PHY-MAC dialogue with Multi-Packet Reception

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Abstract.- Cross-layer design has been considered recently as a new approach when designing MAC protocols in systems with diversity such as CDMA. This paper goes one step further in the cross layer design by proposing a PHY-MAC dialogue involving the exchange of parameters such as BER and active users. By means of this PHY-MAC dialogue, system performance can be improved. A two-stage receiver is used at PHY level. The first stage tracks active users while the second stage is a data demodulator. The Modified Dynamic Queue Protocol (MDQP) is proposed as the MAC protocol of our system. When the knowledge of active users is possible, it is demonstrated by simulations that MDQP outperforms DQP.

I. Introduction

In wireless random access channels, a common channel is shared by many users. The conventional assumption on the reception capability of the common channel is that when two or more packets are transmitted simultaneously a collision occurs and consequently, the information is lost. To recover the information, the colliding packets have to be retransmitted involving undesired effects on the throughput and packet delay of the network. Many current signal processing techniques introduce multi-packet reception capability at physical layer by means of spatial, time, frequency or code diversity. The improvement in throughput performance when spatial or code diversity is introduced is demonstrated in [1],[2],[3]. However, none of them consider cross-layer design, i.e., the MAC techniques applied are still working under the conventional assumption of collision. The idea of cross-layer design is based on the interaction between layers in order to improve system performance.

Many articles in the literature make reference to the physical layer packet reception capability by using the so called multi packet reception (MPR) matrix. Each element of this matrix is the probability of successfully receive k packets when n packets have been sent. Basically, these probabilities can be obtained from bit error rate and binomial distributions. Some MAC algorithms are developed based on this MPR matrix and hence, PHY-MAC dialogue reduces to a BER exchange. The work in [4] is perhaps the first to introduce the concept of MPR matrix. In this article, modifications of the retransmission probability of the Aloha protocol are presented. In [5] and [6] new MAC proposals are shown. In [5], the Dynamic Queue Protocol (DQP) is described. Assuming that each user has a probability q to have a packet waiting for transmission and considering the MPR matrix, an optimal user access set is obtained which minimises packet delay and maximises network throughput. Besides, QoS constraints are included in [6].

An improved zero forcing estimator for CDMA is developed in [7]. That is a two-stage multi user detector based on traffic burstiness theory: i)In the first stage, active users are detected by means of both power detection and traffic information. ii)In the second stage, a zero forcing estimator is implemented using the active users' signature vectors only.

Our goal is to go one step further on the cross-layer design in order to achieve even better performances. Basically, by means of PHY-MAC dialogue, system performance can be improved.

Since the problem of detecting active users in a dynamic CDMA system is not new [8],[9],[10], we propose to use the knowledge of active users as an information parameter to improve MAC efficiency. In our work, the first stage of the traffic-aided multi user detector for CDMA presented in [7] is considered. Changes from CDMA to spatial diversity systems are straightforward.

On the other hand, the DQP in [5] has been modified and used as the reference MAC protocol of our system to demonstrate the improvements achieved using PHY-MAC information.

The organisation of this paper is as follows. In the next section, the concept of the MPR matrix is described thoroughly and a PHY-MAC dialogue is proposed. In section III the modified dynamic queue protocol is presented. Section IV gives some simulations to show the improvements achieved by means of PHY-MAC dialogue. Conclusions are given in section V.

II. Multi-Packet Reception

The MPR matrix is the tool used to describe the capability of the receiver to detect more than one packet simultaneously. Considering a system with M users and that the channel is such that the probability of receiving k packets successfully when there are n transmissions depends only on the transmitted packets, the following probability can be defined,

$$C_{n,k} = P[k \text{ packets are correctly received } | \; n \text{ packets are transmitted}] \quad (1)$$
$$1 \le n \le M (\text{num. of users}) \; ; \; 0 \le k \le n$$

