

行政院國家科學委員會專題研究計畫成果報告

廣義的機會式通訊：無線行動網路中之競爭、合作與感知-總計畫

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

Spectrum sensing and management in cognitive wireless mobile networks

計畫編號：NSC 96-2221-E-009-115-MY3

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中文摘要：

近年來興起的感知無線電開啓許多新的無線通訊可能性，一般認為將是下一代無線行動網路的新技術典範。感知無線電技術之所以被廣泛的研究是因為其具有偵測周圍環境無線通訊資源現況（即那些資源如頻段等是可供信號的傳送或接收）的能力，並可因應現況作最適當的波形調整（例如：調整訊號頻寬、訊號波形、載波頻率、調變種類、功率及傳輸方向等）以達到有效率的使用無線通訊資源並同時獲致最佳的效能表現。另一新興的無線傳輸技術則是所謂的協力式通訊（Cooperative Communications）。這種通訊方式藉由周遭暫時閒置的通訊傳收機的協助來合力一起傳收信號，因此可視為另外一種機會式（opportunistic）無線通訊空間資源的感知與利用。

事實上，除了信號的傳收之外，感知無線電對環境的感測與瞭解也可透過多個在不同位置傳收機的合作來提升其感測與瞭解的能力。我們可以說，感知無線電與協力式通訊是廣義機會式通訊不同面貌的呈現。這種廣義機會式通訊的具體實現之一就是所謂的感知（無線電為基礎的）無線行動網路（cognitive radio based wireless mobile networks, or cognitive wireless mobile networks）。在現有無線通訊資源有限傳輸需求卻日增的情形下，廣義機會式通訊能爭取新的資源並有效的動態運用所有資源，的確是十分值得且需要深入探討的新領域。

本計畫針對不同的層面加以區分，主要集中在合作與競爭通訊理論的建構。因此包

括四個子計劃，計劃名稱分別為：

子計畫一：感知無線行動網路之頻譜偵測與管理

子計畫二：感知無線行動網路之協力式跨層設計

子計畫三：感知無線行動網路之協力式擇路協定及服務品質控制

子計畫四：感知無線行動網路之協力式媒體存取控制協定設計與用戶/基地台選取研究

關鍵詞：感知、協力式、機會式

Abstract

Cognitive radio (CR) technology has in recent years emerged as a new communication paradigm for next generation wireless mobile networks. It promises much more efficient radio resource (especially electromagnetic spectrum) utilization, improved system performance and novel new functionalities. The main theme of CR is the capability of a radio to sense and adapt to its environment, constantly making spectrum, transmission and networking decisions that optimize radio resources (energy/power, spectrum, cooperative nodes etc.) opportunistically. Another rising paradigm is the so-called cooperative communications. In a cooperative communication network, a terminal would solicit cooperation from surrounding terminals for transmitting or receiving signals, which means it exploits additional spatial radio

resources (in this case, temporary idled terminals) to enhance system performance. Note that a CR can also improve its environmental (spectrum in particular) sensing capability through cooperation with other terminals. Hence both CR and cooperative communications can be regarded as parts of the generalized opportunistic communications and one of its realizations is the class of cognitive (radio-based) wireless mobile networks.

We divide the task of designing a CR system into four subtasks. They are:

1. Spectrum sensing and management in cognitive wireless mobile networks
2. Cooperative Cross-Layer Design in Cognitive Wireless Mobile Networks.
3. Cooperative Routing Protocols and QoS Control in Cognitive Wireless Mobile Networks.
4. Cooperative MAC Protocol Design and User/Base Station Selection in Cognitive Wireless Mobile Networks.

Key words: *cognitive, CR, cooperative, opportunistic*,

Introduction

隨著無線通訊技術的發展，頻譜的壅塞程度與日遽增，然而，根據美國聯邦電信委員會在 2003 年的報告[1]，在傳統頻譜分配方式下，其使用效率範圍只能處於 15%~85%，這意味著頻譜使用率是非常低的。因此，近年來有越來越多的學者在討論如何動態地調整系統參數來提升頻譜使用率。此外，動態地調整系統參數不僅僅可以提升頻譜使用率，同時也能夠提升系統的效能以及傳輸範圍。

如何動態地調整系統參數是一個多層面的問題，例如：頻譜的偵測，通訊協定的制訂等等。無疑地，跨層面的設計將是一種未來不可避免的趨勢。我們這個計畫分為四個子

計畫，將分別就這些發展中技術做深入的研究。四個子計畫的名稱與主持人分別為：

子計畫一：感知無線行動網路之頻譜偵測與管理（交通大學 蘇育德 教授）

子計畫二：感知無線行動網路之協力式跨層設計（交通大學 李大嵩 教授）

子計畫三：感知無線行動網路之協力式擇路協定及服務品質控制（交通大學 方凱田 助理教授）

子計畫四：感知無線行動網路之協力式媒體存取控制協定設計與用戶/基地台選取研究（交通大學 王蒞君副教授）

以上四個子計畫互相整合程度請參見總計畫書。綜合言之，各子計畫負責傳輸介面的一特定環節，互補性與相關性至為明顯，缺一不可。基本上，我們是集中在合作與競爭通訊理論的建構。

