A New Medium Access Protocol Based on Distributed Queues for a CDMA Environment

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ABSTRACT*

This paper presents and analyses a new stable near–optimum random access protocol. The proposed access scheme is adapted for being used in a CDMA environment. It is based on distributed queues and a collision resolution algorithm. The structure of a minislot state detection receiver is presented and analysed in a Rayleigh fading channel situation. Computer simulations have been carried out to validate a system using this MAC and the obtained results show that the protocol has very good stability and delay performance, even taking into account the errors produced by the radio link channel propagation.

1 INTRODUCTION

In the past few years, many research efforts have been focused in the design of Medium Access Control (MAC) protocols. In the future third generation communication systems, mixed services and different traffic patterns will have to share the same channel structure and resources. MAC techniques must provide flexibility and efficiency to allow the existence of this kind of systems with a reasonable complexity and reliability.

ALOHA and Slotted–ALOHA techniques have been largely used in the past as random access protocols. However, their low throughput (0.18 and 0.36 maximum) and potential instability at heavy traffic load have originated the appearance of collision resolution algorithms (CRA), also called tree algorithms [1], which have a higher performance. One of the best–performing MAC protocols based on collision resolution proposed to date is DQRAP [2], a protocol initially designed for a TDMA wired environment. Its performance approaches that of an ideal M/D/1 queue, reaching maximum stable throughputs close to one and maintaining its stability for traffic loads up to the channel capacity.

On the other side, Direct-Sequence Code Division Multiple Access (DS-CDMA) is one of the most likely candidates for the 3rd generation mobile telecommunication systems. Schemes based on Wide-band CDMA (WCDMA) [3] have been chosen as radio interface in the standardisation body in Japan (ARIB), and also in Europe by the ETSI for the UMTS Terrestrial Radio Access (UTRA) [4]. This access scheme is also being considered in the International Mobile Telecommunication 2000 (IMT-2000) [5] by the ITU. In this paper, we propose a random near–optimum medium access protocol that modifies and extends DQRAP techniques for being used in a CDMA environment as those mentioned above. The protocol is a free random access protocol when the traffic load is light and switches smoothly and automatically to a reservation protocol when traffic load becomes heavier. This behaviour is the key of its good delay and throughput performance.

The protocol uses extremely simple control minislots for accessing purposes. A receiver scheme for the minislot state detection is also presented and analysed. It consists in a bank of matched filters and a decision block. Minislot misdetection probabilities are derived as a function of the false alarm and detection probabilities of each matched filter. Finally, a comparison with other access techniques has been carried out in order to show the benefits of this proposed scheme.

The paper is organised as follows. The protocol description is detailed in section 2. In section 3, an analytical model is presented and studied. Expressions for the total system delay are derived also in this section. Section 4 presents and analyses the minislot receiver scheme. Section 5 shows computer simulation results and comparisons with other protocols. Finally, section 6 is devoted to the conclusions.

2 PROTOCOL DESCRIPTION

Let consider N data terminals who share a CDMA channel with K available spreading codes to communicate with a base station. The time axis is divided into slots, and each slot has two parts. The first part is the access part which is further divided into control minislots. The second part is the data part, where terminals will transmit their user packets. We assume that every station has perfect slot and minislot synchronisation. The K spreading codes are put in order and we will denote K_i for the i–th code. Data terminals generate Poisson-distributed messages of exponential-distributed length with mean $(1/\mu)$. The messages generated by

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one terminal are splitted into slot-duration packets and put into a buffer. Each packet will be sent with the same spreading code but not all the packets pertaining to one message will be necessarily sent with the same spreading code.

The protocol uses two concatenated distributed logical queues: the collision resolution queue and the data transmission queue. When a message arrives to the system, the corresponding terminal sends a request in one randomly chosen control minislot. If it fails (the request collides with one or more requests from other terminals), it enters the collision resolution queue. The transmission queue contains the messages that have succeeded in their request and are waiting to be transmitted to the base station.