If the packet success probability (Ps(n)) of one packet is independent of the others, $C_{n,k}$ can be computed analytically as,

$$C_{n,k} = B(k,n,Ps(n)) \quad (2)$$

Where B(k,n,Ps(n)) denote de binomial distribution with probability Ps(n), i.e,

$$B(k,n,Ps(n)) = \binom{n}{k} Ps(n)^k (1-Ps(n))^{n-k} \quad (3)$$

Then, the MPR matrix can be defined as,

$$C = \begin{pmatrix} C_{1,0} & C_{1,1} & 0 & \cdots & \cdots & 0 \\ C_{2,0} & C_{2,1} & C_{2,2} & 0 & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots & 0 \\ C_{M,0} & \cdots & \cdots & \cdots & \cdots & C_{M,M} \end{pmatrix}$$

If the expected number of correctly received packets when n packets are sent is defined as,

$$C_n = \sum_{k=1}^{n} k C_{n,k} \quad (4)$$

Then, the capacity of the channel is

$$\eta = \max_{n=1,..,M} (C_n) \quad (5)$$

and consequently,

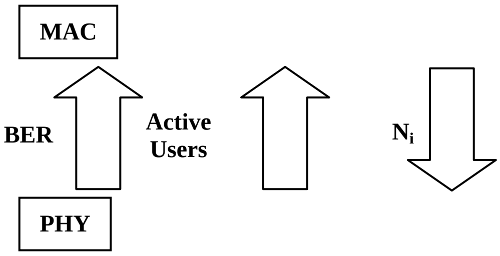

Figure 1. PHY-MAC dialogue

$$\eta_0 = \arg(\max_{n=1,..,M} (C_n)) \quad (6)$$

gives the number of packets that should be transmitted simultaneously to achieve channel capacity.

Since the MPR matrix entries depend on the packet success probability and consequently on the bit error rate (BER), the BER exchange between PHY and MAC is implicit when a MAC algorithm uses the MPR matrix.

On the other hand, by means of the first stage of the receiver presented in [7], it is possible to detect the active users in a slot. Assuming no error in the knowledge of the active users, this additional information is used at MAC level to improve system performance.

The Information flows between PHY and MAC layers of our system are described in figure 1. Parameter N_i refers to the optimal size of the users access set as described by the MDQP in section III. The knowledge of the N_i at the physical layer could be used to focus the active users' search on the N_i polled users. In essence, it could be used to simplify MUD user codes selection in the second stage of the receiver in [7]. However, we focused our work in the design of a more efficient MAC protocol by means of the information obtained from the physical layer.

III. Modified Dynamic Queue Protocol

III.a MDQP Vs DQP

We consider the DQP as the basis for the Modified DQP (MDQP). The DQP is described in [5]. It is designed for a system with M users (or nodes) who transmit data to a central controller.

The DQP divides the time axis in transmission periods (TP). In each TP, the packets generated in the previous TP are transmitted. A TP ends when all the M users of the system have been polled and the packets generated in the previous TP have been successfully received. An example is given in figure 2.

P is defined as the probability of a node to generate a packet in a slot and q_i is the probability of a node to have a packet waiting for transmission at the beginning of the *ith* TP. Then,

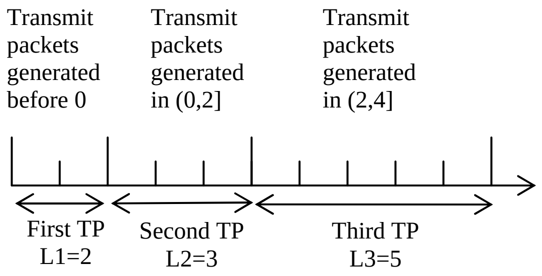

Figure 2. DQP Transmission Period

$$q_i = 1-(1-P)^{L_{i-1}} \qquad (7)$$

where L_{i-1} is the length of the previous TP.

The basic structure of this protocol is a waiting queue where all users are processed in groups of access set size (N_i). Based on q_i and the MPR matrix, the value of N_i is chosen so that the expected length for the *ith* TP is minimised.

When processing the received packets, the DQP assumes that the central controller is capable to distinguish between empty slots and non-empty slots. In the case of a non-empty slot, the central controller is only capable to determine the users of the access set who have successfully transmitted their packet in the current slot. On the contrary, in a non-empty slot, the central controller is incapable to determine whether the remaining users in the access set have transmitted a packet with a collision or have not transmitted any packet.