在下列章節中，我們將就各子計劃內容做一重點性說明。

2. 廣義的機會式通訊：無線行動網路中之競爭、合作與感知-子計畫一：感知無線行動網路之頻譜偵測與管理

2.1 Introduction

Cognitive radio (CR) which allows distributed dynamic spectrum usage was therefore proposed to remedy such a shortcoming in spectrum management. Based on the CR concept, Chakravarthy *et al.* [2] proposed a dynamic modified direct-sequence spread spectrum (DS-SS) system to which they referred as adaptive waveform communication system (AWCS). Since the spreading sequence of AWCS is synthesized in the transform domain, the system is also called transform domain communication system (TDCS).

The basic idea behind TDCS is to generate a spreading sequence whose spectrum avoids existing users or jammers within the SS band. The spectrum conditions at transmitter and receiver are independently estimated at both sides. If the spectrum seen (or measured) by transmitter is different from that seen at receiver, the mismatch between two spreading sequence spectra will cause performance degradation [3]. Spectra mismatches arise because of geographic separation and/or spectrum estimation errors, i.e., either the "true" spectrum represented at two sides are different or the estimated spectra are different although the spectrum representation are the same. In this report, we analyze the effect of spectrum estimation error induced spectrum mismatches on the symbol error rate (SER) performance in additive white Gaussian noise (AWGN) and Rayleigh fading channels, respectively.

2.2. Performance Analysis of BPSK-TDCS

The basic idea behind TDCS is to produce a so-called time-domain fundamental modulation waveform (FMW) or a complex spreading sequence which avoids existing users or jammers by dynamically selecting the subcarriers used over a given bandwidth. A block diagram of the TDCS transmitter is illustrated in Fig. 1. The transmitter partitions the signal band into N equal-spaced subbands (tones) and performs spectrum estimation to determine which subbands are being used. The spectrum estimator output is an N -dimensional binary vector

$$\mathbf{A}_x = (A_x(w_0), A_x(w_1), \dots, A_x(w_{N-1})) \text{ with } A_x(w_i) =$$

1 or 0 depending on whether the i -th subband is available (1) or not (0). The subscript x will be Tx or Rc to denote if the vector is associated with the transmitter (Tx) or the

receiver (Rc). The binary vector $\mathbf{A}_{Tx}$ is multiplied element-wise by a user-specific random vector e^{jw_i} and scaled by constant factor before being inverse discrete Fourier transformed to produce the time-domain FMW. The multiplication of the random vector is to make the FMW noise-like and to provide the multiple access capability. The FMW is used to spread (or as a carrier of) the binary phase shift keying (BPSK) or cyclic code shift keying (CCSK) modulated data sequence.

We shall assume that $A(w_i) = 0$ with probability $1 - P_{sa}$ and $A(w_i) = 1$ with probability P_{sa} . Define two complementary sets of subbands (channels)

$$\mathbf{G}_0 = \{w_i \mid A(w_i) = 0, 0 \leq i \leq N-1\}$$

$$\mathbf{G}_1 = \{w_i \mid A(w_i) = 1, 0 \leq i \leq N-1\}.$$

$\mathbf{G}_0$ contains all subbands that are currently in use and $\mathbf{G}_1$ is the set of available (unused) subbands. Let $|\mathbf{G}_1| = N_1$ be the cardinality of $\mathbf{G}_1$, then $|\mathbf{G}_0| = N - N_1$.

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

$$P_{t0} = \Pr(A_{Tx}(w) = 1 \mid A(w) = 1)$$

$$P_{t1} = \Pr(A_{Tx}(w) = 0 \mid A(w) = 0)$$

$$P_{r0} = \Pr(A_{Rc}(w) = 1 \mid A(w) = 1)$$

$$P_{r1} = \Pr(A_{Rc}(w) = 0 \mid A(w) = 0)$$

and their complementary probabilities are independent of w_i . These assumptions imply that $\mathbf{A}$ is binomial distributed with parameter P_{sa} and furthermore, $\mathbf{A}_{Tx}$ and $\mathbf{A}_{Rc}$ are obtained by modifying $\mathbf{A}$ based on P_{t0} , P_{r0} ,

P_{t1} , and P_{r1} , respectively.

The SER in AWGN for coherent demodulation is given by (1) at the last page, where P_e is summarized in Table II.