All the terminals must keep four integer counters, which represent the two logical distributed queues. We will denote them as TQ, RQ, pTQ and pRQ. TQ is the number of messages waiting for transmission in the distributed transmission queue. RQ is the number of collisions waiting for being resolved in the distributed collision resolution queue. pTQ is the position of the terminal in the data transmission queue and pRQ is the position of the terminal in the collision resolution queue. TQ and RQ have the same value for all terminals, while pTQ and pRQ are specific to each terminal. All queues are FIFO. This values are initially set to zero and must be kept updated using the feedback information sent by the base station and following the set of rules described below. This feedback information must be sent to all the terminals every slot using a broadcast channel. It simply consists of a ternary state data for each control minislot of every spreading code, and includes a final-message-bit per code. The three different states the base station must be able to distinguish are: empty, success and collision. A collision will occur when more than one station transmits in the same minislot of the same spreading code. Note that it is not necessary for the base station to know exactly how many access requests produced the collision. The final-message-bit is the mark that all the data terminals must send when they are transmitting the last packet from one message. We will consider an ideal broadcast feedback channel.

The protocol algorithm consists in three sets of rules that each data terminal has to follow at the end of every slot. They are, in order of execution, the Queueing Discipline Rules (QDR), the Data Transmission Rules (DTR) and the Request Transmission Rules (RTR).

2.1 Algorithm Rules

This algorithm rules must be executed by each data terminal at the end of every slot, assuming that, at this moment, the feedback information from the base station about the state of the control minislots of the previous slot has already been received by the terminal. They must be executed in the same order that they are presented. When a condition is not accomplished, the execution simply jumps to the next rule.

2.1.1 QDR (Queueing Discipline Rules)

1. Each station increments the value of TQ by one unit for each control minislot that has the success state, taking into account all the control minislots from any of the K spreading codes.
2. Each station reduces the value of TQ by one unit for each packet correctly received by the base station with the final-message-bit set to ON from any of the spreading codes.
3. If RQ>0, each station reduces the value of RQ by $min(\mathrm{RQ}, K)$ units.
4. Each station increments the value of RQ by one unit for each control minislot that has the collision state, taking into account all the control minislots from any of the K spreading codes.
5. Depending on its state, and the results of the control minislots, each station calculates the values for pTQ and pRQ. That is, if it has sent a request and this request has succeed, calculates its position between all the control minislots with this state and sets pTQ to the corresponding value at the end of TQ. For this purpose, all the successes are sorted using the order of the spreading code to which they belong, and within the same spreading code, using time arrival criterion. On the other hand, if the request has collided, the terminal calculates its position between all the collisions and sets pRQ to the corresponding value at the end of RQ. If it has not sent any request, then pTQ and pRQ follow the same update rules as TQ and RQ respectively, but only if the initial values are other than zero.

2.1.2 DTR (Data Transmission Rules)

1. If $\mathrm{TQ}<K$ and pTQ=0 and pRQ=0, each station that has data packets ready to be sent transmits a packet using the spreading code $K_{\mathrm{TQ}+1}$.
2. If pTQ>0 and $\mathrm{pTQ}\leq K$, the station transmits a packet using the spreading code K_{pTQ}.

2.1.3 RTR (Request Transmission Rules)

1. If $\mathrm{RQ}<K$ and pRQ=0 and pTQ=0, each station that has data packets ready to be sent, randomly selects one of the control minislots of the spreading code $K_{\mathrm{RQ}+1}$ and transmits a request in it.

2. If pRQ>0 and pRQ≤K, the station randomly selects one of the control minislots of the spreading code K_{pRQ} and transmits a request in it.

3 PROTOCOL MODEL AND ANALYSIS

The DQRAP/CDMA protocol can be modelled as shown in Figure 1. We have two queue subsystems, the collision resolution subsystem and the transmission subsystem. The Enable Transmission Interval (ETI) Queue represents the time each message has to wait since it arrives to the system until the next time slot starts. Both subsystems have as many servers as available spreading codes (i.e. K). The service time of both subsystems is exponentially distributed, therefore they are two M/M/K systems.

