Slotted CDMA _ALOHA Protocol with Hybrid ARQ in Wireless Communication Network

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Abstract—In this paper, a slotted CDMA_ALOHA protocol with hybrid ARQ is proposed for the wireless CDMA communication networks. The proposed protocol combines the characteristics of the slotted ALOHA, CDMA, and the hybrid ARQ, in order to increase the throughput by reducing the number of retransmissions when the channel experiences heavy traffic. The main feature of the proposed protocol is the utilization of the forward error correction capability to correct errors that appear after the CDMA dispreading of the packets. The base station does not need to ask so often for retransmission of erroneous packets. It will request for retransmission only when the FEC capability is exceeded. The performance of the proposed protocol is analyzed by considering the packet collision probability as well as the bit error probability. The numerical results show that the system throughput is closely related to the bit error rate of the wireless link and the FEC coding rate.

Index Terms—CDMA, Hybrid ARQ, Medium access control protocol, Slotted ALOHA.

I. INTRODUCTION

With the rapid growth in wireless access technologies, wireless communication networks and mobile terminals have become popular. In particular, a wireless communication network provides a flexible and convenient subscriber interface to the fixed network. An example of a wireless network is a cellular system that is designed to provide voice-oriented communication services [1][2]. Another example is a wireless LAN, where data communication is the main service [3][4].

In the wireless communication network, research was carried out on both time division multiple access (TDMA) and code division multiple access (CDMA). Spread spectrum CDMA systems offer the potential of high spectrum efficiency, soft capacity, multipath-resistance, and inherent frequency diversity [1][5]. Among many issues related to the wireless communication network, the medium access control (MAC) protocol that coordinates multiple access of a shared medium is one of the most important issues. The MAC protocol has a primary effect on the system throughput and the delay performance of wireless networks. The MAC protocol, therefore, might be efficient and robust enough to utilize the radio resources efficiently among all users.

Among a lot of MAC protocols, the slotted ALOHA protocol [6], having a distinguished advantage of simplicity, experiences the rapid decrease of the system throughput under heavy traffic due to collisions. On the other hand, many researchers have been devoted for applying the slotted ALOHA to CDMA systems [7]-[10]. They have shown that the slotted CDMA_ALOHA techniques have an improved performance.

The bit error rates due to multiple access interferences have significant influences on the quality of service and the system performance [12][13]. Until now, many researches did not considered the BER due to multiple access interferences but only the packet collision probability in a wireless link [9][11]. This paper analyzes the slotted CDMA_ALOHA protocol by considering the packet collision probability as well as the BER of the wireless link. This paper also proposes a slotted CDMA_ALOHA protocol with the hybrid ARQ, which uses a block FEC code in the data link control layer for improving the system performances. The numerical results show that the system throughput is significantly improved by using a block FEC code, approaching to value, which is competitive with the error-free channels.

This paper is organized as follows. Section II describes the system model and the proposed protocol. The system performance of the proposed protocol is analyzed in Section III. Section IV discusses the numerical results and conclusions are given in Section V.

II. PROTOCOL DESCRIPTIONS

It is assumed that the system consists of a base station and M mobile stations. There are R receivers in the base station. For simplicity, it has a focus on a single-cell system. Mc spreading codes, which are orthogonal to each other, provides multiple channels. Mobile stations share a group of spreading codes.

A packet generated by mobile station can be transmitted during one slot with one spreading code. The uplink packet structure is illustrated in Fig. 1. The preamble field is used for a spreading code acquisition by the base station receiver. The header field contains the terminal identifier, the packet sequence number, etc. The FEC field is used for detecting and correcting errors of a

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received packet at the base station. In this paper, (L, k) BCH codes are assumed as FEC codes.

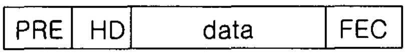

Fig. 1 Packet structure.

The detailed descriptions of the proposed protocol are shown in Fig. 2 and Fig. 3. In general, the length of a data message is variable. To transmit a data message, a mobile station first segments the message into several fixed-size packets. The mobile station that does not have a message to transmit is said to be in the idle state. When a mobile station in the idle state generates a new message, it then enters into the contending state. The mobile station in the contending state randomly selects a spreading code from a group of spreading codes $\{c_i, i=1, ..., M_c\}$, and transmit a packet with the transmission permission probability P_r. If base station successfully captures a data packet and can correct errors of the received packet, it broadcast an acknowledgement.