TABLE II
 P_e IN AWGN

$P_e(x)$	Modulation Type
$Q(2\sqrt{x})$	BPSK
$1 - [1 - Q(\sqrt{x})]^2$	QPSK
$\frac{1}{\pi} \int_0^{\frac{(M-1)\pi}{M}} \exp\left[-\frac{\sin^2(\frac{\pi}{M}x)}{\sin^2 \phi}\right] d\phi$	MPSK
$\frac{2(M-1)}{M} Q\left(\sqrt{\frac{6x}{M^2-1}}\right)$	MPAM
$1 - \left(1 - \frac{2(\sqrt{M}-1)}{\sqrt{M}} Q\left(\sqrt{\frac{3x}{M-1}}\right)\right)^2$	MQAM

The error floor becomes

$$P_s = C [P_{sa}(1 - P_{t0}P_{r0}) + (1 - P_{sa})(P_{t1} + P_{r1} - P_{t1}P_{r1})]^N \quad (2)$$

where C is a parameter depending on modulation type. The exact value of C is tabulated in Table III.

TABLE III
 C IN AWGN CHANNEL

C	Modulation Type
$\frac{1}{2}$	BPSK
$\frac{3}{4}$	QPSK
$\frac{M-1}{M}$	MPSK
$\frac{M-1}{M}$	MPAM
$1 - \left(1 - \frac{\sqrt{M}-1}{\sqrt{M}}\right)^2$	MQAM

2.3 Simulation results

In this section, we show that the simulation of the performance of TDCS agrees with (1) for different cases with the special case: $P_{sa}=0.5$. The size of IDFT N is set equal to 8.

Example 2: The effect of P_{t0} .

The effect of P_{t0} is illustrated in Fig. 2. The parameters are set as followed: $P_{t1}=0.5$,

$P_{r0}=0.7$, $P_{r1}=0.4$ and $\frac{E_b}{N_I}=0$ dB. It is

obvious that the simulation result is almost identical to what has been predicted by analysis.

Example 3: The effect of P_{r0} and P_{r1} .

Fig. 3 plots the simulated performance with varying P_{r0} and P_{r1} . Again, our analytic result is validated by computer simulation. The other parameter values used are: $P_{t0}=0.9$,

$P_{t1}=0.5$ and $\frac{E_b}{N_I}=0$ dB. Notice that the values of P_{r0} and P_{r1} imply

$$A_{Rc}(w) = \begin{cases} 1, & \text{with } P_{r0} \\ 0, & \text{with } P_{r1} = 1 - P_{r0} \end{cases},$$

i.e., it is determined by receiver without considering the environment. It is a good strategy to always assign $A(w)=1$ without estimating the spectrum at the receive side.

Example 4: The effect of P_{t1}

The effect of P_{t1} is plotted in Fig. 4. We can see that they are almost identical. The parameter values used are:

$P_{t0}=P_{r0}=P_{r1}=0.9$ and $\frac{E_b}{N_I}=0$ dB. An

interesting observation is that the BER curves have different cross-over points for different P_{t1} . This is due to the fact that only $j = N - N_1$ has nonzero value in (2) if $P_{t1}=0$. Since $j = N - N_1$, $l_2 = 0$. This implies it is possible that the interference is smaller than

that in other cases at high $\frac{E_b}{N_0}$. To illustrate

this argument, consider Fig. 5. where it is assumed that $P_{t0}=P_{r0}=1$, and $\frac{E_b}{N_I}=0$ dB.

When $P_{r1}=0.7$, the interference is more serious and centered at higher l_1 than that in $P_{r1}=0.9$. For $P_{t1}=0$, it is possible to reduce interference at cost of E_b , which can be expected by noticing

$$P_b = \sum_{N_1=0}^N \sum_{l_1=0}^{N-N_1} \binom{N}{N_1} \frac{1}{2}^N \binom{N-N_1}{l_1} P_{r1}^{N-N_1-l_1} (1-P_{r1})^{l_1} f$$

where

$$f = \begin{cases} Q \left(\sqrt{\frac{2E_b \left(\frac{N_1+l_1}{\max(N_1, 1)} \right)}{\max(N_1+l_1, 1) N_I}} \right), & P_{t1} = 0 \\ Q \left(\sqrt{\frac{2E_b \left(\frac{N_1}{\max(N_1, 1)} \right)}{\max(N_1, 1) N_I}} \right), & P_{t1} = 1 \end{cases}$$

2.4. Conclusions

CR has attracted much interest because of its potential to greatly enhance the spectrum utilization efficiency. TDCS is a novel new candidate SS technique that invokes the CR concept. In this report, we consider the effect of spectra mismatches due to spectral estimation error. BER expressions for BPSK signals in various operating conditions are given. We also derive analytical SER expressions for other modulations like MPSK, QAM signals and flat Rayleigh fading channels. Our analysis can easily be extended to other flat-fading channels by deriving the corresponding $P_s(x)$. It is shown that the spectral estimation error results in error floor. As expected, the BER/SER performance is improved and the error floor is reduced when the per-tone (single-subcarrier) detection error decrease. Increasing the number of subcarriers (processing gain) in the SS band also has similar effect. Based on this, it suggests that the best access police is to choice all subbands in terms of BER/SER if the subbands are estimated as idle state. We also find that the BER/SER performance is more sensitive to the spectral estimation error at the receiver than that at the transmitter.

