1 - 1 + \frac{\delta(A_i + B_i)}{A_i + \delta B_i} + \tilde{p}_i^a(2)\Delta_i\right] \\ &= \tilde{s}_i(2)\left[\frac{\delta(A_i + B_i)}{A_i + \delta B_i} + \tilde{p}_i^a(2)\Delta_i\right] \\ &\le \frac{\delta(A_i + B_i)}{A_i + \delta B_i} + \Delta_i. \end{aligned} \tag{F-14}$$

With the bound of packet blocking probability (F-14), the throughput with/without cooperation can be obtained and compared as follows:

$$\begin{aligned}\frac{\tilde{T}_i}{T_i} &= \frac{p\left(1-\tilde{p}_i^B\right)}{p\left(1-p_i^B\right)} \\ &\geq \frac{1-\left(\frac{\delta\left(A_i+B_i\right)}{A_i+\delta B_i}+\Delta_i\right)}{1-\delta} \\ &\geq 1-\left(\frac{\delta\left(A_i+B_i\right)}{A_i+\delta B_i}+\Delta_i\right).\end{aligned} \tag{F-15}$$

In other words, the user $i$ suffers from a throughput penalty bounded by $\frac{\delta\left(A_i+B_i\right)}{A_i+\delta B_i}+\Delta_i$ due to packet relaying. □

## G. Proof of Theorem 3.2

Without loss of generality, we assume that $u_j = j$ and $u_k = k$ for simplicity. The throughput of user $j$ can be derived by (F-5):

$$\begin{aligned}T_j &= p\left(1-p_j^B\right) \\ &= p\left(1-\frac{A_j\left[1-p_j^a(2)p_j^s(2)\right]}{B_jp_j^a(2)p_j^s(2)+A_j}\right) \\ &= p\left(1+\frac{A_j}{B_j}-\frac{A_jB_jp_j^a(2)+A_j^2p_j^a(2)}{B_j^2\left(p_j^a(2)\right)^2p_j^s(2)+A_jB_jp_j^a(2)}\right).\end{aligned} \tag{G-1}$$

According to (G-1), the throughput of user $j$ is a convex function of $p_j^s(2)$, i.e., the throughput is larger than the line function with the endpoints $\left(0,\ T_j(0)\right)$ and $\left(1,\ T_j(1)\right)$. As $p_j^a(2)$ tends to one under low traffic condition, we have

$$\begin{aligned} T_j(0) &= p\left(1+\frac{A_j}{B_j}-\frac{A_jB_jp_j^a(2)+A_j^2p_j^a(2)}{A_jB_jp_j^a(2)}\right) \\ &\approx p\left(1+\frac{A_j}{B_j}-\frac{A_jB_j+A_j^2}{A_jB_j}\right) \\ &= p\left(1+\frac{A_j}{B_j}-1-\frac{A_j}{B_j}\right) \\ &= 0, \end{aligned} \tag{G-2}$$

$$\begin{aligned} T_j(1) &= p\left(1+\frac{A_j}{B_j}-\frac{A_jB_jp_j^a(2)+A_j^2p_j^a(2)}{B_j^2\left(p_j^a(2)\right)^2+A_jB_jp_j^a(2)}\right) \\ &\approx p\left(1+\frac{A_j}{B_j}-\frac{A_jB_j+A_j^2}{B_j^2+A_jB_j}\right) \\ &= p\left(1+\frac{A_j}{B_j}-\frac{A_j}{B_j}\right) \\ &= p. \end{aligned} \tag{G-3}$$

Thus, we can derive the incremental throughput as

$$\begin{aligned} \triangle T_j &\geq \left(T_j(1)-T_j(0)\right)\triangle p_j^s(2) \\ &= p\triangle p_j^s(2). \end{aligned} \tag{G-4}$$

Now, let us turn to $\triangle p_j^s(2)$, which is the incremental successful packet transmission probability due to relaying. We consider the worst case that all relayed packets are the same and no special combining mechanism is available. Therefore $\triangle p_j^s(2)$ should be larger than the maximal value of $C_{n_0(U)}(U)-C_{n_0(U)-1}(U\setminus\{k\})$ for $k\in\left\{u_2,\cdots,u_{n_0(U)}\right\}$ as shown in (F-12), i.e.,

$$\begin{aligned} \triangle p_j^s(2) &\geq \max_{k\in\left\{u_2,\cdots,u_{n_0(U)}\right\}}\left\{C_{n_0(U)}(U)-C_{n_0(U)-1}(U\setminus\{k\})\right\} \\ &= C_{n_0(U)}(U)-\min_{k\in\left\{u_2,\cdots,u_{n_0(U)}\right\}}C_{n_0(U)-1}(U\setminus\{k\}). \end{aligned} \tag{G-5}$$

Substituting (G-5) into (G-4), we conclude

$$\begin{aligned}\triangle T_j &\geq p\triangle p_j^s(2)\\ &\geq p\left(C_{n_0(U)}(U) - \min_{k\in\left\{u_2,\cdots,u_{n_0(U)}\right\}} C_{n_0(U)-1}(U\setminus\{k\})\right).\end{aligned} \tag{G-6}$$

□

# Bibliography


[1] S. Adireddy and L. Tong, “Exploiting decentralized channel state information for random access,” *IEEE Transactions on Information Theory*, vol. 51, no. 2, pp. 537–561, 2005.