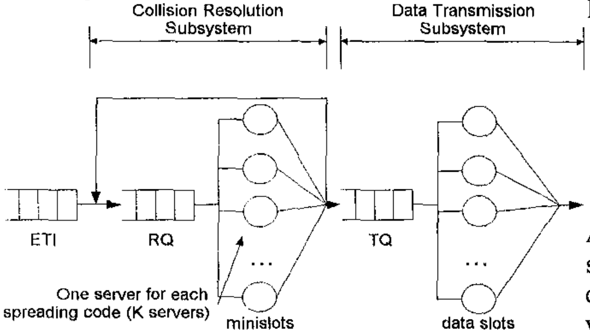

Figure 1. Model of DQRAP/CDMA protocol

The only stability condition is that the input traffic has to be less or equal the total server capacity for the data transmission subsystem, that is, the total transmission rate. Simulation results will confirm this issue.

3.1 Delay Analysis

The total service time for a message (t_T) can be decomposed in four terms: the ETI delay (t_{ETI}), the total delay of both subsystems (t_{RQ} and t_{TQ}), and the delay produced by the collision of a data packet in a data slot (t_c). The latter term appears when more than one terminal transmits its packet using the rule 1 of the DTR in the same slot. The expected value of this total delay will be

$$E[t_T]=E[t_{ETI}]+E[t_{RQ}]+E[t_c]+E[t_{TQ}] \tag{1}$$

The residual time of the ETI, $E[t_{ETI}]$, equals 0.5 because the arrival of messages is independent of the slot synchronisation.

Following the M/M/K analysis [6], and adding the waiting time in the queue plus the service time, we can write de total delay for the collision resolution subsystem:

$$E[t_{RQ}]=\frac{1}{\ln\left(\frac{1}{1-e^{-\lambda/m}}\right)}+\frac{P_{KRQ}}{K\ln\left(\frac{1}{1-e^{-\lambda/m}}\right)\left(1-\rho_{RQ}\right)} \tag{2}$$

where

$$\rho_{RQ}=\frac{\lambda}{K\mu_{RQ}} \tag{3}$$

λ is the offered input traffic rate and P_{KRQ} is the Erlang C formula for the delay probability for K servers. The total delay for the transmission subsystem has the same terms as for the collision resolution subsystem but changing the service time rate μ_{RQ} by a new value μ_{TQ}. This value equals to:

$$\frac{1}{\mu_{TQ}}=\frac{1}{\mu(1-BLER)} \tag{4}$$

where $BLER$ is the block error probability and $1/\mu$ is the mean length of the messages generated by the data terminals. It is assumed that the system has an error detection system and a S&W ARQ strategy.

Finally, it can be proved [7] that

$$E[t_c]=\frac{\sum_{n=0}^{K-1}\frac{(K\rho_{TQ})^n}{n!}}{\sum_{n=0}^{K-1}\frac{(K\rho_{TQ})^n}{n!}+\frac{(K\rho_{TQ})^K}{K!(1-\rho_{TQ})}}\left(1-e^{-\lambda}(1+\lambda)\right) \tag{5}$$

4 MINISLOT RECEIVER SCHEME

Access requests in control minislots must be as simple as possible in order to minimise the overhead they add to the system. For the protocol to work correctly, the base station only needs to distinguish between three different states: (i) empty, that is, no request has been received, (ii) success, a single request has been received and (iii) collision, two *or more* access from *any* terminal have been received. Note that nor the exact number of access requests neither the identification of the accessing terminals are required to be detected.

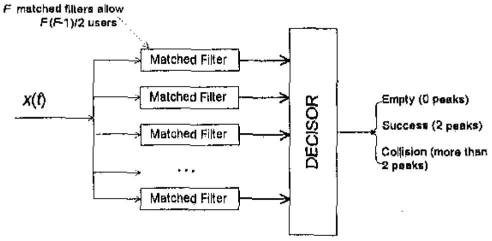

Figure 2. Minislot receiver scheme

Figure 2 shows a receiver scheme that allows this kind of detection using a very low number of matched filters (much less than terminals). A unique *couple* of chip sequences is assigned to each user. Each filter is matched to one of the possible chip sequences assigned to any user. Terminals may share one sequence, but not the same couple of sequences. Each time a terminal needs to send an access request, it will transmit both sequences simultaneously. Then, if the decision block detects more than two correlation peaks at the filter bank output, it will know that more than one user has sent an access request. Note that with F filters it is possible to manage up to $F(F-1)/2$ users.

