

# A Proposal for an Adaptive S-ALOHA Access System for a Mobile CDMA Environment

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**Abstract**—This paper presents a novel adaptive direct-sequence code-division multiple-access (DS-CDMA) slotted-ALOHA (S-ALOHA) packet random-access scheme with transmitter-based spreading codes for mobiles. It is aimed at improving throughput and message delay delivery when traffic load values below the saturation point of the conventional DS-CDMA S-ALOHA system are sensed in the channel. For this purpose, one mobile-station (MS) and two base-station (BS)-assisted algorithms are envisaged to control the change of the transmission rate according to the traffic load. These algorithms revealed that the optimum behavior, obtained using a Markov chain model, may almost be reached at a low-complexity cost. A traffic model based on a realistic statistical length distribution of the messages illustrates how the delay delivery can be greatly reduced with the proposed algorithms. Finally, the impact of forward-error-correction (FEC) coding on the adaptive system is also studied.

**Index Terms**—Access protocols, code-division multiaccess, packet radio.

## I. INTRODUCTION

SLOTTED ALOHA (S-ALOHA) has been widely recognized for packet radio applications because of both its simplicity in managing bursty traffic and its ability to deliver a shorter delay than that of fixed multiple-access techniques in the presence of low traffic loads. The original version of this protocol assumes that whenever more than one packet is transmitted at the same time, the information contained in all the transmitted packets will be lost. This would not be the case if S-ALOHA was used with a multireceiver direct-sequence code-division multiple-access (DS-CDMA) technique. This CDMA S-ALOHA scheme allows several users to transmit at the same time using a different spreading code for each one [1], [2] so that unsuccessful transmissions are caused entirely by multiple-access interference, provided negligible thermal noise effects are assumed. Such an access technique could also benefit from the advantages of CDMA in operation flexibility and robustness to undesired interferences. In a CDMA-based wireless multimedia system, DS-CDMA S-ALOHA is certainly a simple choice for bursty data transmission.

This paper is intended to improve the throughput achieved with a multireceiver DS-CDMA S-ALOHA when a light load is offered to the system, and accordingly the delay decreases. For this purpose, we will focus on the transmission rate used

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instead of on the access protocol itself. In particular, different transmission rates are proposed in order to utilize the most suitable one according to the channel load at any time slot. Fast and simple algorithms that command the processing gain of the spread-spectrum DS scheme as a function of the channel load are envisaged. For low channel loads, a high CDMA processing gain is no longer necessary, and it can be reduced so as to increase the actual bit rate. Thus, an adaptive S-ALOHA in which the packet duration does not change is considered, though depending on the rate used, a different number of bits can be transmitted in a single time slot. In this way, system throughput increases and message transmission delay can be shortened to the extent that the packets resulting from the breaking down of these messages are able to increase the number of transported bits. This is also noticeable in a multireceiver CDMA, where the users are asked to contend for a lower number of channels when the user bit rate increases. This number of channels would coincide with the processing gain of an ideal CDMA, i.e., it would be able to operate with orthogonal spreading sequences. Therefore, in an extreme situation with a processing gain equal to one, all the users would access the same channel at their maximum bit rate according to a pure S-ALOHA. Certainly, the greatest access randomness, deriving from the greatest contention activity, would benefit the low traffic loads by shortening message delay delivery.

The paper is organized as follows. In Section II, an analytical model for the DS-CDMA S-ALOHA system is presented, which is used to evaluate the optimum achievable throughput with an adaptive change of transmission-rate algorithm. In Section III, several S-ALOHA adaptive algorithms are proposed and assessed depending on whether the algorithm is managed by a mobile station (MS) or by a base station (BS). Section IV considers a realistic situation where users generate messages that must be segmented into several packets to access the radio channel. Performance in this situation is also studied. Section V covers the impact of coding on the proposed schemes. Finally, some conclusions close the paper in Section VI.

## II. MODEL FOR AN S-ALOHA DS-CDMA ACCESS SYSTEM

From now onwards,  $N$ -registered users will be considered. These users may be in either of two different operation modes: “idle mode” (I mode) and “backlogged mode” (B mode). In the former, there is no packet to be retransmitted, and new packets are generated with probability  $p_o$ . Terminals enter the backlogged mode when an attempt to transmit a new packet

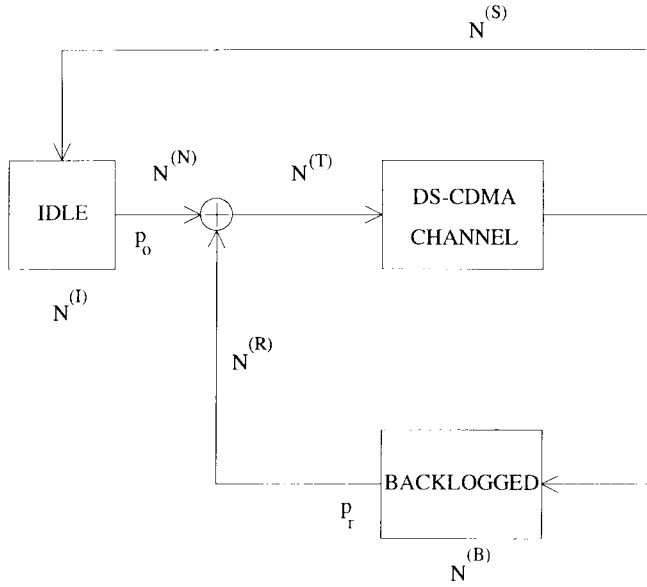


Fig. 1. Model for an S-ALOHA DS-CDMA system.

fails. In this mode, the retransmission of the backlogged packet occurs in any given slot with probability  $p_r$ . While in the backlogged mode the user does not generate any new packet.

Let  $N_k^{(B)}$ ,  $k = 0, 1, \dots$  denote the number of backlogged users at the beginning of the  $k$ th slot. It is easy to show that  $\{N_k^{(B)}\}$  is a finite-state discrete-time Markov chain over the state space  $N_k^{(B)} \in \{0, 1, \dots, N\}$ , whose performance has been studied among others in [3] and [4]. When considering DS-CDMA, the formulation must be modified as was done in [5]. The same notation is followed in this paper. The S-ALOHA DS-CDMA channel model and the flow of users between I and B modes are represented in Fig. 1, while in Table I all the parameters are defined.