There are quite a few issues that remain to be solved. Firstly, we use a simple Bernoulli distribution to model the estimation

error, which is appropriate if the spectral estimation is carried out in a tone-by-tone manner. A more realistic model depends on the spectral estimation method used. It would be interesting to see how the system behaves under different spectral mismatch models. Secondly, a soft decorrelation process might be useful to reduce the impact of spectral mismatches and enhance system performance.

Furthermore, cooperative spectrum sensing and prediction should be considered in the future to reduce the mismatch probability.

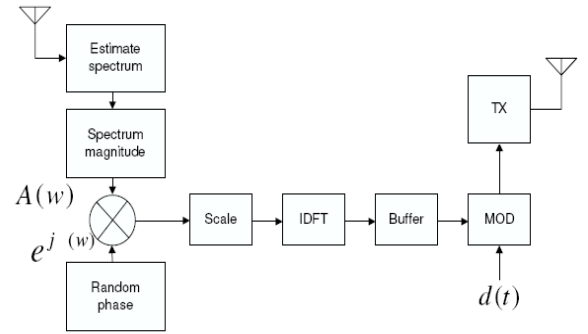


Fig. 1. Block diagram for a TDCS transmitter

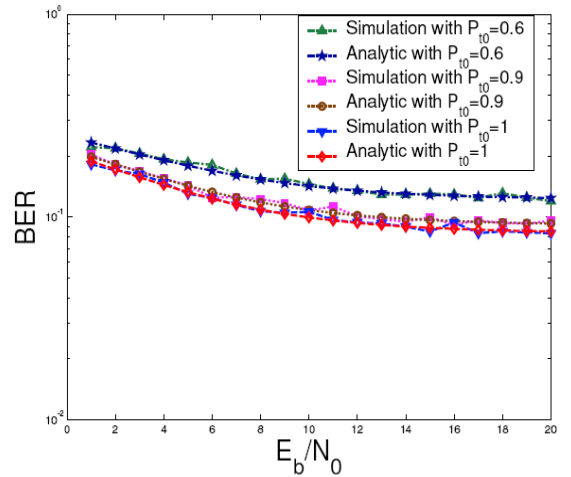


Fig. 2. BER performance for different P_{t0}

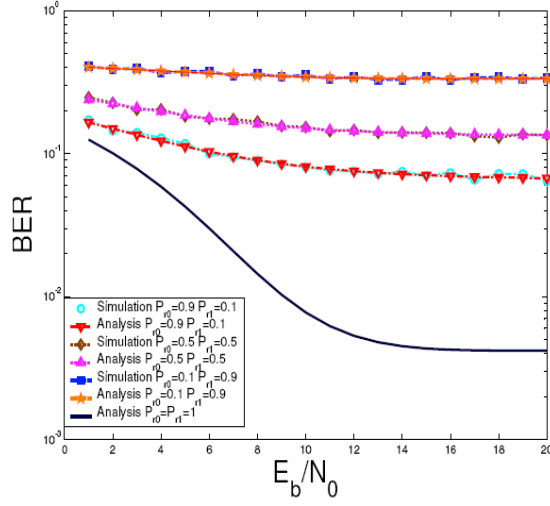


Fig. 3. BER performance for different P_{r0} and P_{r1}

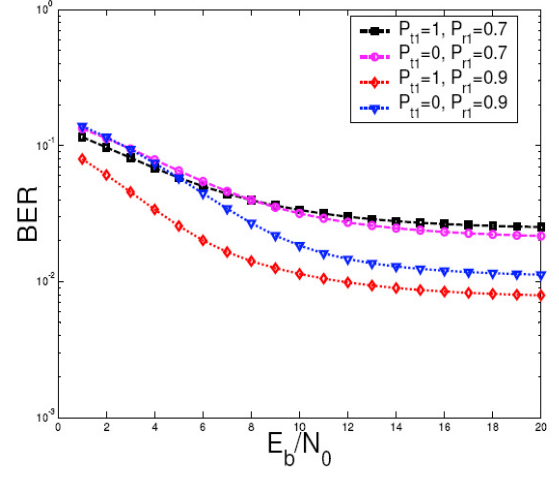


Fig. 5. The effect of interference

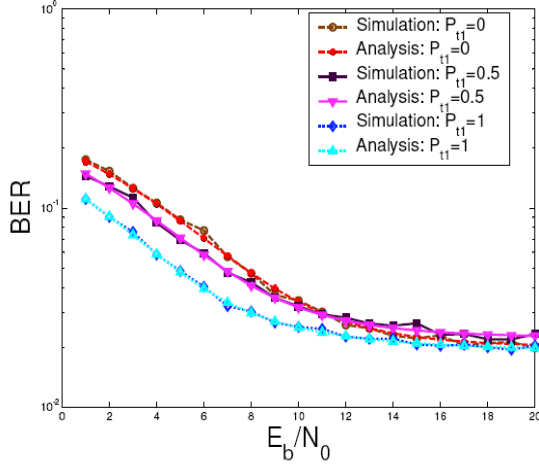


Fig. 4. BER performance for different P_{t1} 's

TABLE I
EIGHT POSSIBLE SCENARIOS FOR A TDCS LINK.