On the other hand, with the additional information about users activity given by the physical layer of our system, the central controller is capable to distinguish users whose packets have been transmitted successfully, users whose packets have collided and users who have not transmitted. Hence, the assumptions made about the central controller in DQP are no longer correct and must be modified. This is shown in figure 3. In that figure, the central controller sets Nopt to 3. In consequence, the users of the system are polled in groups of three. For the DQP, the central controller can not distinguish whether node 1 and 5 have empty buffers or their packets are lost due to collision. The MAC protocol polls nodes 1 and 5 again even though they have empty buffers. When all the nodes polled in a slot have empty buffers then, the central controller determines that non of the polled nodes have a packet waiting to be transmitted.

Opposite to that, by means of the user activity detector in the MDQP, the central controller is able to determine that nodes 1 and 5 have not transmitted a packet in the first slot and consequently they are processed and not polled again. Since the time taken to transmit all the packets with the MDQP is shorter, throughput and packet delay are improved.

III.b The optimal size of the access set

The procedure to determine the optimal size of the access set (N_i) is the same as in the DQP. The N_i for the *ith* TP is chosen so that the expected length of that TP is minimised. N_i is then,

$$N_i = \arg\left\{\min_{N=1,..,M} E[L_i \mid q_i, N]\right\} \qquad (8)$$

where $E[L_i|N]$ is the expected length of the *ith* TP when the size of the access is N.

It can be shown that a finite state discrete Markov chain can be formed with states (j,k). Where j (M ≥ j ≥0) determines the number of unprocessed users at the beginning of one slot and k (N ≥ k ≥0) determines the number of packets to be transmitted in that slot.

The transition probability from state (j,k) to state (l,m) is different depending if we are dealing with the DQP protocol or with the MDQP. For the MDQP protocol that probability is given at the bottom of this page. Consequently, the transition probability matrix can be written as

$$R = \begin{pmatrix} I & 0 \\ A & N \end{pmatrix}$$

$$r_{(j,k),(l,m)} = \left\{\begin{array}{c} B(m, \min\{N,l\}, q_i) \\ (if\ \ k=0, l=\max\{j-N,0\}, 0\le m \le \min\{N,l\}) \\ C_{k,j-l-N+k} B(m, \min\{j-l, \max\{j-N,0\}\}, q_i) \\ (if\ \ 1\le k\le \min\{N,j\}, l=j-N, N+l-j\le m\le \min\{N,l\}) \\ C_{k,j-l-N+k} B(m+j-l-N, \min\{j-l,\max\{j-N,0\}\}, q_i) \\ (if\ \ 1\le k\le \min\{N,j\}, l\ne j-N, N+l-j\le m\le \min\{N,l\}, \max\{j-N,0\}\le l\le \min(N,l)) \\ 0 \\ (otherwise) \end{array}\right\}$$

where I denotes the transition probability from an absorbing state to an absorbing state, i.e., the identity matrix (in our system the absorbing state is the state (0,0)), 0 is a null matrix representing the transition probability matrix from an absorbing state to a non-absorbing state, A is the transition probability matrix with entries representing the transition probability from a non-absorbing state to an absorbing state and finally, the transition probabilities from non-absorbing states to non—absorbing states are the entries of N. With that representation, the expected time until absorption for the *ith* state is the sum of the *ith* row of the $(I-N)^{-1}$ matrix. Hence, we can define a vector e with components e(j,k) representing the expected time until absorption of the state j,k.

Besides, the initial state of this Markov chain is always with j=M (M unprocessed users). Hence, the initial condition of this Markov chain is given by

$$P[X0=(M,k)]=B(k,N,q_i) \quad \text{for } k=0,..,N \tag{9}$$

Since $E[L_i|N]$ can be viewed as the expected time until absorption, $E[L_i|N]$ is computed as

$$E[Li|N] = \sum_{k=0}^{N} B(k,N,q_i)\, e(M,k) \tag{10}$$

Computing $E[L_i|N]$ for all possible N, the N_i which accomplishes (8) is chosen as the optimum one.

IV. Simulations

This section presents some numerical results aimed to demonstrate the advantages in terms of throughput and packet delay given by the knowledge of the active users at MAC layer. For these simulations, throughput is defined as the number of correctly received packets in one slot and packet delay is the average time (in slots) for a packet to be successfully transmitted in a TP.

