行政院國家科學委員會補助專題研究計畫 □ 成 果 報 告 ■期中進度報告

廣義的機會式通訊：無線行動網路中之競爭、合作與感知--

子計畫二:感知無線行動網路之協力式跨層設計（1/3）

計畫類別：□ 個別型計畫　■ 整合型計畫
計畫編號：NSC 96-2628-E-009-003-MY3
執行期間： 2007 年 8 月 1 日至 2008 年 7 月 31 日

計畫主持人：李大嵩 教授
共同主持人：
計畫參與人員：楊雯芳、黃崇榮、廖晨吟、陳秋如、黃姿璇

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中 華 民 國 97 年 5 月 31 日

中文摘要

在無線網路中協力式通訊是一種利用分散的空間資源的重要技術，然而，節點間的 合作關係及各節點在網路中的位置造成協力通訊系統在設計上的困難。而在有限的傳送 能量限制下，如何有效率的利用能量在訊源端與中繼端之間傳送訊號是一個非常重要的 議題，因此在設計任何可以提升網路服務品質的技術時，亦都必須考慮網路的分散特性。 另一方面，為了能夠有效率的使用網路資源，能夠自我重置（Reconfigurable）的感知式 （Cognitive）網路功能（例如軟體無線電）亦逐漸變成一種典型的策略。本子計畫目標 在設計各種能應付協力式網路特有問題的軟體無線電解決方案，於計畫第一年中，吾人從跨層設計的角度建立利用實體層多封包接收能力的節點對節點協力式媒體存取控制協定，能有效改善傳統非跨層、非協力式的媒體存取控制性能。

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***Abstract*—An enhanced medium access control (MAC) protocol for wireless networks with multi-packet reception (MPR) capability is proposed. The proposed protocol is based on the dynamic multi-group priority queueing protocol recently introduced in [1] to exploit the cooperative diversity for improving the system throughput. Two kinds of throughput losses, i.e., over-loaded loss and under-loaded loss, are defined first to clarify the opportunity of improvement. A Markov chain analysis is provided as the theoretical background. It is shown that the under-loaded loss can be compensated by cooperation among users in light traffic environment, and the system throughput can be improved accordingly. Simulations further compare the delay and packet loss ratio with and without cooperation, it is found the average performance is improved too.**

Keywords—Multi-packet Reception; Medium Access Control; Wireless Networks; Cooperation; Decode-and-forward.

I. 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 [2].

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 [3]. The impact of capture effect on various existing MAC protocols such as slotted ALOHA and FCFS has been addressed in [4]-[6]. 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 [8]-[13]. 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 [14], CoopMAC [15], and ALLIANCES [16] are proposed.

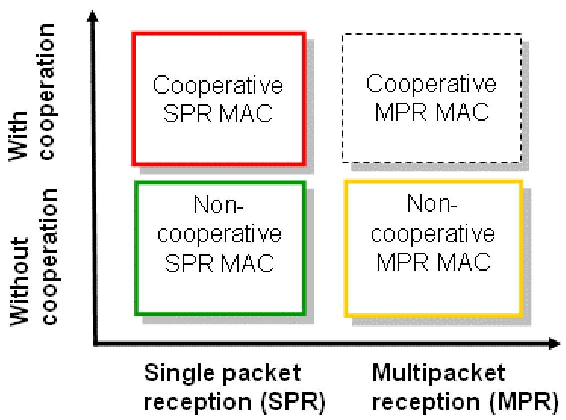


Figure 1. Two directions of MAC protocol design.

As shown in Fig. 1, 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 multi-packet reception capability into cooperative SPR MAC unless certain assumption, such as separate channels in [16], is assumed. One 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 [1]. 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.

The rest of the paper is organized as follows. Section II introduces the considered system in general MPR channel model. Section III describes the proposed cooperative MPR MAC protocol. The Markov chain based analysis is given in Section IV. Simulation results are shown in Section V. Finally, Section VI concludes this paper.

II. 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 [13]. 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 0 denote the ID of central controller, and $1 \sim M$ the users' IDs respectively. Thus, the multi-packet reception channel for each node $i \in \{0,1,2,\cdots,M\}$ can be characterized by generalizing the conventional MPR matrix [9] into

$$\mathbf{C_i}(U) \triangleq \begin{bmatrix} C_{1,0}(U_i) & C_{1,1}(U_i) & & & \\ C_{2,0}(U_i) & C_{2,1}(U_i) & C_{2,2}(U_i) & & \\ \vdots & \vdots & \vdots & & \\ C_{M,0}(U_i) & C_{M,1}(U_i) & C_{M,2}(U_i) & \cdots & C_{M,M}(U_i) \end{bmatrix}, \quad (1)$$