4.1 Receiver analysis

In a Rayleigh fading channel condition, the matched filters have a detection and false alarm probabilities given by [8]:

$$P_d = P_{fD}^{\frac{2(k_D-1)}{2(k-1)+3M}} \tag{6}$$

$$P_f = P_{fD}^{\frac{k_D-1}{k-1}} \tag{7}$$

where P_{fD} and k_D are the values chosen for design of, respectively, the false alarm probability and the number of simultaneous access sequences present in the minislot. This values determine the threshold of the matched filter correlation peak trigger. On the other hand, k is the actual number of accessing sequences sent in the minislot and M is the number of chips of the sequence.

As there are three different possible minislot states, there are consequently six different error situations. If we use F matched filters and $F(F-1)/2$ users (the maximum available), it is possible to derive explicit expressions for the six conditioned error probabilities. Denoting E, S, and C, respectively, as the empty, success and collision states, it can be proved that:

$$P(S \mid k=0) = \binom{F}{2} P_f^2 (1-P_f)^{F-2} + F P_f (1-P_f)^{F-1} \tag{8}$$

$$P(C \mid k=0) = \sum_{k=3}^{F} \binom{F}{k} P_f^k (1-P_f)^{F-k} \tag{9}$$

$$P(E \mid k=1) = (1-P_d)^2 (1-P_f)^{F-2} \tag{10}$$

$$\begin{aligned} P(C \mid k=1) &= (1-P_d)^2 \sum_{k=3}^{F-2} \binom{F-2}{k} P_f^k (1-P_f)^{F-k-2} + \\ &+ 2P_d(1-P_d) \sum_{k=2}^{F-2} \binom{F-2}{k} P_f^k (1-P_f)^{F-k-2} + P_d^2 \sum_{k=1}^{F-2} \binom{F-2}{k} P_f^k (1-P_f)^{F-k-2} \end{aligned} \tag{11}$$

$$P(E \mid k>1) = \sum_{n=2}^{N} P(p=0 \mid k=n) P(k=n \mid k>1) \tag{12}$$

$$P(S \mid k>1) = \sum_{n=2}^{M} \left[P(p=1 \mid k=n) + P(p=2 \mid k=n) \right] P(k=n \mid k>1)$$

where:

$$P(p \mid k=n) = \binom{\binom{F}{2}}{n}^{-1} \sum_{f=0}^{p} \binom{p}{f} P_d^{p-f} P_f^f \sum_{m=0}^{F-p} \binom{p-f+m}{m} \binom{F}{p-f+m} (1-P_d)^m (1-P_f)^{F-p-m} F_{p-f+m}(n)$$

$$P(k=n \mid k>1) = \frac{\lambda^n}{n!\left(e^{\lambda}-\lambda-1\right)} \tag{15}$$

$$F_a(b) = \binom{\binom{F}{2}}{k} - \sum_{n=1}^{a-3} \binom{a}{n} F_{a-n}(b) \tag{16}$$

which is a recursive formula with the initial values

$$F_2(b) = \begin{cases} 1 & b=1 \\ 0 & b>1 \end{cases} \qquad F_3(b) = \begin{cases} 0 & b=1 \\ 3 & b=2 \\ 1 & b=3 \\ 0 & b>3 \end{cases}$$

As a representative result, Figure 3 shows the state misdetection probabilities as a function of the false alarm probability for M=256 and k_D=20.

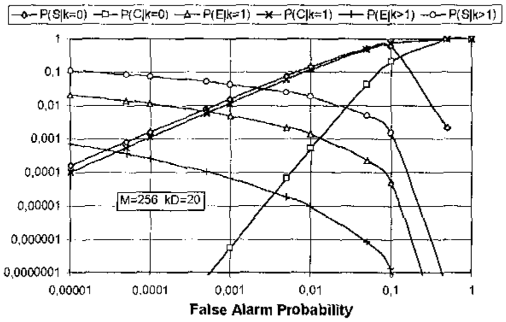

Figure 3. Minislot state misdetection probability

Due to this misdetection probabilities, some algorithm modification have been introduced to preserve the protocol operation. Computer simulations show the great robustness of this transmission technique. These results are now presented and analysed.