As the first main expression, we have

$$p_{ij} = P\{N_{k+1}^{(B)} = j | N_k^{(B)} = i\} \quad (1)$$

where  $p_{ij}$  is the one-step transition probability from state  $i$  to state  $j$ . The equilibrium distribution, where the subscript  $k$  denoting the time dependence can be dropped, will be

$$\pi = [\pi_0, \pi_1, \dots, \pi_N] \quad \pi_i = P\{N^{(B)} = i\} \quad (2)$$

which can be obtained by previously solving the set of linear equations

$$\pi = \pi P \text{ together with } \sum_{t=0}^N \pi_t = 1 \quad (3)$$

with  $P$  being the transition probabilities matrix

$$P = [p_{ij}]_{(N+1) \times (N+1)}. \quad (4)$$

To evaluate  $p_{ij}$ , it will be useful to take into account that there will be  $i$  users in B mode at the start of time slot  $k$  and  $j$  users in B mode at the start of time slot  $k+1$ .  $j$  results from the initial value  $i$  plus the number of users in I mode at the start of slot  $k$  transmitting and failing in the current slot, i.e.,  $N_k^{(N)} - N_k^{(S),I}$ , with  $N_k^{(S),I}$  denoting the number

of successful users in slot  $k$  that were already in I mode at the start of slot  $k$ , minus the number of users in B mode at the start of slot  $k$  transmitting successfully in the current slot, denoted by  $N_k^{(S),B}$ . Since  $N_k^{(S)} = N_k^{(S),I} + N_k^{(S),B}$ , it holds

$$\begin{aligned} N_{k+1}^{(B)} - N_k^{(B)} &= [N_k^{(N)} - N_k^{(S),I}] - N_k^{(S),B} = N_k^{(N)} - N_k^{(S)} \\ \left. \begin{aligned} N_k^{(S)} &= s \\ N_k^{(B)} &= i \\ N_{k+1}^{(B)} &= j \end{aligned} \right\} &\Rightarrow N_k^{(N)} = j - i + s \end{aligned} \quad (5)$$

and keeping this result in mind, it can be found that

$$\begin{aligned} p_{ij} &= \sum_{n=0}^N \sum_{s=0}^n \binom{N-i}{j-i+s} p_o^{j-i+s} (1-p_o)^{N-j-s} \\ &\quad \times \binom{i}{n-s+i-j} p_r^{n-s+i-j} (1-p_r)^{j+s-n} \\ &\quad \times P\{N^{(S)} = s | N^{(T)} = n\} \end{aligned} \quad (6)$$

which can be easily interpreted: for any total number of simultaneous users  $n$ , any number of successful packets,  $s$  is averaged. Since  $s$  is thus fixed, the number of users in I mode at the start of the time slot and transmitting  $[N_k^{(N)}]$  that cause transition from state  $i$  to state  $j$  is known from (5), and so it is only necessary to compute the probability that  $(j-i+s)$  out of  $(N-i)$  users in I mode at the start of the time slot, and, consequently,  $[n-(j-i+s)]$  out of  $i$  users in B mode at the start of the slot, transmit. A more formal derivation of this formula is presented in [5].

The expression for the equilibrium distribution of the composite packet arrivals in a time slot in terms of the equilibrium distribution of the Markov chain is

$$P\{N^{(T)} = n\} = \sum_{i=0}^N P\{N^{(T)} = n | N^{(B)} = i\} \pi_i \quad (7)$$

$$\begin{aligned} P\{N^{(T)} = n\} &= \sum_{i=0}^N \left[ \sum_{m=\max(0, n-i)}^{\min(n, N-i)} \binom{i}{n-m} \right. \\ &\quad \times p_r^{n-m} (1-p_r)^{i-n+m} \binom{N-i}{m} \\ &\quad \left. \times p_o^m (1-p_o)^{N-i-m} \right] \pi_i. \end{aligned} \quad (8)$$

The above formulation will be necessary to evaluate system performance analytically. In particular, the throughput measurements can be obtained as

$$S = \sum_{n=0}^N \left[ \sum_{s=0}^n s \times P\{N^{(S)} = s | N^{(T)} = n\} \right] \times P\{N^{(T)} = n\} \text{ packets/slot} \quad (9)$$

where, if all users employ the same modulation and transmission rate, the following expression arises:

$$P\{N^{(S)} = s | N^{(T)} = n\} = \binom{n}{s} [P_c(n)]^s [1 - P_c(n)]^{n-s} \quad (10)$$

TABLE I  
LIST OF PARAMETERS FOR THE S-ALOHA DS-CDMA MODEL

$N$	Number of mobiles in the system
$N_k^{(B)}$	Number of mobiles in B-mode at the beginning of the time slot $k$
$N_k^{(I)}$	Number of mobiles in I-mode at the beginning of the time slot $k$
$N_k^{(T)}$	Total number of mobiles transmitting packets in the time slot $k$
$N_k^{(R)}$	Number of mobiles in B-mode transmitting packets in the time slot $k$
$N_k^{(N)}$	Number of mobiles in I-mode transmitting packets in the time slot $k$
$N_k^{(S)}$	Number of packets correctly received in the time slot $k$
$p_o$	Probability that a mobile in I-mode generates a packet in a time slot
$p_r$	Probability that a mobile in B-mode retransmits a packet in a time slot
$P_c(n)$	Average correct packet probability given $n$ simultaneous DS-CDMA transmissions

with  $P_c(n)$  being the probability of correctly detecting a packet when  $n$  users have attempted transmission in a time slot. In the following sections, we will introduce an expression for  $P_c(n)$ .

#### A. S-ALOHA DS-CDMA Access System

A BPSK DS-CDMA access system with a processing gain given by  $G_p$  is considered. All users have been assigned random signature sequences. The network topology consists of a multiple-receiver scheme at the central BS and a number of users located around according to the conventional star architecture that enables uplink and downlink transmission paths in two different frequency bands. The transmission channel is modeled by a flat fading. Moreover, a perfect power control capable of mitigating fading of the channel is introduced, i.e., the terminal transmits the power level necessary always to keep the same received power. With a view to achieving this, a continuous link between BS and MS is needed so that the mobile transmits at rate  $v$  b/s when there is information to be sent and at rate  $v'$  b/s (in general, much lower) when the terminal is not active.  $v'$  should be high enough to allow the fading on the uplink path to be tracked by updating transmitted power in response to the BS commands.

