ADAPTIVE ALGORITHMS FOR IMPROVING THE THROUGHPUT IN AN INDOOR MOBILE S-ALOHA DS-CDMA SYSTEM

Oriol Sallent, Ramon Agustí
Departament de Teoria del Senyal i Comunicacions
Universitat Politècnica de Catalunya
C/ Gran Capitan s/n - 08034 Barcelona - Spain

Abstract: **This paper presents a novel Adaptive DS-CDMA Slotted-ALOHA packet random access scheme with transmitter-based spreading codes for mobiles. It is aimed at improving the throughput and message delay delivery when traffic load values below the saturation point of the conventional DS-CDMA Slotted-ALOHA system are sensed in the channel. For this purpose, one Mobile and two Base Station 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 be almost reached at a low complexity cost.**

I. INTRODUCTION

Slotted ALOHA (S-ALOHA) has been widely recognized for packet radio applications because of both its simplicity to manage 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 S-ALOHA CDMA 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.

This paper is intended to improve the throughput achieved with a multi-receiver DS-CDMA S-ALOHA when a light load is offered to the system, and accordingly decreasing the delay. For this purpose we will focus on the transmission rate used instead of the access protocol itself. In particular, different transmission rates are proposed to be used in order to utilize the most suitable rate according to the channel load at any time slot. Then, fast and simple algorithms that command the processing gain of the DS-CDMA scheme as a function of the channel load are envisaged.

The paper is organized as follows. In Section 2 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 3 several S-ALOHA adaptive algorithms are proposed and assessed depending on whether the algorithm is managed by mobile station (MS) or by base station (BS). Finally, some conclusions close the paper in Section 4.

II. MODEL FOR A S-ALOHA DS-CDMA ACCESS SYSTEM

From now onwards *N* registered users will be considered. These users can be in two different operation modes: 'origination mode' and 'backlogged mode'. In the former mode 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 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 $N_k^{(B)}$ denote the number of backlogged users at the beginning of the k^{th} slot. The process defined by $N_k^{(B)}$ $k=0,1,...$ is a Markov chain, whose performance has been studied among others in [3,4]. When considering DS-CDMA, the formulation must be modified as it was done in [5]. The same notation is followed in this paper, and it is summarized in Table 1 and Fig. 1.

Throughput measurements can be obtained from the markovian model considering that

$$S=\sum_{n=0}^{N}\left(\sum_{s=0}^{n} s\times P\left\{N^{(S)}=s\middle|N^{(T)}=n\right\}\right)\times P\left\{N^{(T)}=n\right\} \quad (1)$$

where S is in packets per slot and, if all users employ the same modulation and transmission rate, the following expression arises

$$P\left\{N^{(S)}=s\,\middle|\,N^{(T)}=n\right\}=\binom{n}{s}\left[P_c(n)\right]^s\left[1-P_c(n)\right]^{n-s} \qquad (2)$$

being $P_c(n)$ the probability of correctly detecting a packet when n users have attempted transmission in a time slot. $P\{N^{(T)}=n\}$ in (1) stands for the equilibrium distribution of the composite packet arrivals in a time slot, which could be reached in terms of the equilibrium distribution of the Markov chain. The complete derivation of the expression for this probability can be found in [5].

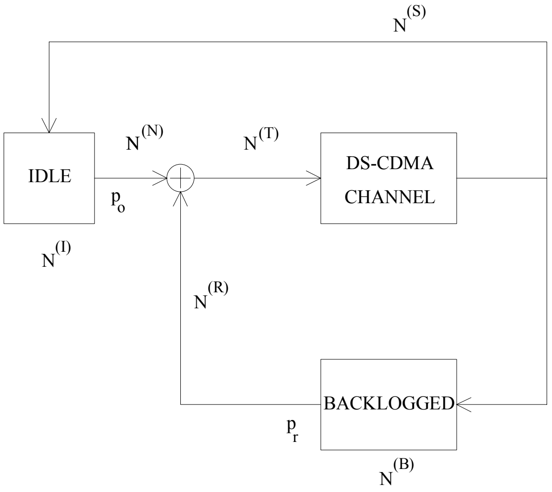

Fig. 1. Model for a S-ALOHA DS-CDMA system.