In the examples shown, the SNR at the receiver is always 10dB, data modulation is BPSK. CDMA diversity is used and the user spreading codes are obtained from different phases of an m-sequence with length $2^m - 1$. The user activity detector is assumed to detect active users without error and hence, only the active user codes are used for data demodulation. For the second stage of the receiver, a bank of matched filters (MF) have been used.

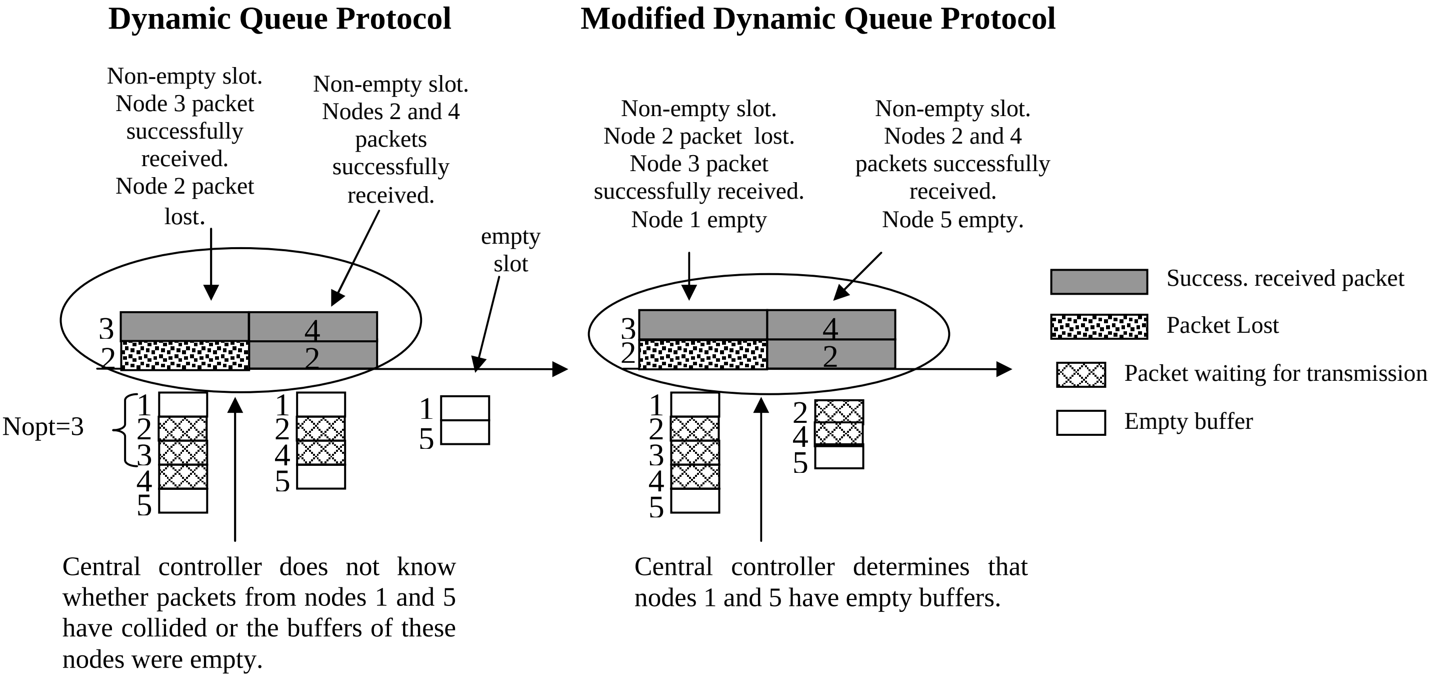

Figure 3. DQP Vs. MDQP

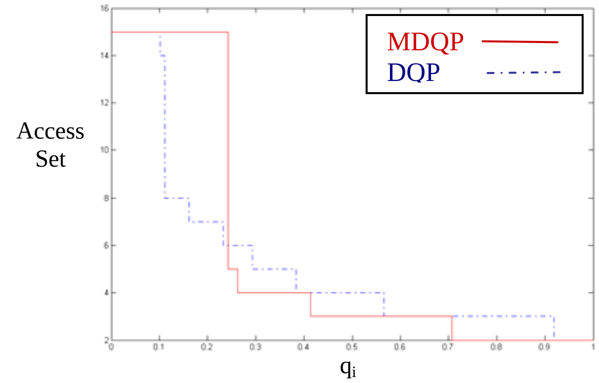

Figure 4. Access Set Vs. User Packet Prob.