The interference caused by an inactive user (in the sense that this user does not have an information packet to send at a given moment) is not zero in this case, due to the continuous link to keep the power control. However, we can expect this interference to be low, mainly in low mobile speed environments like manufacturing or indoor business, where channels change slowly and so power updates should also be at a low rate, requiring low transmitted power.

An instantaneous power control permits a huge improvement in system performance when compared with an open-loop power control, and it is, in fact, considered in the already operative [6] and the proposed CDMA systems [7]. Although an instantaneous power control could be envisaged for packet radio on a packet-by-packet basis [8], we have retained the continuous link approach because in this case no synchronization overhead at the beginning of time slot would be required, since the mobile is already synchronized. Whether continuous power control is retained or not it is in any case irrelevant for the proposed S-ALOHA scheme since it is taken for granted that a throughput decrease should be considered in the noncontinuous packet based power control approach.

#### B. S-ALOHA DS-CDMA Performance

By assuming an ideal instantaneous power control, the channel can be seen as an AWGN if we use the Gaussian hypothesis to model the interference originated by other users [9]. Although it can be argued that for a reduced number of simultaneous users, as could happen in a packet-access system, the Gaussian hypothesis of the interferences is a weak assumption in a CDMA scenario, this is true only when very low bit-error rates (BER's) are considered. Actually, when the number of simultaneous users is small, the BER is also very low, and the probability of receiving the packet correctly is close to one, regardless of how low the BER is. Hence, considering the Gaussian hypothesis should not greatly influence throughput behavior [2].

Under these conditions and considering a transmission rate of  $v$  b/s for active users to send information and  $v'$  b/s for inactive users to keep the power control, the following expressions hold for the evaluation of the BER:

$$P_b(n) = Q\left(\sqrt{2\frac{E_b}{N_o}}\right) \quad \text{with} \quad \frac{E_b}{N_o} = \frac{1}{\frac{2(n-1)}{3G_p} + \frac{2(N-n)}{3G_p} \frac{v'}{v}} \quad (11)$$

where  $n$  is the number of simultaneous users and the term  $v'/v$  takes into account that to keep the same  $E_b$  at the receiver, the transmitted power can be reduced in the same proportion as the transmission rate is reduced. Then, the probability of correctly detecting a packet containing  $\alpha B$  b is

$$P_c(n) = [1 - P_b(n)]^{\alpha B}. \quad (12)$$

Keeping the transmission bandwidth constant, and taking as a reference a transmission rate of  $v$  b/s, packet length of  $B$  b and a processing gain  $G_p$ , the transmission rate could be increased by a factor  $\alpha$  ( $\alpha > 1$ ) at the expense of a reduction in the spread capacity. That is, transmitting at rate  $\alpha v$  b/s would allow a processing gain of  $G_p/\alpha$ . However, in exchange for this reduction in processing gain,  $\alpha B$  b per time slot can be allocated instead of only  $B$ .

The achievable global throughput with different transmission rates obtained with the previous Markov model can be seen in Fig. 2, where  $G$  stands for the offered load-average

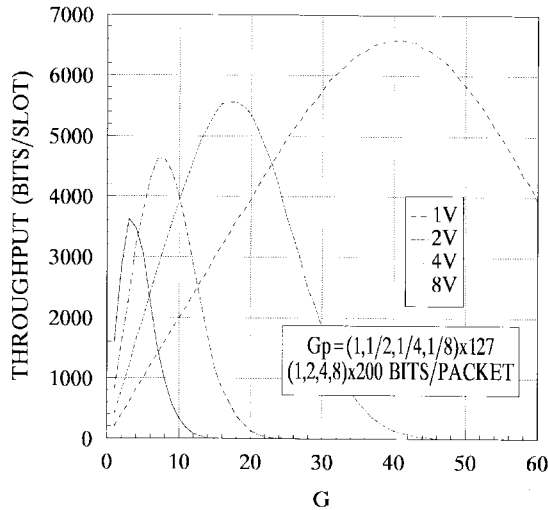


Fig. 2. Throughput performance for different transmission rates.

number of attempted transmissions per time slot, and  $p_o$  is set equal to  $p_r$  so that  $p_o = p_r = p = G/N$ .  $G$  is assumed to vary slowly. Moreover, for numerical results,  $v'$  has been set to zero. It is clear from Fig. 2 that the higher rate (8v b/s) is interesting when the system is lightly loaded: more bits per packet can be sent through the channel since the little interference observed permits correct transmission. When the offered load increases, so does the interference level, and, therefore, the rate 8v b/s is no longer interesting because of the higher BER compared to the 4v b/s rate. Using 4v b/s in this range is better than 8v b/s in the sense that a higher throughput is achieved although the packet contains half the number of bits per packet (errors occur quite often with 8v b/s, but 4v b/s can still bear the interference because of the higher  $G_p$  compared to that of 8v b/s rate). For higher offered loads, the same tradeoff appears: first between 4v and 2v b/s and finally between 2v and v b/s.

Although there are no restrictions on the values of  $\alpha$ , for the sake of brevity and clarity only three rates  $v$ ,  $2v$ , and  $4v$  b/s ( $\alpha = 1, 2, 4$ ) will be considered in the sequel.

### C. Adaptive S-ALOHA DS-CDMA

In light of the above results, an algorithm able to change the transmission rate used by the MS as a function of the traffic load of the system could be foreseen so that the maximum possible throughput could always be obtained. This algorithm should be able to maximize the number of correctly received bits for a given packet duration period by selecting the most suitable rate (4v, 2v, and v b/s) at any given slot depending on the number of active users (i.e., the interference level).

In order to validate later the proposed algorithms for changing the transmission rate, let us first calculate the optimum throughput achievable for an ideal algorithm. This can be analytically obtained from the above Markov model and can be used later as a reference to assess the performance of the change of the transmission-rate algorithms proposed below. To attain this optimum performance, the best combination of transmission rates should be obtained provided  $n$  simultaneous users are present.