Table 1. 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 start of slot k
$N_k^{(I)}$	Number of mobiles in I-mode at start of slot k
$N_k^{(T)}$	Number of mobiles transmitting in slot k
$N_k^{(R)}$	Number of mobiles in B-mode transmit in slot k
$N_k^{(N)}$	Number of mobiles in I-mode transmit in slot k
$N_k^{(S)}$	Number of packets correctly received in slot k

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 PN signature sequences. A perfect power control capable of mitigating fadings of the channel is introduced, i.e. , the terminal transmits the power level necessary to keep always 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 when there is information to be sent and at rate v' (in general much lower) when the terminal is not active.

An instantaneous power control permits a huge improvement in the system performance when compared with an open loop power control, and it is, in fact, considered in the already operative [7] and the proposed CDMA systems [8] respectively. Although an instantaneous power control could be envisaged for packet radio on a packet by packet basis [9], we have retained the continuous link approach because in this case no synchronization overhead at the beginning of time slot would be required.

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 [10], [2]. Under these conditions the following expressions hold for the evaluation of the BER

$$P_b(n)=Q\left(\sqrt{2\frac{E_b}{N_o}}\right)\;;\;\frac{E_b}{N_o}=\frac{1}{\dfrac{2(n-1)}{3G_p}+\dfrac{2(N-n)}{3G_p}\dfrac{v'}{v}} \qquad (3)$$

where n is the number of simultaneous users. The probability of detecting correctly a packet containing αB bits is

$$P_c(n)=\left[1-P_b(n)\right]^{\alpha B} \qquad (4)$$

Using the same bandwidth, to transmit at double rate (*2v bits/s*, where v is the basic rate) half the spread capacity should be given up, thus allowing a processing gain of $G_p/2$, or $G_p/4$ if we transmit at *4v bits/s*. However, in exchange for this reduction in processing gain, *2B* or *4B* bits per time slot can be allocated instead of only B.

The achievable throughput with each one of the transmission rates obtained with the previous Markov model can be seen in Fig. 2, where G stands for the offered load -average number of attempted transmissions per time slot-, and p_o is set equal to p_r. It is clear from Fig. 2 that the high rate (*4v*) is interesting when the system is lightly loaded since more bits per packet can be sent through the channel, due to the fact that the little interference observed permits a correct transmission. When the offered load increases so does the interference level, and therefore the rate *4v bits/s* is no longer interesting because of the higher BER if it is compared to the medium rate (*2v bits/s*). Even for higher offered loads the same trade-off appears between medium rate (*2v bits/s*) and low rate (*v bits/s*). Transmission rate could be increased over *4v bits/s*, but the marginal gain is each time lower as Fig. 2 shows. So, for the sake of brevity only three rates v, $2v$ and $4v$ *bits/s* will be considered in the sequel.

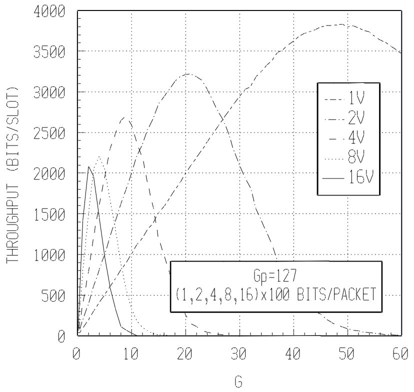

Fig. 2. Throughput performance for different transmission rates.

C. ADAPTIVE S-ALOHA DS-CDMA

In the 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.

The optimum throughput attained can be analytically obtained from the above Markov model, and this result can be later used as a reference to assess the performance of the transmission rate change algorithm proposed below. In order to attain this optimum performance, the best combination of transmission rates should be obtained provided that *n* simultaneous users are present. The resulting optimal table would be reached after an exhaustive search, as it is further explained in [6].