in which $U = \{u_1, u_2, \cdots, u_M\}$ [1], $u_i \in \{1,2,\cdots,M\}$, is the index set of users after certain permutation such as priority sorting, $U_i = U - \{i\}$, and $U_0 = U$. For $1 \le n \le M$ and $0 \le k \le n$, $C_{n,k}(U_i) \triangleq$ Pr{ k packets correctly received | n packets from first n users transmitted}. For example, the channel between central controller and all users, i.e., the conventional MPR channel matrix in [9], can be presented as

$$\mathbf{C_0}(U) \triangleq \begin{bmatrix} C_{1,0}(U_0) & C_{1,1}(U_0) & & & \\ C_{2,0}(U_0) & C_{2,1}(U_0) & C_{2,2}(U_0) & & \\ \vdots & \vdots & \vdots & & \\ C_{M,0}(U_0) & C_{M,1}(U_0) & C_{M,2}(U_0) & \cdots & C_{M,M}(U_0) \end{bmatrix}. \quad (2)$$

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

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

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

$$PSP_j(U_{i,n}) = \sum_{l=0}^{t} \binom{L_P}{m} \left[BEP_j(U_{i,n})\right]^l \left[1 - BEP_j(U_{i,n})\right]^{L_P - l}, \quad (4)$$

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

$$C_{n,k}(U_i) = \sum_{\Psi \subset U_{i,n}, |\Psi| = k} \left(\prod_{j \in \Psi} PSP_j(U_{i,n}) \prod_{j \in U_{i,n} - \Psi} \left[1 - PSP_j(U_{i,n})\right] \right). \quad (5)$$

With the above equation, the GMPR matrix (2) can be constructed accordingly. Denotes $C_n(U) \triangleq \sum_{k=1}^{n} kC_{n,k}(U_0)$ the expected number of correctly received packets when total n packets from $U_{0,n} = \{u_1, u_2, \cdots, u_n\}$ are transmitted. The channel capacity with certain users permutation U is defined as $\eta(U) \triangleq \max_{n=1,\cdots,M} C_n(U)$. Note that the numbers of simultaneously transmitted packets to achieve the channel capacity may not be unique. Let

$$n_0(U) \triangleq \min\left\{\arg \max_{n=1,\cdots,M} C_n(U)\right\} \quad (6)$$

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

III. COOPERATIVE MULTI-GROUP PRIORITY QUEUEING PROTOCOL

A. Motivation

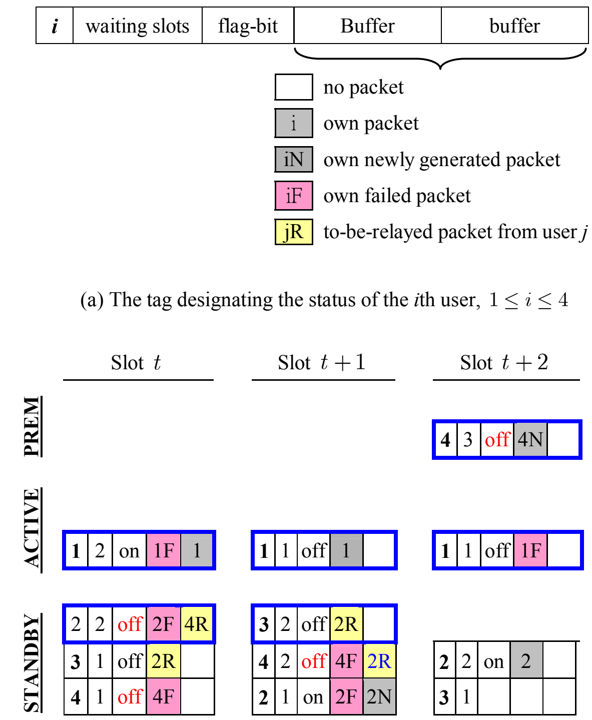
As shown in (6), exact $n_0(U)$ packets shall be transmitted simultaneously to achieve the maximal channel capacity. Transmitting either more or less than $n_0(U)$ packets concurrently will incur undesired loss. We call it *over-loaded loss* caused by transmitting more than $n_0(U)$ packets in one slot, and *under-loaded loss* caused by transmitting less than $n_0(U)$ packets in one slot respectively. As exact $n_0(U)$ users are selected for accessing the channel in each time slot by DMGPQ [1], thus no over-loaded loss occurs at all. However, under-loaded loss may occur while selected user has no packet to send. This phenomenon motivates us to utilize the idle

[1] The time slot index is omitted hereafter for simplicity.

period of users for reducing under-loaded loss and then improve the overall throughput performance accordingly.