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

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

3. 廣義的機會式通訊：無線行動網路中之競爭、合作與感知-子計畫二：感知無線行動網路之協力式跨層設計

3.1 Introduction

Effective medium access control (MAC) mechanisms are crucial for realizing high throughput, low delay, and good quality-of-service (QoS) performances. Conventional MAC protocol design is based on the so-called collision channel model, that is, a transmitted packet is successfully received only when there is no concurrent transmission. We call the above model as a single packet reception (SPR) channel [5].

Such a design paradigm, however, ignores the multi-packet reception (MPR) capability at the physical layer. An initial attempt to reflect the MPR facility is the channel model with capture effect characterized via the probability of successful reception [6]. The impact of capture effect on various existing MAC protocols such as slotted ALOHA and FCFS has been addressed in [7]-[9]. 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 [10], based on which several MAC protocols have been proposed [11]-[16]. Cooperative communication is another research area, which draw increasing attention in recent years. 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 [17], CoopMAC [18], and ALLIANCES [19] are proposed.

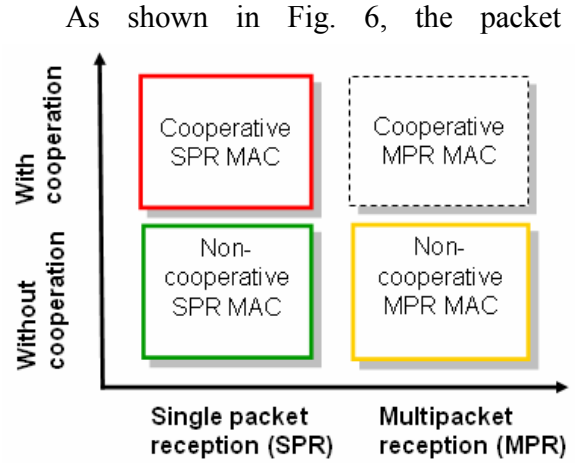


Fig. 6 Two directions of MAC protocol design.

reception capability and cooperation diversity are never jointed together to design the MAC protocol. On the one hand it is difficult to take multi-packet reception capability into cooperative SPR MAC unless certain assumption, such as separate channels in [19], is assumed. On the other the existing non-cooperative MPR MACs are too complicated to further include cooperation into analysis. Recently, a simple dynamic multi-group priority queueing (DMGPQ) protocol is proposed for the MPR channel [4]. Benefited from the non-prediction based user selection scheme, it becomes possible to let the idle users relay (decode-and-forward) the packets from other users without altering the user selection criteria of the central controller. The contributions of this paper are summarized as follows.

- 1) The proposed protocol is, to our best knowledge, the first cooperative MPR MAC without assumptions imposed on the channel type or user's homogeneity.

- 2) The cooperation is self-contained in the network, i.e., there is no extra relay deployment required. As the user may act as relay during idle period, no dedicated relay is required and no relay selection issue exists.

3) The isolated server-client design for cooperation make it flexible on the incentive plan, because the operation of server MAC is independent with the number of users joining cooperation.

3.2 Preliminary

A. System Description

Consider the *uplink* of a centralized wireless network such as CDMA cellular network or wireless LAN, and there are M users within this network. We propose to make each packet have one tail flag-bit for indicating if there is a buffered packet [15]. The extra flag-bit has the advantage to provide explicit information about the incoming traffic condition. Note that the buffered to-be-relayed packet is not indicated by the flag-bit to maintain the priority of own packets.

B. GMPR Channel

Let θ denote the ID of central controller, and $1 \sim M$ the users' IDs respectively. Thus, the multi-packet reception channel for each node $i \in \{0, 1, 2, \dots, M\}$ can be characterized by generalizing the conventional MPR matrix [3.9] into

$$\mathbf{C}_i(U) \triangleq \begin{bmatrix} C_{1,0}(U_i) & C_{1,1}(U_i) \\ C_{2,0}(U_i) & C_{2,1}(U_i) & C_{2,2}(U_i) \\ \vdots & \vdots & \vdots \\ C_{M,0}(U_i) & C_{M,1}(U_i) & C_{M,2}(U_i) & \dots & C_{M,M}(U_i) \end{bmatrix} \quad (3)$$

in which $U = \{u_1, u_2, \dots, u_M\}$ ¹, $u_i \in \{1, 2, \dots, M\}$, is the index set of users after certain permutation such as priority sorting, $U_i = U - \{i\}$, and $U_0 = U$. For $1 \leq n \leq M$ and $0 \leq k \leq n$, $C_{n,k}(U_i) \triangleq \Pr\{k \text{ packets correctly received} | n \text{ packets from first } n \text{ users transmitted}\}$.