[2] ANSI/IEEE Standard 802.11b–1999 (R2003), “Wireless LAN medium access control (MAC) and physical layer (PHY) specifications: higher-speed physical layer extension in the 2.4GHz band,” IEEE SA Standards Board, Tech. Rep., 1999.

[3] M. X. Cheng, Y. Li, and D. Z. Du, Eds., *Combinatorial Optimization in Communication Networks, Springer*, New York, NY, USA, 2006.

[4] H. M. Deitel, *An Introduction to Operating Systems*, Addison-Wesley, Reading, Mass, USA, 1984.

[5] F. H. P. Fitzek, M. D. Katz, *Cooperation in Wireless Networks: Principles and Applications*, Springer, 2006.

[6] R. H. Gau and K. M. Chen, “Predictive multicast polling for wireless networks with multipacket reception and queuing,” *IEEE Transactions on Mobile Computing*, vol. 5, no. 6, pp. 725– 737, 2006.

[7] S. Ghez, S. Verdu, and S. C. Schwartz, “Optimal decentralized control in the random access multipacket channel,” *IEEE Transactions on Automatic Control*, vol. 34, no. 11, pp. 1153–1163, 1989.

[8] I. M. I. Habbab, M. Kavehrad, and C. E. W. Sundberg, “ALOHA with capture over slow and fast fading radio channels with coding and diversity,” *IEEE Journal on Selected Areas in Communications*, vol. 7, no. 1, pp. 79–88, 1989.

[9] M. Hadzialic, M. Hamza, and P. Begovic, “An approach to cell signal coverage reliability in presence of different fading models,” *Proceedings of the 5th ACM international workshop on Mobility management and wireless access*, pp. 91–98, Oct. 2007.

[10] W. L. Huang, K. Letaief, Y. J. Zhang, "Cross-layer multi-packet reception based medium access control and resource allocation for space-time coded MIMO/OFDM," *IEEE Trans. on Wireless Communications*, vol.7, no.9, pp.3372-3384, September 2008.

[11] L. Kleinrock, *Queueing Syste*ms. Volume1: Theory, John Wiley & Sons, New York, NY, USA, 1975.

[12] R. Lin and A. P. Petropulu, "A new wireless medium access protocol based on cooperation," *IEEE Trans. on Signal Processing*, vol. 53, no. 12, pp. 4675–4684, December 2005.

[13] P. Liu, Z. Tao, S. Narayanan, T. Korakis, and S. S. Panwar, "CoopMAC: a cooperative MAC for wireless LANs," *IEEE J. Select. Areas Commun.*, vol. 7, pp.340–354, Feb. 2007.

[14] A. Papoulis, *Probability, Random Variables, and Stochastic Processes*, McGraw-Hill, New York, NY, USA, 2nd edition, 1984.

[15] M. Realp and A. I. P´erez-Neira, "PHY-MAC dialogue with multi-packet reception," in *ETSI Workshop on Broadband Wireless Ad-Hoc Networks and Services*, Sophia Antipolis, France, September 2002.

[16] A. K. Sadek, K. J. R. Liu, A. Ephremides, "Cooperative multiple access for wireless networks: protocols design and stability analysis," *40th Annual Conference on Information Sciences and Systems*, 22–24 March 2006.

[17] M. Sidi and I. Cidon, "Splitting protocols in presence of capture," *IEEE Transactions on Information Theory*, vol. 31, no. 2, pp. 295–301, 1985.

[18] L. Tong, Q. Zhao, and G. Mergen, "Multipacket reception in random access wireless networks: from signal processing to optimal medium access control," *IEEE Communications Magazine*, vol. 39, no. 11, pp. 108–112, 2001.

[19] S. Verdu, *Multiuser Detection*, Cambridge University Press, 1998.

[20] L. C. Wang, A. Chen, and S. Y. Huang, "A cross-layer investigation for the throughput performance of CSMA/CA-based WLANs with directional antennas and capture effect," *IEEE Trans. Vehicular Technology*, vol. 56, no. 5, Sep. 2008.

[21] Z. Wang, H. R. Sadjadpour, J. J. Garcia-Luna-Aceves, "Capacity-delay tradeoff for information dissemination modalities in wireless networks," *IEEE International Symposium on Information Theory*, 2008, pp.677-681, 6-11 July 2008.

[22] X. Wang and J. K. Tugnait, “A bit-map-assisted dynamic queue protocol for multiaccess wireless networks with multiple packet reception,” *IEEE Transactions on Signal Processing*, vol. 51, no. 8, pp. 2068–2081, 2003.

[23] Z. Wang and X. Yang, *Birth and Death Processes and Markov Chains*, Springer-Verlag, 1992.