Since the same channel is shared by users transmitting at different rates, the probability of getting *s* successful packets over *n* transmitted packets is given now by

$$P\left\{N^{(S)} = s \middle| N^{(T)} = n\right\} = \sum_{i=max(0,s-n^{2v}-n^{4v})}^{min(n^v,s)} \sum_{j=max(0,s-i-n^{4v})}^{min(n^{2v},s-i)} \binom{n^v}{i}\left[P_c^v\right]^i \cdot\left[1-P_c^v\right]^{n^v-i}\binom{n^{2v}}{j}\left[P_c^{2v}\right]^j\left[1-P_c^{2v}\right]^{n^{2v}-j} \cdot\binom{n^{4v}}{s-i-j}\left[P_c^{4v}\right]^{s-i-j}\left[1-P_c^{4v}\right]^{n^{4v}-s+i+j} \tag{5}$$

instead of (2), which applies when all users employ the same transmission rate. In turns, it is assumed that 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 a *(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 (5). Thus, the modified throughput expression is

$$S = \sum_{n=0}^{N}\left[\sum_{i=max(0,s-n^{2v}-n^{4v})}^{min(n^v,s)} \sum_{j=max(0,s-i-n^{4v})}^{min(n^{2v},s-i)}\left[Bi+2Bj+4B(s-i-j)\right] \cdot\binom{n^v}{i}\left[P_c^v\right]^i\left[1-P_c^v\right]^{n^v-i}\binom{n^{2v}}{j}\left[P_c^{2v}\right]^j\left[1-P_c^{2v}\right]^{n^{2v}-j} \cdot\binom{n^{4v}}{s-i-j}\left[P_c^{4v}\right]^{s-i-j}\left[1-P_c^{4v}\right]^{n^{4v}-s+i+j}\right]\times P\left\{N^{(T)}=n\right\} \quad bits/slot \tag{6}$$

where *B* is the number of bits in a BPSK *v* rate packet (*B*=100 bits all over this paper) and *S* is expressed in *bits/slot*. Fig. 3 shows this optimum throughput in comparison with the individual behaviors.

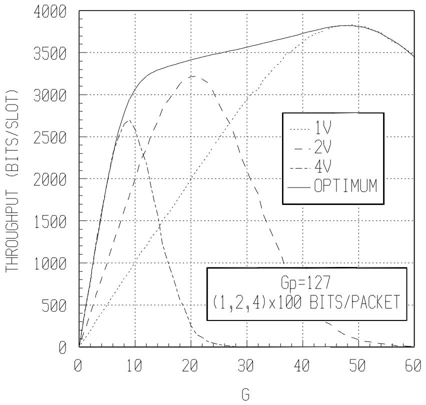

Fig. 3. The very best achievable throughput for the S-ALOHA DS-CDMA system.

III. CHANGE OF TRANSMISSION RATE ALGORITHMS

In this section several proposals of adaptive change of the transmission rate algorithms are addressed. The common idea consist 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 mobile station (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 tries 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 and tries a lower transmission rate. In this case fewer bits per packet are transmitted, but a global improvement of the throughput should also follow since processing gain increases accordingly.

Let us note that this decision is taken by the mobile without any exchange of information with the Base Station (BS) except for the packets acknowledgment.

Even the MS does not need to indicate its choice of transmission rate before using it because the very same BS could be able to detect which one is arriving.
Specifically, the MS only needs to establish 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*).

Fig. 4 shows the throughput attained for N=60 registered mobiles. 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 *max_tr*=1 and *min_suc*=6, which is the best choice, once other possibilities have been studied.

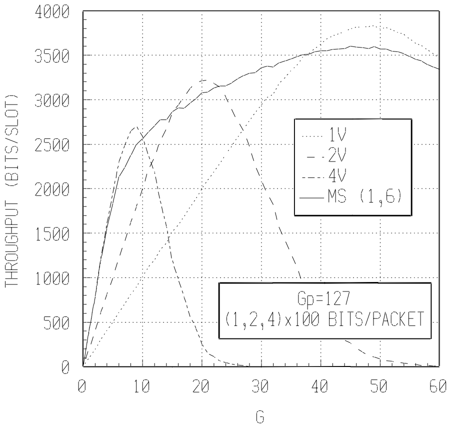

Fig. 4. Throughput performance for MS algorithm.