¹ The time slot index is omitted hereafter for simplicity.

For example, the channel between central controller and all users, i.e., the conventional MPR channel matrix in [12], can be presented as

$$\mathbf{C}_0(U) \triangleq \begin{bmatrix} C_{1,0}(U_0) & C_{1,1}(U_0) \\ C_{2,0}(U_0) & C_{2,1}(U_0) & C_{2,2}(U_0) \\ \vdots & \vdots & \vdots \\ C_{M,0}(U_0) & C_{M,1}(U_0) & C_{M,2}(U_0) & \dots & C_{M,M}(U_0) \end{bmatrix} \quad (4)$$

The statistical characteristic $C_{n,k}(U_i)$ can be determined via the physical layer performance metric such as bit error probability (BEP); an illustrative example based on CDMA cellular network is the standard Gaussian approximation (SGA) shown below. Let $U_{i,n}$ denote the subset consisted of the first n nodes of U_i , then

$$BEP_j(U_{i,n}) = Q \left(\sqrt{\frac{3G}{\sum_{k \in U_{i,n} - \{j\}} \frac{P_{k,i}}{P_{j,i}} + 3G\sigma^2}} \right), \quad (5)$$

where $j \in U_{i,n}$, G denotes the processing gain, $P_{k,i}$ is the signal power transmitted by the user k and received by the user i , and σ^2 is the noise power. Assuming that errors occur independently in a packet, we then have the packet success probability (PSP) in the presence of interfering packets as

$$PSP_j(U_{i,n}) = \sum_{l=0}^t \binom{L_P}{m} [BEP_j(U_{i,n})]^l [1 - BEP_j(U_{i,n})]^{L_P - l}, \quad (6)$$

where L_P stands for packet length, and up to t bit errors can be corrected by assumed block error control code. Thus,

$$C_{n,k}(U_i) = \sum_{\Psi \subset U_{i,n}, |\Psi|=k} \left(\prod_{j \in \Psi} PSP_j(U_{i,n}) \prod_{j \in U_{i,n} - \Psi} [1 - PSP_j(U_{i,n})] \right) \quad (7)$$

With the above equation, the GMPR matrix (4) can be constructed accordingly.

Denotes $C_n(U) \triangleq \sum_{k=1}^n k C_{n,k}(U_0)$ the expected number of correctly received packets when total n packets from $U_{0,n} = \{u_1, u_2, \dots, u_n\}$ are transmitted. The channel capacity with certain users permutation U is defined as $\eta(U) \triangleq \max_{n=1, \dots, M} C_n(U)$. Note that the numbers of simultaneously transmitted packets to achieve the channel capacity may not be unique. Let

$$n_0(U) \triangleq \min \left\{ \arg \max_{n=1, \dots, M} C_n(U) \right\} \quad (8)$$

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

3.3 Cooperative Multi-Group Priority Queueing Protocol

A. CMGPQ Algorithm

The proposed cooperative multi-group priority queueing (CMGPQ) MAC protocol has two independent parts, one in the central controller (server-end) and the other in the users (client-end).

Server-end:

- 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. 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.
- V. Repeat steps II to IV.

Client-end:

- I. If the packet of user i is received successfully by the unselected user j , and then the unselected user j will store that packet in its buffer if it is not full yet.
- II. If an ACK is received by the user, then the user will check and remove corresponding packet from its buffer.
- III. The newly generated own packet will be put in front of the to-be-relayed packet(s).

Note that the newly generated own packet may cause the dropping of the to-be-relayed packet due to limited buffer size.

3.4 Theoretical Background

As shown in [3.13], there existed an optimal S to strike a balance between high throughput and low delay without considering cooperation. Taking cooperation into consideration, the optimal S is not only dependent on the delay requirement, but also the packet generating probability and GMPR matrix. Nevertheless, the Markov chain analysis is still valid for searching such an optimal S .