[24] W. F. Yang, J. Y. Wu, L. C. Wang, and T. S. Lee, "A multigroup priority queueing MAC protocol for wireless networks with multipacket reception," *EURASIP Journal on Wireless Communications and Networking*, vol. 2008, July 2008.

[25] W. F. Yang; J. Y. Wu; T. S. Lee, "An enhanced multi-packet reception MAC protocol: Cooperative approach," *Third International Conference on ChinaCom 2008*, pp.516-520, 25-27 Aug. 2008.

[26] J. Yu and A. P. Petropulu, “Cooperative transmissions for random access wireless networks with MPR channels,” *Conference on Information Sciences and Systems*, The Johns Hopkins University, 2005.

[27] Q. Zhao and L. Tong, “A multiqueue service room MAC protocol for wireless networks with multipacket reception,” *IEEE/ACM Transactions on Networking*, vol. 11, no. 1, pp. 125– 137, 2003.

[28] Q. Zhao and L. Tong, “A dynamic queue protocol for multiaccess wireless networks with multipacket reception,” *IEEE Transactions on Wireless Communications*, vol. 3, no. 6, pp. 2221–2231, 2004.

[29] M. Zorzi, “Mobile radio slotted ALOHA with capture and diversity,” *Wireless Networks*, vol. 1, no. 2, pp. 227-239, 1995.

[30] M. Zorzi and, R. R. Rao, “Capture and retransmission control in mobile radio,” *IEEE Journal on Selected Areas in Communications*, vol. 12, no. 8, pp. 1289–1298, 1994.

# 簡歷

姓　名 ： 楊 雯 芳

性　別 ： 男

出生年月日 ： 民國 56 年 12 月 20 日

籍　貫 ： 廣東省羅定縣

學　歷 ：中原大學電機系學士 (75/9 ~ 80/6)

台灣大學電機研究所碩士 (80/9 ~ 82/6)

交通大學電信研究所博士 (91/9 ~99/1)

經　歷 ：陸軍步兵排長、旅行政官(代理) (82/7 ~ 84/5)

美台電訊工程師 (84/7 ~ 85/2)

仲琦科技工程師 (85/3 ~ 86/7)

利翔航電高級工程師、專案組長 (86/8 ~ 89/4)

興瑞通信課長、經理、協理 (89/4 ~ 93/3)

論文題目 ：多封包接收無線網路之上鏈媒體存取控制協定設計

# Publication List

## Journal Paper

[J1] W. F. Yang, J. Y. Wu, L. C. Wang and T. S. Lee, "A Cooperative Multi-Group Priority MAC Protocol for Multi-Packet Reception Channels," *IEEE Trans. Wireless communications*, vol. 8, no. 11, pp. 5416-5421, Nov. 2009.

[J2] W. F. Yang, J. Y. Wu, L. C. Wang and T. S. Lee, “A Multi-Group Priority Queueing MAC Protocol for Wireless Networks with Multipacket Reception,” *EURASIP Journal on Wireless Communications and Networking*, vol. 2008, Article ID 970842, 2008.

[J3] W. F. Yang, H. L. Pan, S. Y. Liu, J. Y. Wu, L. C. Wang and T. S. Lee, "Dynamic User Set Based Uplink Throughput Optimization for Wireless Networks," to be submitted to *IEEE Trans. Wireless communications*.

## Conference Paper

[C1] W. F. Yang, J. Y. Wu, L. C. Wang and T. S. Lee, “A Multi-Group Priority Based Cooperative MAC Protocol for Multi-Packet Reception Channels,” *IEEE PIMRC 2009*, Tokyo, Japan, September 2009.

[C2] W. F. Yang, S. L. Pan and T. S. Lee, “Uplink Throughput Optimization for Wireless Networks with Multipacket Reception,” *IEEE VTS APWCS 2009*, Seoul, Korea, August 2009.

[C3] W. F. Yang, J. Y. Wu and T. S. Lee, “An Enhanced Multi-Packet Reception MAC Protocol: Cooperative Approach,” *ChinaCom 2008*, Hangzhou, China, pp. 516-520, August 2008.

[C4] J. Y. Wu, W. F. Yang, L. C. Wang and T. S. Lee, “Signal Modulus Design for Blind Source Separation via Algebraic Known Modulus Algorithm: a Perturbation Perspective,” *IEEE ISCAS 2008*, Seattle, USA, pp. 3013-3016, May 2008.

[C5] W. F. Yang, J. Y. Wu, L. C. Wang and T. S. Lee, “A Multi-Group Priority Queueing MAC Protocol for Multipacket Reception Channel,” *IEEE WCNC 2008*, Las Vegas, USA, pp. 1673-1678, April 2008.

[C6] W. F. Yang, J. Y. Wu, L. C. Wang and T. S. Lee, “Dynamic Multi-Group Priority Queueing MAC Protocol for Wireless Networks in A Heterogeneous Channel Environment,” *IEEE VTS APWCS 2007*, Hsinchu, Taiwan, August 2007.