B. Example

Figure 2 shows an illustrative example for the proposed cooperative MGPQ (CMGPQ) protocol, where the total number of users is $M = 4$ and $n_0(U) = 2$ users are selected to simultaneously access the channel. In CMGPQ, all users are grouped into three different priority groups (PREM, ACTIVE, and STANDBY in order). The traffic condition of the user *i* is summarized in a tag as shown in Fig. 2(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 buffers. Figure 2(b) depicts the operation of the proposed protocol during three consecutive time slots. At the start phase of slot *t*, there is no user in PREM group. Only one user 1 with two own packets is in ACTIVE group, the packet "1F" was failed to be received by central controller in previous transmission. There are three users 2, 3, and 4 in the STANDBY group. User 2 has one own packet and one to-be-relayed packet "4R" from user 4. User 3 has one to-be-relayed packet "2R" from user 2. And user 4 has one own packet only. The detailed operations of the proposed CMGPQ are described as follows.



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

Figure 2. (b) The priority grouping process by central controller within three consecutive time slots

In slot t:

1) Since no user in PREM group and only one user in ACTIVE group, user 1 in ACTIVE group and user 2 in STANDBY group are selected for transmission.
2) Upon successful packet reception, user 1 is retained in the ACTIVE group due to the flag-bit is on.
3) Assume that the packet of user 2 is correctly received by user 4 but not the central controller. Therefore, user 2 keeps the packet "2F" in its buffer and is retained in the original STANDBY group.
4) Waiting slots of both served users 1 and 2 are reset to 1, and waiting slots of the yet-to-be-served users 3 and 4 are increased to 2.

In slot $t+1$:

1) There is no user in PREM group and only one user 1 in ACTIVE group, so users 1 and 3 are selected.
2) Assume that the packet of user 1 is correctly received by user 2 and 4, but not central controller. Therefore, user 1 keeps the packet "1F" in its buffer and is retained in the original ACTIVE group. User 2 and 4 will not keep the packet from user 1 due their buffers are full.
3) Upon successful packet reception, user 3 is moved into the STANDBY group. The packet "2R" in the buffers of users 3 and 4, and packet "2F" in user 2 are all cleared.
4) Both waiting slots of served users 1 and 3 are reset to 1, and waiting slots of users 2 and 4 are increased to 2 and 3.

In slot $t+2$:

1) 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.
2) There is one user 4 in PREM group and one user in ACTIVE group, so users 4 and 1 are selected for next channel accesses.

C. 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.

IV. THEORETICAL BACKGROUND

As shown in [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 ($1 \le i \le M$) 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, the contents (0 stands for no packet) in the primary buffer and the additional buffer at the tth 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 $Z(t) = \left(z_{1,0}(t), z_{1,1}(t),\cdots,z_{M,0}(t),, z_{M,1}(t)\right)$. The proposed protocol can be described by a Markov chain with state space

$$\Omega := \{E(t) \mid E(t) = (X(t), Y(t), Z(t)), t \ge 0\}. \qquad (7)$$

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

V. NUMERICAL RESULTS

We consider a CDMA network with randomly generated spreading codes, and obtain the associated GMPR channel model. The packet length, spreading gain, number of correctable errors in a packet were respectively, 200, 6, and 2,

[2] S is assumed to be larger than $\lceil M/n_0 \rceil$ for simplicity [13].

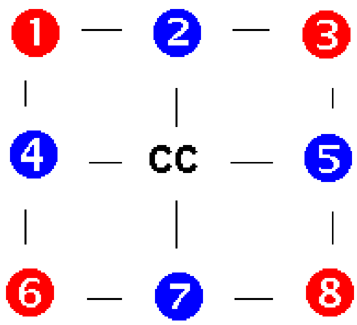


Figure 3. Network deployment

as in [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

Figure 4 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 [13]. There are some interesting phenomenon can be observed from the figure. 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. 5, 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. 6. As we can see, the infinite delay of far user is shifted from light traffic to middle traffic. This was attained with the increasing delay of near users.

Figure 7 shows the performance of average packet loss ratio. The reduction of packet loss is obvious in the light traffic condition.