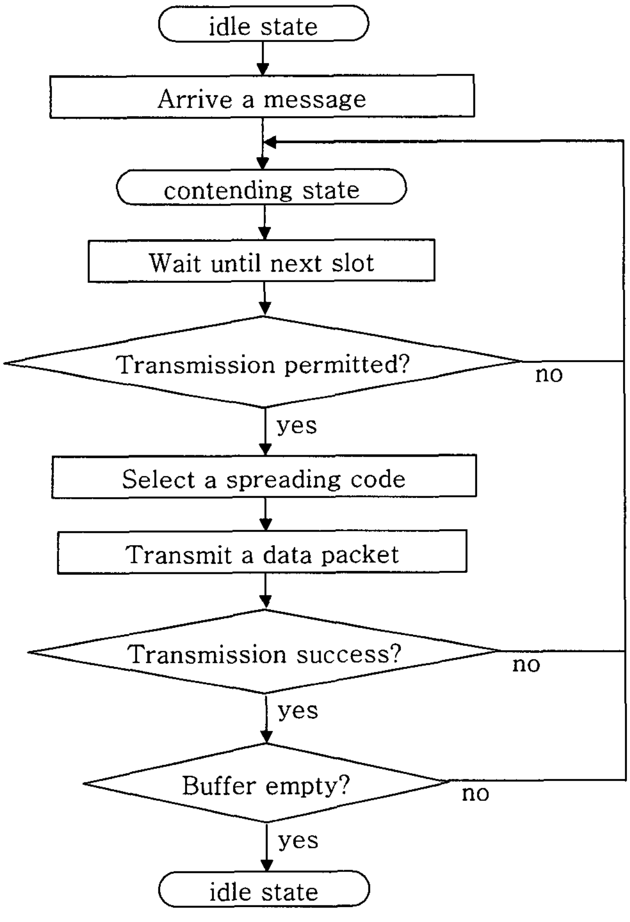

Fig. 2 Operation of mobile station.

If the mobile station receives an acknowledgement and has packets in its buffer, it remains in the contending state and tries to transmit another packet in the next slot. The mobile station that receives an acknowledgement and does not have any packet goes into the idle state. If the mobile station decides not to transmit a packet (with probability $1-P_r$), or if it fails to transmit a packet even in the case of transmission permission, it remains in the contending state and tries to send the same packet in the next state.

In this scheme, the mobile station fails in transmitting a packet by one of the following reasons:

(1) It is not permitted to transmit a packet.
(2) Packet collision occurs, that is, at least two mobile stations select one particular spreading code.
(3) The base station cannot correct errors of the received packet with the FEC code.
(4) All receivers in the base station are busy.

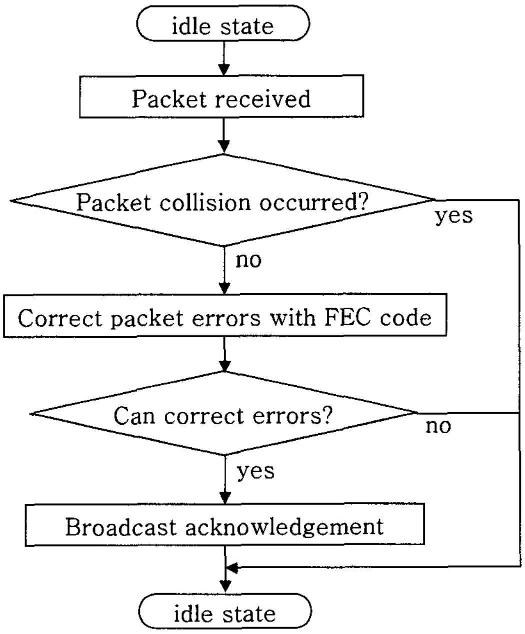

Fig. 3 Operation of base station.

III. PERFORMANCE ANALYSIS

A. BER Model of DS/CDMA System

In analyzing the system throughput of the proposed protocol, this paper assumes the following approximate expression for the bit error rate of a DS/CDMA system, which was originally derived in [13]:

$$P_e(m) = Q\left(\left[\frac{m-1}{3N} + \frac{N_0}{2E_b}\right]^{-\frac{1}{2}}\right) \tag{1}$$

where

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-u^2/2} du$$

In (1), E_b/N_0 is the ratio of energy-per-bit-to-noise power spectral density, N is the processing gain (i.e., the number of chips-per bit), and m is the total number pf active users. Equation (1) is based on the Gaussian approximation, i.e., the multiple access interference is approximated as a Gaussian random variable, and has been found to hold reasonably well when long spreading sequences are used.

The numerical result for the bit error rate is depicted in Fig. 4 according to the number of the multiple access interferences and the E_b/N_0. As shown in Fig. 4, the bit error rate increases rapidly along with the increase of the number of multiple access interferences. Thus, the bit error rate must be considered in analyzing the performance of wireless MAC protocol. Also to reduce the number of retransmissions due to the high bit error rate of a wireless channel, it is reasonable to use the forward error correction scheme. In this paper, (L,k) BCH code is used as a FEC scheme, where a FEC coding rate r is k/L. The packet success probability with (L,k) BCH code is given by

$$P_s(m)=\sum_{i=0}^{t}\binom{L}{i}P_e^i(m)\left(1-P_e(m)\right)^{L-i} \qquad (2)$$

where t is the number of bits to be corrected with a FEC code.