The best combination of transmission rates would be obtained after an exhaustive search

$$\max_{(n_v, n_{2v}, n_{4v})} S(n_v, n_{2v}, n_{4v}) \text{ subject to} \\ n_v + n_{2v} + n_{4v} = n \quad (13)$$

where  $n_v$  means the number of users transmitting at  $v$  b/s,  $n_{2v}$  the number using  $2v$  b/s,  $n_{4v}$  the number at  $4v$  b/s,  $n$  the total number of simultaneous users, and  $S$  is the throughput in such combination of transmission rates. Then

$$S(n_v, n_{2v}, n_{4v}) = n_v \times [P_{c,(v)}(n_v, n_{2v}, n_{4v})] \times B + n_{2v} \\ \times [P_{c,(2v)}(n_v, n_{2v}, n_{4v})] \times 2B + n_{4v} \\ \times [P_{c,(4v)}(n_v, n_{2v}, n_{4v})] \times 4B \quad (14)$$

where, in turns, it is shown that the packet correct probabilities,  $P_{c,(\alpha v)}(n_v, n_{2v}, n_{4v})$ , depends on the transmission rates associated to any  $(n_v, n_{2v}, n_{4v})$  combination since the interference caused by different kinds of user is not the same. The expressions used to evaluate BER must be modified in order to take into account the fact that the channel will be shared by users with different rates. Then, if a reference user transmits BPSK at  $v$  b/s, it holds that

$$\left(\frac{E_b}{N_o}\right)_v = \frac{1}{\frac{2(n_v - 1)}{3G_p} + 2\frac{2n_{2v}}{3G_p} + 4\frac{2n_{4v}}{3G_p} + \frac{2(N - n)}{3G_p} \frac{v'}{v}} \quad (15)$$

and

$$P_{b,(v)}(n_v, n_{2v}, n_{4v}) = Q \left[ \sqrt{2 \left(\frac{E_b}{N_o}\right)_v} \right] \\ P_{c,(v)}(n_v, n_{2v}, n_{4v}) = [1 - P_{b,(v)}(n_v, n_{2v}, n_{4v})]^B. \quad (16)$$

In order to keep the same received  $E_b$ , (15) shows how the power received for  $v$  b/s is half of that required for  $2v$  b/s and a quarter of that needed with  $4v$  b/s. It has also been considered that inactive users employ  $v'$  b/s to keep the power control.

The probability of getting  $s$  successful packets out of  $n$ -transmitted packets is now given by

$$P\{N^{(S)} = s | N^{(T)} = n\} \\ = \sum_{i=\max(0, s-n_{2v}-n_{4v})}^{\min(n_v, s)} \sum_{j=\max(0, s-i-n_{4v})}^{\min(n_{2v}, s-i)} \binom{n_v}{i} \\ \times [P_{c,(v)}]^i [1 - P_{c,(v)}]^{n_v-i} \binom{n_{2v}}{j} [P_{c,(2v)}]^j \\ \times [1 - P_{c,(2v)}]^{n_{2v}-j} \binom{n_{4v}}{s-i-j} [P_{c,(4v)}]^{s-i-j} \\ \times [1 - P_{c,(4v)}]^{n_{4v}-s+i+j} \quad (17)$$

instead of (10), which applies when all users employ the same transmission rate. In turn, it is assumed that the optimal combination  $(n_v, n_{2v}, n_{4v})$  is available for any  $n$ , and users are in fact using it. That is,  $n$  is readily associated to an  $(n_v, n_{2v}, n_{4v})$  set, and so  $P\{N^{(S)} = s | N^{(T)} = n\}$  is evaluated considering all possible cases giving  $s$  correctly received packets when  $n_v$  users transmit at low rate,  $n_{2v}$  at medium, and  $n_{4v}$  at high, leading to (17). Thus, the modified

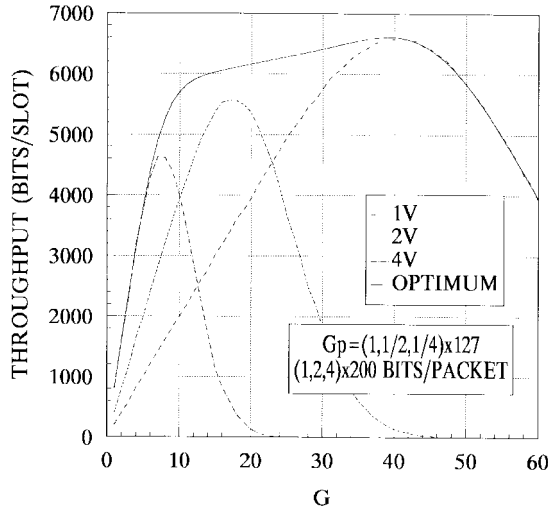


Fig. 3. The very best achievable throughput for the S-ALOHA DS-CDMA system.

throughput expression is

$$\begin{aligned}
 S = \sum_{n=0}^N \left\{ \sum_{s=0}^n \sum_{i=\max(0, s-n_{2v}-n_{4v})}^{\min(n_v, s)} \sum_{j=\max(0, s-i-n_{4v})}^{\min(n_{2v}, s-i)} \right. \\
 \times [Bi + 2Bj + 4B(s-i-j)] \binom{n_v}{i} [P_{c,(v)}]^i \\
 \times [1 - P_{c,(v)}]^{n_v-i} \binom{n_{2v}}{j} [P_{c,(2v)}]^j \\
 \times [1 - P_{c,(2v)}]^{n_{2v}-j} \binom{n_{4v}}{s-i-j} [P_{c,(4v)}]^{s-i-j} \\
 \left. \times [1 - P_{c,(4v)}]^{n_{4v}-s+i+j} \right\} \times P\{N^{(T)} = n\} \\
 \text{bits/slot} \quad (18)
 \end{aligned}$$

where  $B$  is the number of bits in a BPSK  $v$  rate packet ( $B = 200$  b throughout this paper) and  $S$  is expressed in *bits/slot*. Fig. 3 shows this optimum throughput in comparison with individual behavior patterns.