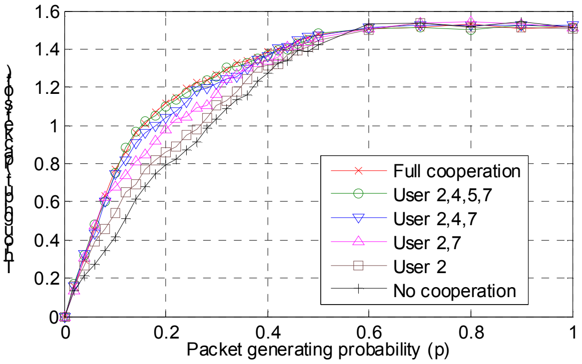


Figure 4. Throughput performance

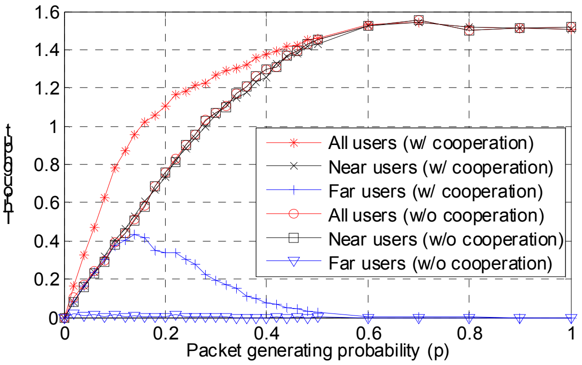


Figure 5. Average throughput of near, far and all users

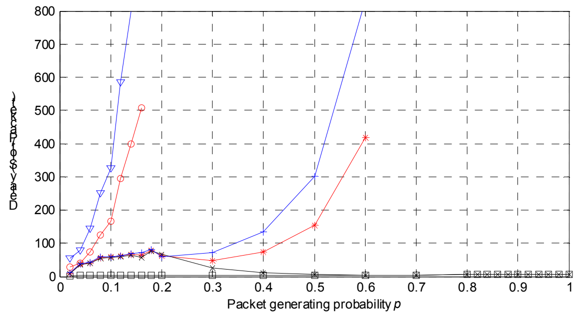


Figure 6. Average delay of near, far and all users

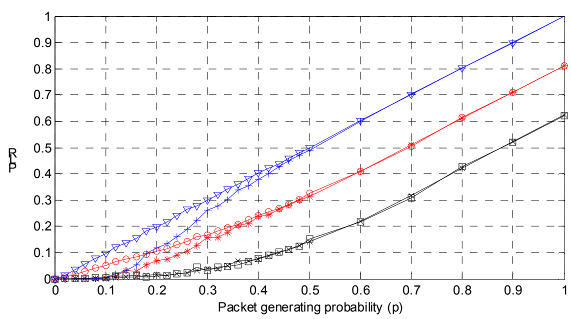


Figure 7. Average packet loss ratio of near, far and all users

VI. 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 demonstrates its superiority.

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計畫成果自評

一、研究內容與原計畫相符程度

大部份相符。

二、達成預期目標情況

1. 完成協力無線通訊系統效能分析，包含整體系統容量等。
2. 建立能同時考慮實體層、MAC 層設計參數之跨層優化協定。
3. 建立多節點協力式通訊系統模擬平台，以驗證整體研究成果。
4. 計畫成果投稿於國際會議（ChianCom 2008）並已接受。

三、研究成果之學術或應用價值

第一個一般化的協力式多封包接收媒體存取控制協定。

四、是否適合在學術期刊發表或申請專利

適合在學術期刊發表。

五、主要發現或其他有關價值

由於數位信號處理能力及微波技術的日新月異，通訊網路的實體層多具備多封包接收的能力，例如 CDMA、MIMO、WiMAX 等。因此能充分利用此特性的跨階層媒體存取控制愈顯重要。

可供推廣之研發成果資料表

□ 可申請專利　　■ 可技術移轉　　日期：97 年 5 月 31 日

國科會補助計畫	計畫名稱：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 計畫主持人：李大嵩 教授 計畫編號：NSC 96-2628-E-009-003-MY3　　學門領域：通訊
技術/創作名稱	具多封包接收能力之協力式媒體存取控制協定
發明人/創作人	楊雯芳、吳卓諭、李大嵩
技術說明	中文： 吾人從跨層設計的角度建立利用實體層多封包接收能力的節點對節點協力式媒體存取控制協定，能有效改善傳統非跨層、非協力式的媒體存取控制性能。
	英文： From the viewpoint of cross-layer design, we design a point-to-point cooperative medium access control (MAC) protocol by utilizing the multi-packet reception capability on physical layer. As a result, the proposed solution can improve the system performance such as throughput very much compared with conventional MAC protocols.
可利用之產業及可開發之產品	可利用之產業： 1. 寬頻無線通訊產業 可開發之產品： 1. 第四代行動通訊系統
技術特點	利用實體層多封包接收的能力來設計協力式媒體存取控制協定，能有效改善傳統非跨層 、非協力式的媒體存取控制性能。
推廣及運用的價值	由於數位信號處理能力及微波技術的日新月異，通訊網路的實體層多具備多封包接收的能力，例如 CDMA、MIMO、WiMAX 等。因此能充分利用此特性的跨階層媒體存取控制愈顯重要。

※　1. 每項研發成果請填寫一式二份，一份隨成果報告送繳本會，一份送　貴單位研發成果推廣單位（如技術移轉中心）。

※　**2. 本項研發成果若尚未申請專利，請勿揭露可申請專利之主要內容。**

※　3. 本表若不敷使用，請自行影印使用。