5 SIMULATIONS AND COMPARISONS

Figure 4 shows the comparison between the analytical evaluation and the computer simulation results of the total delay for a system with N=100 data terminals, average message length of 6400 bits, CDMA channel with K=16 spreading codes and a spreading factor S_f=64. The slots are of L=640 bits. We have used the gaussian hypothesis for the interference power evaluation in the calculation of the *BLER* and assumed perfect power control.

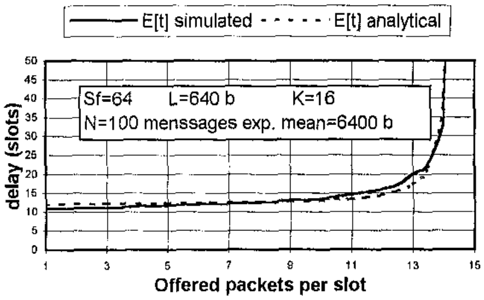

Figure 4. Analytical and Simulation results for the protocol

Simulation results fit correctly with the analytical model. Afterwards, we have introduced the receiver scheme and the needed protocol modifications mentioned above. Figure 5 shows the comparison delay between the system with the ideal receiver scheme and the one with Rayleigh fading conditions. It can be explicitly seen the little loss in performance produced by the real channel situation. Finally, a comparison with other random access protocols designed for a CDMA environment were carried out. Slotted-ALOHA/CDMA has been extendedly used as an access scheme for systems where the number of spreading codes is comparable with the number of terminals. With this scheme, whenever a terminal has data to send, makes the transmission immediately. ISMA/CDMA [9] is also a widely-studied scheme that adapts the CSMA ideas to a wireless environment.

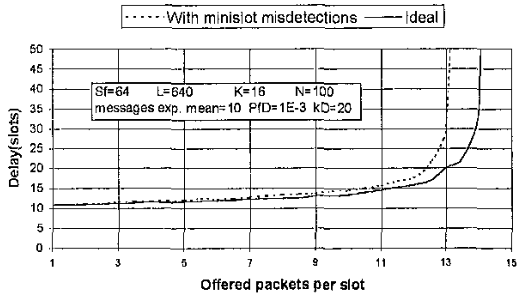

Figure 5. Non-ideal minislot misdetection.

Figure 6 shows the delay comparison between a Slotted-ALOHA system with N=100 users, where each terminal has an assigned spreading code, an ISMA/CDMA system using K=32 spreading codes and a system using DQRAP/CDMA with the same number of users but using only K=16 available spreading codes. Channel conditions are the same for all systems (spreading factor S_f=64, slots of length L=640 bits and messages of exponential-distributed length with mean 6400 bits).

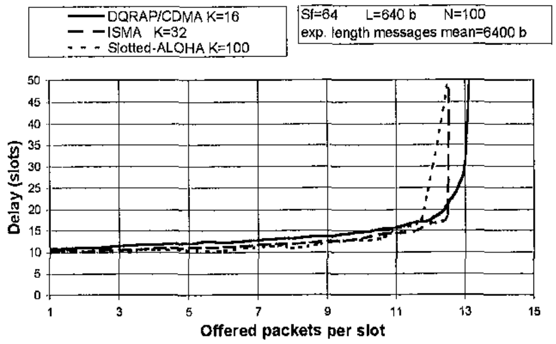

Figure 6. Delay comparison of protocols

We can see that DQRAP/CDMA outperforms the other schemes using a lower number of spreading codes.

6 CONCLUSIONS

It has been presented a proposal of a near-optimum random access protocol for a CDMA environment suitable for the future third generation mobile communication systems. An analytical model has been introduced and the obtained results fit correctly with those obtained by computer simulations. It has been shown that the protocol has good delay and stability characteristics. So it becomes a good proposal for the improvement in the use of the capacities of random access channels in the reverse link.

The receiver scheme for minislot detection has been proposed and analysed in order to show the applicability of the proposal. It has been also shown that the protocol outperforms other medium access schemes even using a much reduced set of spreading codes.

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