### III. CHANGE OF TRANSMISSION-RATE ALGORITHMS

In this section, several proposals for adaptive change of the transmission-rate algorithms are addressed. The common idea consists in sensing the traffic load through the channel in order to accommodate transmission rates accordingly. Three algorithms with increasing order of complexity are proposed in the following subsections:

#### A. Mobile-Controlled Algorithm

The proposed simple algorithm carried out by the MS works as follows: each terminal traces its own evolution during the transmission time, that is, terminals count their successful and erroneous packets. In the absence of errors, the mobile will assume a low traffic load and try to use a higher transmission rate. The throughput should be increased in this way. If errors occur, the mobile decides that the channel is too loaded

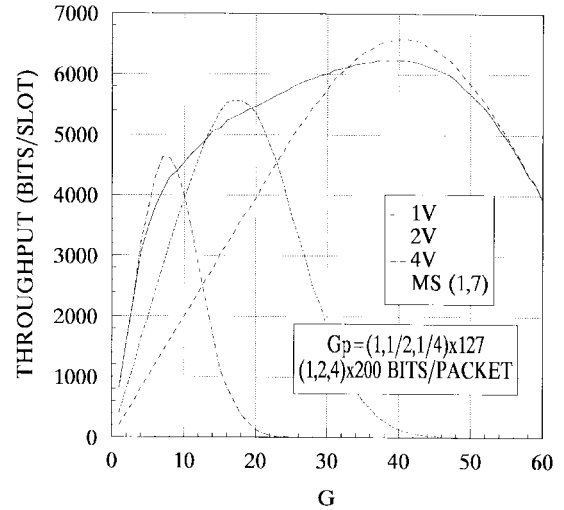


Fig. 4. Throughput performance for MS algorithm.

and tries a lower transmission rate. In this case, fewer bits per packet are transmitted, but an overall improvement in throughput should also follow because these bits can be now detected correctly since processing gain increases accordingly.

Let us note that this decision is taken by the mobile without any exchange of information with the BS except for the packet acknowledgment. Even the MS does not need to indicate its choice of transmission rate before using it because the BS itself could be able to detect which one is arriving.

Specifically, the MS needs to establish only two parameters: the number of consecutive packet failures before changing to a lower rate ( $\max\_tr$ ) and the number of consecutive packet successes before trying a higher rate ( $\min\_suc$ ). So, the practical implementation of this algorithm would be at a very low-complexity cost since it only requires a counter in the mobile terminal and there is no spending on radio resources for signaling purposes. Moreover, priorities between mobiles could be established by assigning different ( $\max\_tr$ ,  $\min\_suc$ ) sets to the different priority groups [10]. These parameters could even be adaptively changed according to the channel load.

Fig. 4 shows the throughput attained for  $N = 60$  registered mobiles. Fig. 2 has been taken as a reference in order to appreciate whether mobiles choose the most suitable rate or not. In spite of the simplicity of the algorithm, the envelope of the three individual graphs is almost reached, and this is not far from the optimum behavior. Results have been obtained with fixed  $\max\_tr = 1$  (if a packet fails, the next attempt will be made at a lower rate) and  $\min\_suc = 7$  (if the last seven packets have been received correctly, the next packet will be sent at a higher rate). The couple (1, 7) is seen as the best choice, once other possibilities have been studied. Increasing  $\max\_tr (>1)$  means delaying the reaction capacity of the algorithm. Reducing  $\min\_suc (<7)$  results in an overoptimistic policy, while  $\min\_suc > 7$  is too cautious.

#### B. Base-Controlled Algorithm

Coordination between mobiles can be achieved if BS manages the algorithm. By doing so a performance improvement is

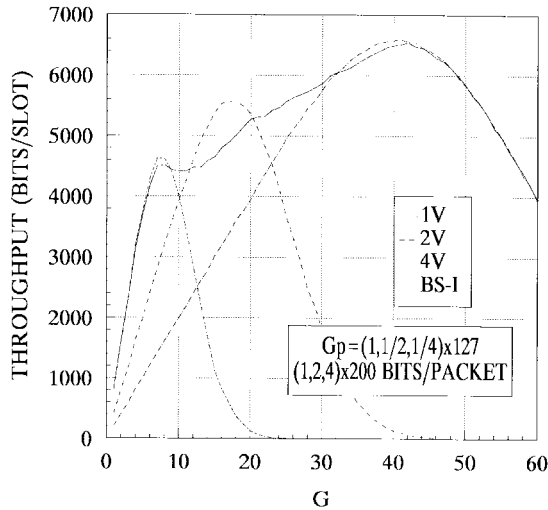


Fig. 5. BS-I algorithm with optimal combination of rates.

expected at the expense of losing a certain degree of simplicity in its implementation.

1) *BS-I Algorithm*: This algorithm is managed by the BS, which decides the transmission rate to be used. The BS estimates the number of users  $n$  who have attempted to transmit in a given time slot. Then, the BS expects  $n$  users to be the most likely value for the next time slot. Note that, given an offered load  $G$ , the number of active users in any time slot follows a binomial distribution. Since the BS does not know which mobiles are going to transmit, it has to broadcast the probability of using each transmission rate that the BS is able to know from (13) and (14). Then, the active users select their actual transmission rate accordingly. For example, when  $G_p = 127$  (for the reference rate) and there have been 12 users transmitting their packets in the last time slot, the BS expects 12 users again for the next time slot, and it knows that the best throughput under this situation is achieved with seven users transmitting at  $2v$  b/s and five users transmitting at  $4v$  b/s, where it is found that for these parameters the highest achievable throughput is roughly 5600 b/slot. Thus, a probability of 7/12 of transmitting at  $2v$  b/s and a probability of 5/12 for  $4v$  b/s is used by an active mobile to transmit in the next time slot. This process is repeated every time slot.

Results obtained following the above procedure can be seen in Fig. 5, where it has been considered that the BS is able to calculate the exact number of mobiles that have attempted transmission in the previous time slot. Fig. 5 shows that such simple information as the crude estimation of the mean offered load is very valuable.