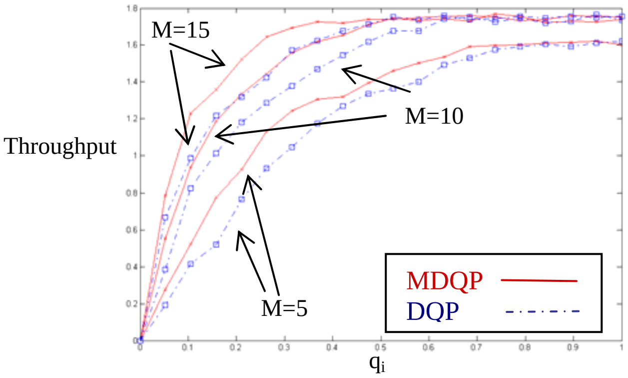

Figure 5. Throughput Vs. User Packet Prob.

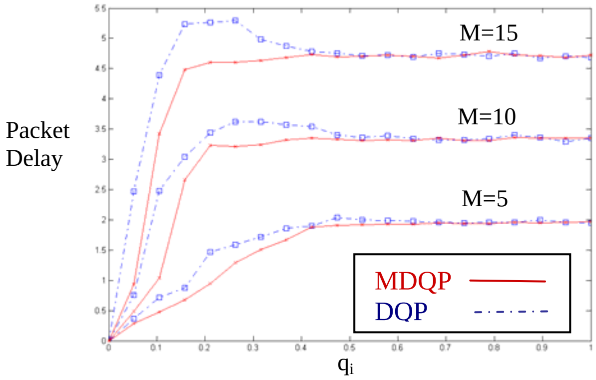

Figure 6. Packet Delay Vs. User Packet

Figure 4, depicts the value of N_i as a function of q_i for both, the DQP and the MDQP. From this figure one can notice that at low traffic the MDQP access set size is bigger than that for the DQP. This can be understood since at low traffic the number of users with a packet waiting for transmission is low. In consequence, for the MDQP it is preferable to poll a large number of users and discard those of them who are not willing to transmit in the first slot of the TP. Contrary, as the traffic increases, a lower N_i is preferable to avoid excessive collisions. At q_i=1, the access set is chosen to achieve channel capacity as described in (6).

Figures 5 and 6 show differences in throughput and packet delay for a MF receiver when using DQP and MDQP. For these simulations, the gain factor is chosen to be 6, packet length equal to 200 bits and an error correcting code is used capable to correct up to 2 bits. It can be noticed that throughput and packet delay improvements are achieved at low and medium traffic. Furthermore, improvements have are shown for M= 5, 10 and 15. In low and medium traffic, the user activity information is used to process users with empty buffers when they are polled for the first time. Hence, the TP length can be optimised. At high traffic, the user activity information is less useful, i.e., almost all users are active and there are no users with empty buffers to allow MDQP reduce TP length. As shown in figure 4, access set is chosen so that channel capacity is achieved.

V. Conclusions

This paper studies the possibility of using PHY-MAC dialogue for system performance improvement. The considered flows of information between PHY and MAC layers go one step further in the cross-layer design.

The system considered is a CDMA system with users sending data to a central controller. On this basis, the receiver at the central controller is composed by i)a user activity detector along with a data demodulator at the PHY level and ii)a MAC protocol which uses user activity information. Particularly, the MAC protocol used is a modification of the DQP protocol. DQP protocol already considers cross-layer design by means of the MPR matrix. However, if only the MPR matrix were considered by the MAC, the receiver capabilities in terms of multi-packet reception would not be not fully exploited. Hence, a modified DQP protocol which uses the additional knowledge of active users has been presented. Simulations depicted system performance improvement in terms of throughput and packet delay.

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