We here derive the Markov chain with $n_0(U)$ equal to a constant n_0 for simplicity. Associated with the user i ($1 \leq i \leq M$) 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, the contents (0 stands for no packet) in the primary buffer and the additional buffer at the t th time slot respectively. Hence we have $x_i(t) \in \{1, \dots, S\}$ ², $y_i(t) \in \{0, 1\}$, $z_{i,0}(t) \in \{0, 1, \dots, M\}$, and $z_{i,1}(t) \in \{0, 1, \dots, M\}$. Let us further collect $x_i(t)$, $y_i(t)$, $z_{i,0}(t)$ and $z_{i,1}(t)$ for all users to form $X(t) = (x_1(t), \dots, x_M(t))$, $Y(t) = (y_1(t), \dots, y_M(t))$, and $Z(t) = (z_{1,0}(t), z_{1,1}(t), \dots, z_{M,0}(t), z_{M,1}(t))$. The proposed protocol can be described by a Markov chain with state space

$$\Omega := \{E(t) \mid E(t) = (X(t), Y(t), Z(t)), t \geq 0\} \quad (9)$$

With the similar procedures in [13], the throughput, delay and packet loss ratio can be derived but skipped here for lack of space.

3.5 Numerical Results

We consider a CDMA network with randomly generated spreading codes, and obtain the associated GMPC channel model. The packet length, spreading gain, number of correctable errors in a packet were respectively, 200, 6, and 2, as in [3.3]. Eight users are deployed as shown in Fig. 3, where the near users (2, 4, 5, and 7) are at a distance L from central controller with SNR equal to 10 dB and the far users (1, 3, 6, and 8) are at a distance $\sqrt{2}L$ from central controller. We note that the incurred overhead due to the insertion of a flag-bit in DMGPQ is $1/201 < 0.005$,

which is pretty small and will be omitted in the performance evaluation.

A. Cooperation by different number of users

Fig. 8 compares the throughput performance with different number of users joining cooperation when the waiting period is set to $M/n_0 = 4$, which is the minimal waiting period [3.13]. There are some interesting phenomenon can be observed. 1) The more users join cooperation; the more cooperation gain is provided. 2) Four near users 2, 4, 5, and 7 can provide the same cooperation gain as that provided by all (near and far) users. That means far users 1, 3, 6, and 8 cannot provide cooperation gain, because their signal quality is much worse than those of near users. 3) The cooperation gain is only available in light traffic condition ($p < 0.6$). Because in heavy traffic condition, all users have their own packets waiting for transmission, and therefore no cooperation happens.

B. Performance comparison between near and far users

We further investigate the average performance of near and far users. As we can see in Fig. 9, the average throughput of far users is almost zero if no cooperation from near users. However, in light traffic condition, the average throughput of far users is improved with the cooperation from near users. Most importantly, the cooperation causes no reduction to the throughput of near users, because the relaying only happens during their idle period. Based on the mechanism of cooperation, the cooperation gain is reduced with increasing traffic.

The delay performance is shown in Fig. 10. As we can see, the infinite delay of far user is shifted from light traffic to middle

² S is assumed to be larger than $\lceil M/n_0 \rceil$ for simplicity [16].

traffic. This was attained with the increasing delay of near users.

Figure 11 shows the performance of average packet loss ratio. The reduction of packet loss is obvious in the light traffic condition.

3.6 Conclusion

In this paper, a cooperative approach is used to enhance the performance of dynamic multi-group priority queueing (DMGPQ) protocol, which is an MAC protocol designed for wireless network with multi-packet reception (MPR) capability. The resulting protocol is the first cooperative MPR MAC without special assumptions imposed on the channel characteristics, and simulations demonstrate its superiority.