The behavior of a simplified version of the algorithm is also presented in Fig. 6. It consists in deciding the transmission rates to broadcast by the BS based on threshold values. That is, threshold  $L_1$  means that for  $n < L_1$  all mobiles will use  $4v$  b/s in the next time slot,  $L_2$  indicates that for  $L_1 < n < L_2$  all mobiles will use  $2v$  b/s during the following time slot, and for  $n > L_2$  all mobiles will use  $v$  b/s. Optimum thresholds obtained by simulation for  $N = 60$  would be  $L_1 = 9$  and

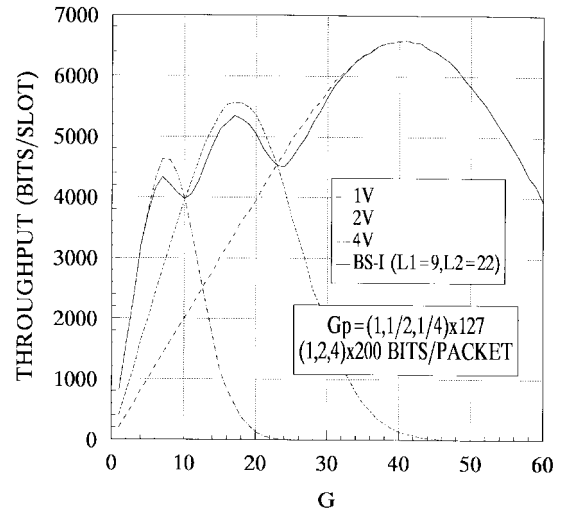


Fig. 6. BS-I algorithm with thresholds.

$L_2 = 22$ . In this way, the envelope of the individual features is almost reached, although compared to the mobile-controlled algorithm performance it is worse. That is explained by the inaccuracy of the information provided to the BS.

2) *BS-II Algorithm*: An improvement in throughput performance attained with the BS-I algorithm could be expected if the BS knew in advance the exact number of users ready to transmit in a given slot. For this purpose, the time slot is split in two parts: the first part is simply used to indicate that a packet is scheduled for transmission, and in the second part information is eventually transmitted.

In the so-called preslot (first part of time slot), mobiles only transmit a signal in an S-ALOHA DS-CDMA mode indicating that they are ready to transmit. Actually, a few preslot bits should be included in any case to allocate some guard time and a sync word to detect the arriving burst. After this, the BS counts how many users will attempt to transmit and selects the optimum combination of transmission rates to be employed, again according to (13) and (14). This information is supplied to the MS and the payload bits are sent at the most suitable rate in the second part of the slot.

There are two possibilities in preslot: each mobile can identify the features of its message besides the indication of its purpose to transmit a packet, or each mobile can simply announce its purpose to transmit a packet by signaling the BS to count a busy user. The first option allows a priority policy among mobiles according to their service needs. Consequently, a mobile with high traffic needs could be allocated the highest transmission rate composing the optimum combination.

Preslot uses an S-ALOHA DS-CDMA operation mode with the BS-I threshold version algorithm because, when possible, users employ a higher rate and then the overhead caused by the preslot is reduced (a fixed number of bits is assumed to be necessary to indicate to the BS that there is information ready to be sent). Worthy of note is the fact that in the preslot it is compulsory to use the threshold version in the BS-I because all users have to use the same rate and so they will need the same time to transmit the required preslot bits.

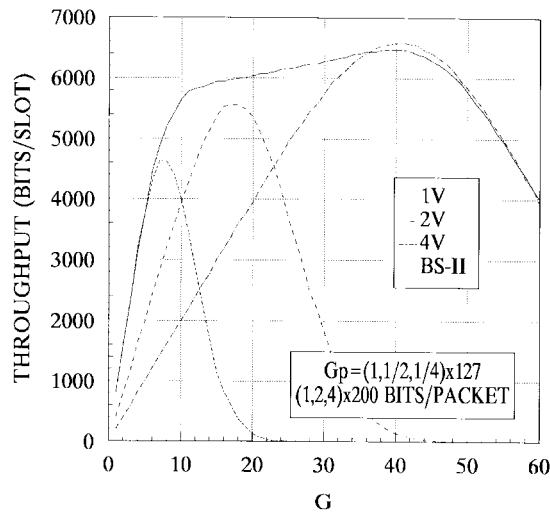


Fig. 7. BS-II algorithm reaches almost optimal performance.

The main difference from BS-I is that-supposing that there are no errors in the preslot period-BS-II lets the BS know the exact number of users by simply counting the number of active receivers at the end of the preslot period.

Performance of BS-II is presented in Fig. 7, where a 5-b preslot was assumed. Simulations were run considering that multiple-access interference can cause errors in the preslot period, and so only those mobiles whose preslot was received correctly were considered in order to select the best mix of transmission rates. BS-II attains nearly the optimum achievable behavior, and outperforms BS-I except for heavy loads, where mainly  $v$  b/s have to be used and both algorithms lead to the same performance (except for the small loss of efficiency caused by the preslot overhead in the BS-II algorithm).

IV. MESSAGE TRAFFIC MODEL

In a real scenario, the transmission of a packet is initiated by a message being generated by a user terminal attached to the system. The length of the message may not coincide with the length of a packet. If too small, it must be completed by dummy bits. If too large, it must be conveyed over several packets.

In order to assess the benefits from using the previous adaptive S-ALOHA DS-CDMA scheme in such a scenario, a simulation aiming at obtaining the average message delay in terms of the throughput was carried out. From now onwards and for simulation purposes, mobiles generating messages of mean length of 8000 b and a uniform distribution between 6000 and 10000 b have been assumed. The silence periods occurring between messages are expressed in time slots and were modeled with a uniform distribution (0–2T), where T was internally introduced in the simulation as a parameter. This value determines the activity factor of the sources given by one message every T time slots on the average (8000/T b/slot).

In order to show some representative results, Fig. 8 plots the throughput versus the delay performance for  $v$ ,  $2v$ , and  $4v$  rates obtained for  $N = 200$  registered users, a fixed

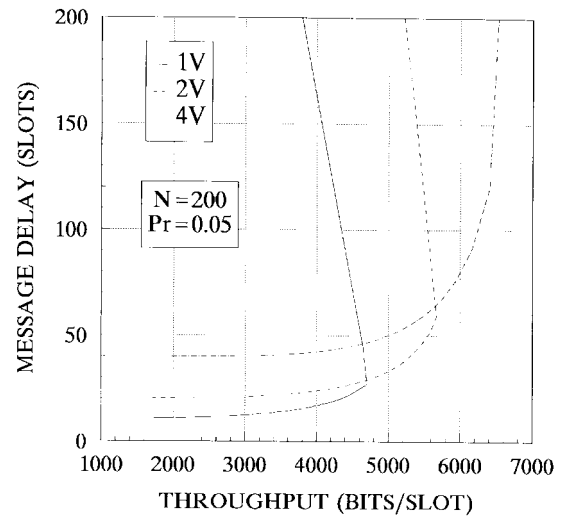


Fig. 8. Delay versus throughput behavior with messages.