B. Base controlled algorithm
Coordination between mobiles can be achieved if BS manages the algorithm. By doing so a performance improvement is expected at the expense of losing 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*, which 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. 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 (12) and (13) in [6]. For example, when G_p=127 and there has been 14 users transmitting their packets in the last time slot, the BS expects 14 users again for the next time slot, and it knows that the best throughput under this situation is achieved with 9 users transmitting at *2v bits/s* and 5 users transmitting at *4v bits/s*. Thus, a probability of 9/14 of transmitting at *2v bits/s* and a probability of 5/14 for *4v bits/s* is broadcasted for next time slot. This process is repeated every time slot.

Results obtained following the above procedure can be seen in Fig. 5. It shows that a so simple information as it is the rude estimation of the mean offered load is very valuable. However, if we compare BS-I algorithm performance with that of the mobile controlled algorithm, no improvement is obtained in spite of the complexity increase.

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 thresholds values. That is, threshold L1 means that for *n*<L1 all mobiles will use *4v bits/s* in the next time slot, and L2 indicates that for L1<*n*<L2 *2v bits/s* rate will be used during the following time slot and *n*>L2 will use *v bits/s*. Optimum thresholds obtained by simulation for N=60 would be L1=11 and L2=26.

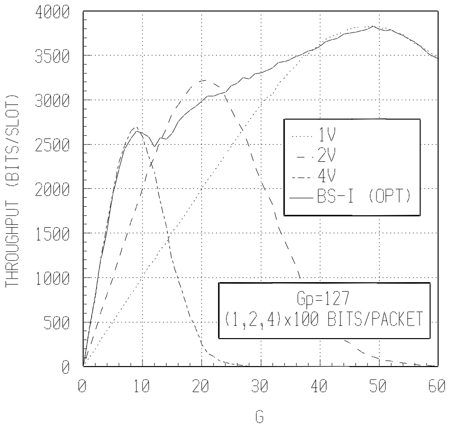

Fig. 5. BS-I algorithm with optimal combination of rates.

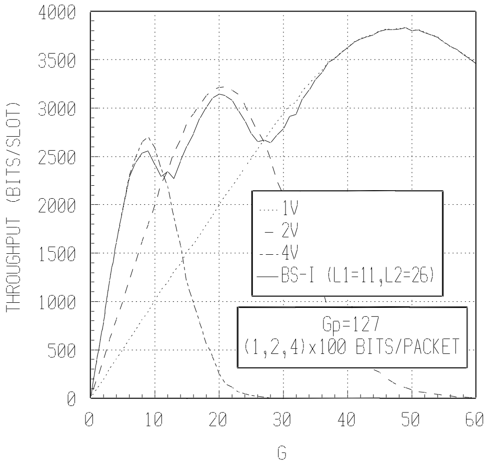

Fig. 6. BS-I algorithm with thresholds.

2) BS-II algorithm
An improvement in throughput performance attained with BS-1 algorithm could be expected if the BS knew in

advance the exact number of users ready to transmit in the present 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 pre-slot (first part of time slot), mobiles only transmit a signal in a S-ALOHA mode indicating that they are ready to transmit. After this, the BS counts how many users will attempt to transmit and selects the optimum combination of transmission rates to be employed. 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. The main difference with BS-I is that BS-II makes the BS to know the exact number of users when there are not errors in the pre-slot period.
Pre-slot uses a S-ALOHA operation mode with the BS-I threshold version algorithm because, when possible, users employ a higher rate and then the overhead caused by the pre-slot is reduced (a fixed amount of bits is assumed to be necessary to indicate the BS that there is information ready to be sent). Worthly of note is the fact that in the pre-slot it is compulsory to use the thresholds 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 pre-slot bits.