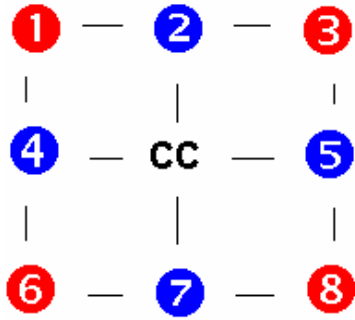


Fig. 7 Network deployment

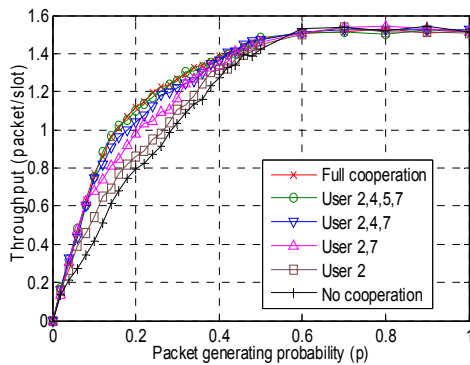


Fig. 8 Throughput performance

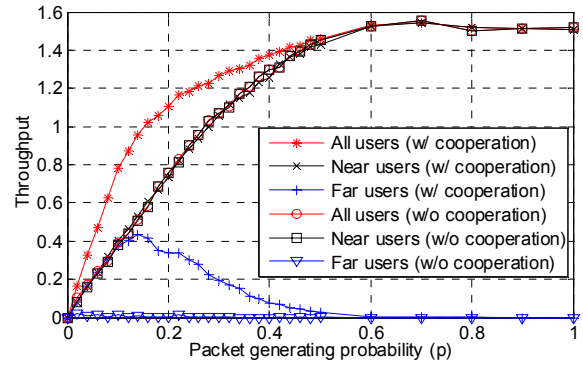


Fig. 9 Average throughput of near, far and all users

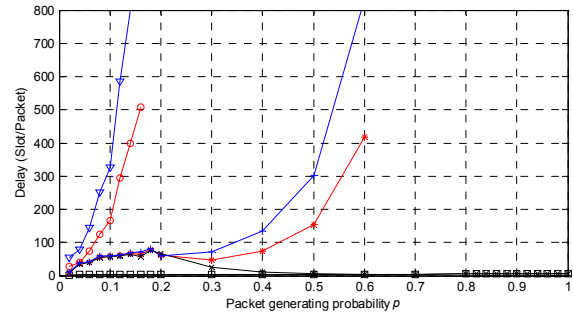


Fig. 10 Average delay of near, far and all users

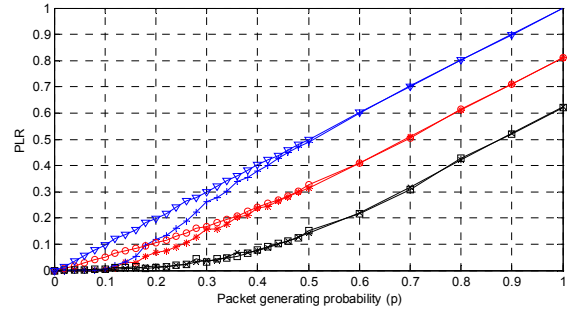


Fig. 11 Average packet loss ratio of near, far and all users

4. 廣義的機會式通訊：無線行動網路中之競爭、合作與感知-子計畫三：感知無線行動網路之協力式擇路協定及服務品質控制

此計畫從媒介接取控制的觀點討論協力式通訊的效能。在協力式通訊系統中，由於實作複雜度的限制下，半工傳輸（Half-Duplex）是現今大部分通訊系統的假設，因而，協力式通訊的模式往往便需要兩個階段才能完成，導致在傳輸時間上延伸變得是無可避免的。因此，若改由整體網路的吞吐量（Network Throughput）觀點來思考，協力式通訊不見得會帶來所期待的效能。在本報告中，將以 IEEE 802.11 媒介接取控制技術為基礎，佐以模擬驗證，利用二維的馬可夫鏈（Two Dimensional Markov Chain）的數學分析來探討協力式通訊於網路吞吐量的表現。在媒介接取控制的考量下，適當地找尋協力式通訊的使用時機。接著，將整合傳統點對點通訊系統及協力式通訊技術，進一步地思考這樣混合式通訊的必要性與存在性。

5. 廣義的機會式通訊：無線行動網路中之競爭、合作與感知-子計畫四：感知無線行動網路之協力式媒體存取控制協定設計與用戶/基地台選取研究

此子計畫共有四個成果，詳細的敘述請參見子計畫四。在此把對於此四部分作一個概要性地敘述：

一、應用於合作式多工的網路編碼

在這一部份的研究中，我們考慮了結合解碼轉送（decode-and-forward, DF）與網路編碼（network coding）的合作式通訊系統（cooperative communication systems）。對於我們提出的合作式網路編

碼（cooperative network coding, CNC）協定，我們推導了中斷機率（outage probability）和分集-多工權衡（diversity-multiplexing tradeoff, DMT）。我們的結果顯示中繼節點不但可以提供合作式的分集增益（diversity gain），也可以提供合作式的多工增益（multiplexing gain）。

二、對於多重天線廣播系統的系統容量近似分析：採用虛擬使用者方式

此研究探討在有限使用者下，使用強制歸零前處理技術之多重天線廣播系統的系統容量。我們探討了沒有考慮使用者排程（或等同於隨機排程）以及考慮了使用者排程的情況。其中，針對使用者排程的情況，我們發展了一種虛擬使用者方式的容量近似分析。而分析的結果也很接近模擬的結果。

三、對於多用戶多重天線廣播系統的涵蓋範圍分析

此部份著重於兩種著名的傳送前處理技術：強制歸零前處理及強制歸零前處理。當沒有考慮使用者排程時，我們提供了兩種前處理技術的連線中斷機率與涵蓋範圍的分析。當考慮了使用者排程，我們對強制歸零前處理進行分析，並對強制歸零前處理做模擬的比較。我們也探討了不同系統參數如傳送功率與通道衰減因子對於連線中斷機率與涵蓋範圍的影響。

四、在合作式多節點跳躍中繼網路下之傳送率導向同伴選取方法

這個研究提出了兩種以傳輸率為導向的中繼站選擇方法，兩種方法的傳輸率表現相較於文獻探討中的方法有大幅的提升，而在中斷機率的表現上第二種方法

比第一種好，也更為接近文獻討論中的中斷機率表現最好的方法。未來的研究方向是將現有的兩種方法從選擇一個中繼站推廣至選擇多個中繼站，以及傳輸功率的配置上。

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