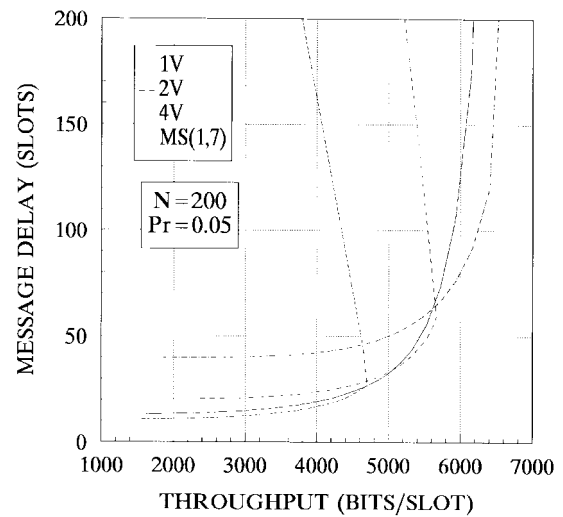


Fig. 9. Mobile-controlled algorithm.

retransmission probability  $p_r = 0,05$ , and an infinite buffer size. It can be seen from Fig. 8 that for low loads, an asymptotic message delay of ten slots, corresponding to ten consecutive successful transmissions of 800 b per time slot, is attained at  $4v$  b/s. Asymptotic message delays of 20 time slots at  $2v$  b/s and of 40 time slots at  $v$  b/s show the potential benefit that can be achieved by using the adaptive transmission-rate procedure described above for a CDMA S-ALOHA system. In fact, for low loads the message is delivered with a shorter delay if  $4v$  b/s is employed. However, if the channel load increases, the delay for  $4v$  b/s grows faster than plots for  $2v$  b/s and  $1v$  b/s, and it is no longer the best choice.

Figs. 9 and 10 show the results obtained for the mobile-controlled algorithm (MS) and the BS-I algorithm, respectively. The former follows the best graph almost perfectly until the load is so high that it becomes clear that  $v$  rate should be used and the MS algorithm procedure becomes useless. The latter works less well because of the above-mentioned inaccuracy in the estimation of the number of simultaneous users.

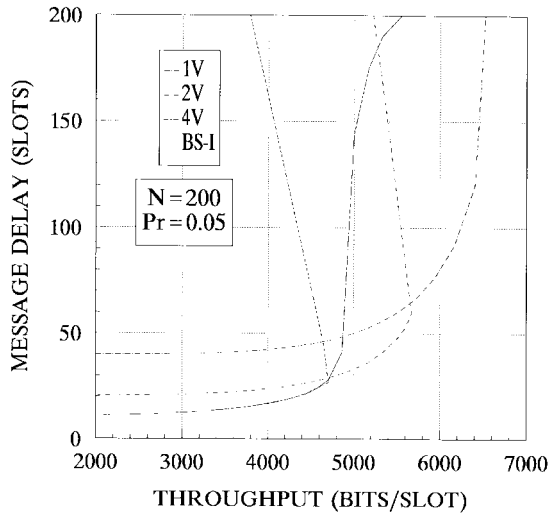


Fig. 10. Performance of BS-I for messages.

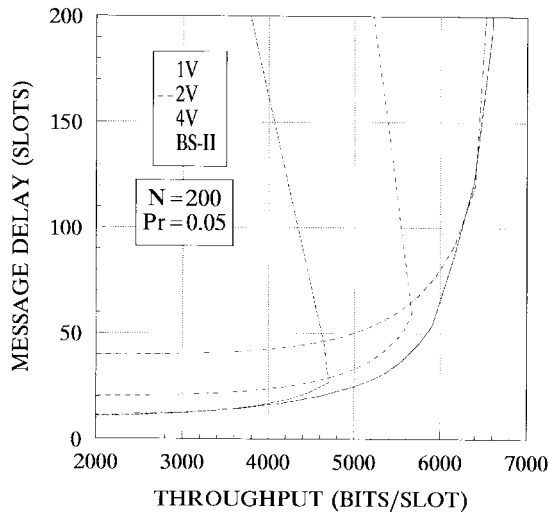


Fig. 11. The BS has *a priori* knowledge of the number of transmitting users.

Finally, Fig. 11 shows the results obtained for the BS-II algorithm. In this case, the behavior is very close to the optimum possible.

### V. IMPACT OF CODING ON THE ADAPTIVE S-ALOHA DS-CDMA SYSTEM

The application of forward-error-correction (FEC) coding is known to provide significant capacity increases. In fact, S-ALOHA DS-CDMA can outperform the bandwidth equivalent multichannel S-ALOHA system in terms of throughput when proper design parameters and FEC coding is used [2], [5]. The objective of this section is to examine the impact of block FEC coding on the proposed adaptive S-ALOHA DS-CDMA system.

Let  $(L, k)$  be a block code of total length  $L$  b and  $k$  user information bits with the capacity for correcting  $t$  or fewer errors. We will use the Varsharmov–Gilbert bound [2], [11] in order to obtain general results not depending on any specific

TABLE II  
 $k$  IS THE MINIMUM NUMBER OF USER INFORMATION BITS THAT CAN BE ALLOCATED IN AN  $L$  BITS PACKET ABLE TO CORRECT UP TO  $t$  ERRORS

$L \setminus t$	$t=1$	$t=2$	$t=3$
$L=200$	$k \geq 179$	$k \geq 168$	$k \geq 158$
$L=400$	$k \geq 376$	$k \geq 363$	$k \geq 351$
$L=800$	$k \geq 773$	$k \geq 758$	$k \geq 744$

TABLE III  
PEAK THROUGHPUT IMPROVEMENT COMPARED TO THE NONCODED SCHEME

$L \setminus t$	$t=1$	$t=2$	$t=3$
$L=200$	22%	38%	48%
$L=400$	23%	40%	51%
$L=800$	21%	34%	46%

type of codes. The bound is given by

$$2^{L-k} \leq \sum_{i=1}^{2t+1} \binom{L}{i}$$

$$k \geq L - \log_2 \left[ \sum_{i=1}^{2t+1} \binom{L}{i} \right] \quad (19)$$

which is a lower bound on the number of information bits that can be allocated in a block of  $L$  b able to correct up to  $t$  errors. Table II summarizes the bound for the packet lengths considered in this paper.