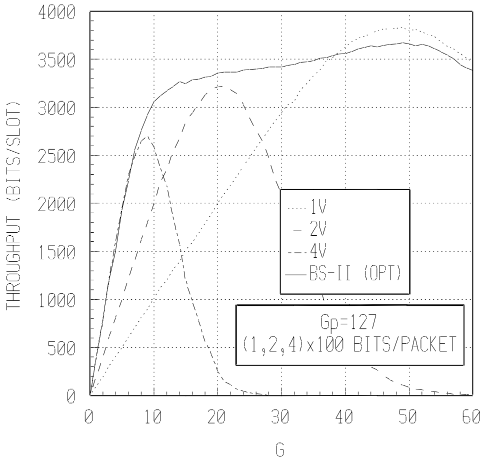

Fig. 7. BS-II algorithm reaches almost optimal performance.

Performance of BS-II is presented in Fig. 7, where a 5 bits pre-slot has been considered. BS-II outperforms BS-I except for the high loads, where it is clear that mainly *v bits/s* have to be used because of the high interference level. Moreover, each mobile can identify itself when indicating its purpose to transmit a packet during pre-slot, so that it allows a priority policy between mobiles according to their service needs. Consequently, a mobile with high traffic needs could be allocated the highest transmission rate composing the optimum combination.

IV. CONCLUSIONS

A new Adaptive DS-CDMA S-ALOHA technique for packet mobile communications access based on the choice of the most 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 Mobile Station or the Base Station are in charge of them. The throughput attained outperforms by far those obtained with a conventional DS-CDMA S-ALOHA scheme when the offered load is under the saturation point. In particular, the mobile assisted algorithm allows to obtain almost the maximum attainable performance at a very low complexity cost.

V. REFERENCES

[1] D. RAYCHAUDHURI, “Performance Analysis of Random Access Packet-Switched Code Division Multiple Access Systems”, IEEE Transactions on Communications, Vol. Com. 29, No. 6, June 1981, pp. 895-901

[2] R. K. MORROW, J.S. LEHNERT “Packet Throughput in Slotted ALOHA DS/SSMA Radio Systems with Random Signature Sequences”, IEEE Transactions on Communications, Vol. Com. 40, No. 4, July 1992.

[3] R. ROM, M. SIDI, *Multiple Access Protocols. Performance and Analysis* , Springer-Verlag, 1990.

[4] L. KLEINROCK, S.S. LAM, “Packet Switching in a Multi-access Broadcast Channel: Performance Evaluation ”, IEEE Transactions on Communications, Vol. Com.-23, No. 4, April 1975, pp.410-422.

[5] Z. LIU, M. EL ZARKI, “Performance Analysis of DS-CDMA with Slotted ALOHA Random Access for Packet PCNs ”, Wireless Networks 1 (1995), pp. 1-16.

[6] O. SALLENT, R. AGUSTÍ, “A Proposal of an Adaptive S-ALOHA Access System for a Mobile CDMA Environment”, submitted for publication.

[7] A. SALMASI, K. S. GILHOUSEN, “On the System Design Aspects of CDMA Applied to Digital Cellular and Personal Communications Networks”, Proc. 41st IEEE Vehicular Technology Conference, May 1991.

[8] A. BAIER *et al.,* “Design Study for a CDMA-Based Third-Generation Mobile Radio System ”, IEEE Journal on Selected Areas in Communications, Vol. 12, No. 4, May 1994, pp. 733-743 .

[9] M. J. McTIFFIN *et al.*, “Mobile Access to an ATM Network Using a CDMA Air Interface ”, IEEE Journal on Selected Areas in Communications, Vol. 12, No. 5, June 1994, pp. 900-908 .

[10] M. B. PURSLEY, “Performance Evaluation for Phase-Coded Spread-Spectrum Multiple-Access Communication - Part I: System Analysis ”, IEEE Transactions on Communications, Vol. Com.-25, No. 8, Aug. 1977.