Increasing  $t$  will increase the average number of successful packets in a time slot given that  $n$  packets are transmitted, but each packet now contains fewer information bits. As a consequence, for a low offered load, increasing the error-correction capability may reduce the throughput. As the offered load increases, the situation eventually reverses and the more powerful error control code produces the greater throughput. Moreover, it is known that the throughput curve peaks more slowly as  $t$  increases.

Table III shows the peak throughput improvement compared to the noncoded scheme for the different individual transmission rates and several error-correction capabilities. For the sake of brevity only plots for the case  $t = 1$ , where the highest marginal gain improvement is achieved, are shown in Fig. 12.

Next, it will be shown that the benefits of channel coding also apply to the proposed adaptive S-ALOHA DS-CDMA system. In particular, Fig. 13 shows the mobile-controlled (MS) algorithm performance in the case of employing block codes with  $t = 1, 2$ , and 3. The throughput achieved follows the individual graphs corresponding to  $1v, 2v$ , and  $4v$  b/s with  $t = 1, 2$ , and 3. The result is thus parallel to that obtained without coding, but the difference is that the individual graph has higher throughput peaks due to the coding effects. Similar conclusions are obtained for the case of the base-controlled algorithms (BS-I and BS-II).



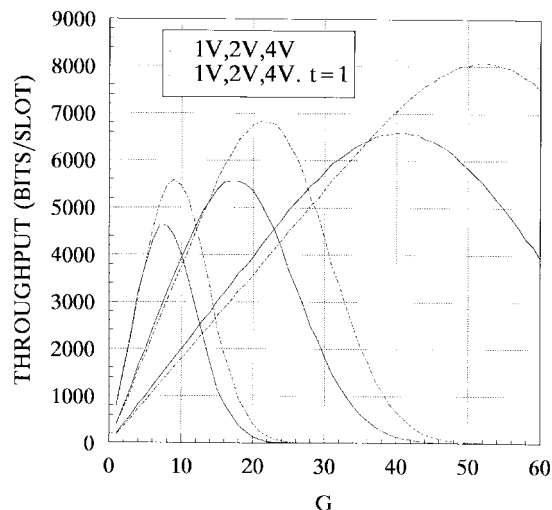


Fig. 12. Noncoded schemes and coded  $t = 1$  schemes are compared for different transmission rates.

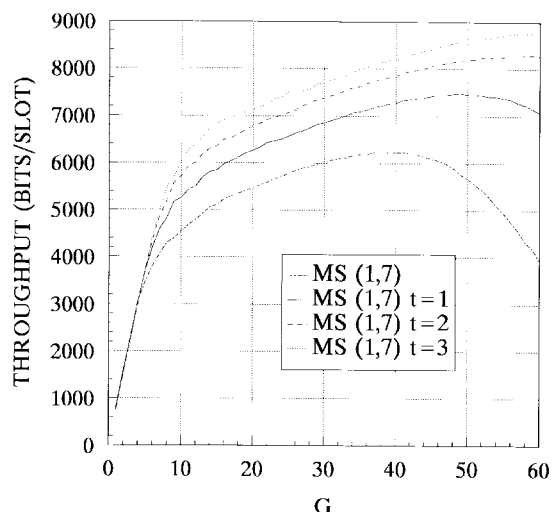


Fig. 13. MS algorithm with coding obtains better throughput.

It is worth noting that with the proposed Adaptive system, the decrease in throughput for low loads due to the redundancy overhead disappears. In fact, for a given offered load, the proposed algorithms try to transmit at the highest possible rate, where the correction capability is exploited, so thus avoiding excessively low interference levels, where FEC schemes are not necessary. The performance of the MS algorithm for the message traffic model is shown in Fig. 14, where the benefits of coding in terms of message delay can be seen. Moreover, as stated above, neither for very low loads, where the redundancy overhead is blurred in long high-rate packets and in the completion of the last packet of a message with dummy bits, nor for higher loads, where the selected transmission rate fully exploits the redundancy, is there a penalty in terms of message delay due to the added redundancy.

## VI. CONCLUSIONS

A new adaptive DS-CDMA S-ALOHA technique for packet mobile communications access based on the choice of the most

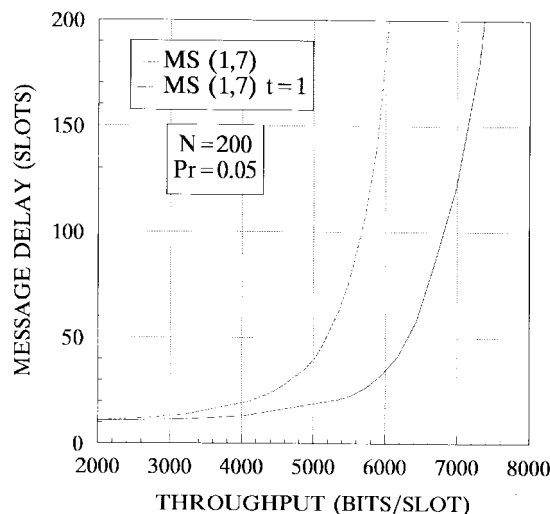


Fig. 14. MS algorithm performance for the message traffic model.

suitable transmission rate at any time slot has been addressed in this paper. Two kinds of low-complexity algorithms have been introduced according to whether the MS or the BS is in charge of them. The throughput and delay performance attained outperform by far those obtained with a conventional DS-CDMA S-ALOHA scheme when the offered load is below the saturation point. In particular, the mobile assisted algorithm allows almost the maximum attainable performance to be obtained at a very low-complexity cost. Moreover, block FEC coding further improves the behavior of the adaptive system and removes the penalty caused by the redundancy overhead.

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