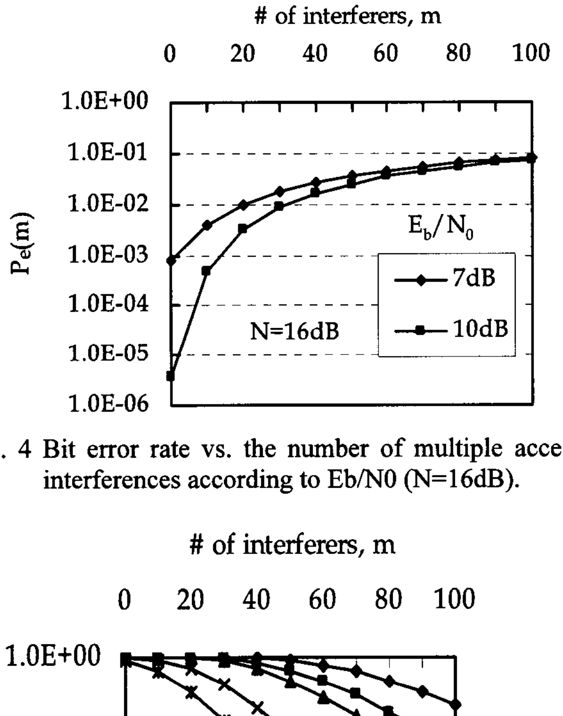

Fig. 4 Bit error rate vs. the number of multiple access interferences according to Eb/N0 (N=16dB).

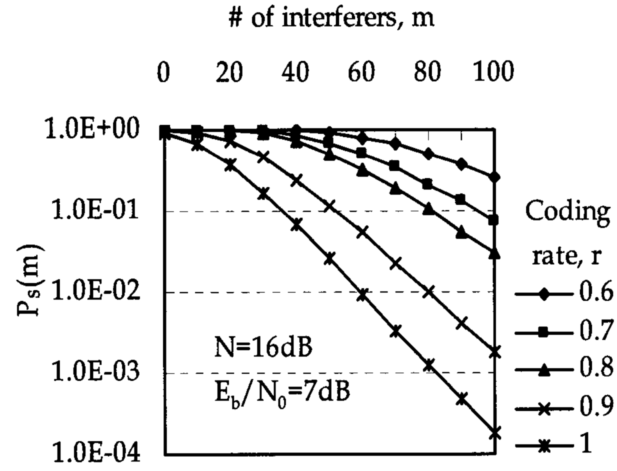

Fig. 5 Packet success probability vs. the number of multiple access interferences according to FEC coding rate (N=16dB, Eb/N0=7dB).

Fig. 5 shows the packet success probability according to the various FEC coding rates. The more decrease the FEC coding rates, the more increase the number of bits to be corrected. Therefore the packet success probability should increase accordingly.

B. System Throughput

This section analyzes the system throughput of the proposed protocol with a Markov model. It is assumed that a mobile station generates a new packet in the following slot with the probability λ. If the mobile station fails to transmit its packet due to one of the reasons described in the above section, it enters into a contending state and tries to retransmit its packet in the next slot with the probability P_r. If we let the system state $x(t)$ be the number of mobile stations in a contending state at the beginning of slot t, it can be shown that $\{x(t)\}$ is a finite state Markov chain.

Let the state transition probability P_{jk} be the probability that the number of mobile stations in a contending state changes from j at the beginning of slot t to k at the next slot. Then, the probability P_{jk}, which is derived from probabilities that n_b mobile stations in a contending state retransmit their packet and n_i stations out of $(M$-$j)$ generate a new packet and s packets out of $(n_b$+$n_i)$ are successfully transmitted, is given by

$$P_{jk}=\sum_{n_b=0}^{j}\sum_{n_i=0}^{M-j}\left\{\begin{matrix}B(j,n_b,P_r)\times B(M-j,n_i,\lambda)\times\\ S_{s|n_b+n_i,M_c,R}\end{matrix}\right\} \qquad (3)$$

Where

$$s=j+n_i-k,$$
$$0\le s\le Min\{M_c,R,n_b+n_i\},$$
$$B(n,i,p)=\binom{n}{i}p^i(1-p)^{n-i}$$

The term $S_{s|n_b+n_i,M_c,R}$ is the conditional probability that s packets out of $(n_b$+$n_i)$ are successfully transmitted with M_c channels and R receivers available.

By conditioning on the number of packets simultaneously transmitted over the arbitrary first channel and using total probability, the conditional probability can be represented by

$$S_{s|n,M_c,R}=\sum_{i=0}^{n}B\left(n,i,\frac{1}{M_c}\right)\times P\left(s|n,i,M_c,R\right) \qquad (4)$$

where i is the number of packets transmitted over the first channel, and $B\left(n,i,\frac{1}{M_c}\right)$ is the probability that i

packets are transmitted over the first channel. The term $P(s|n,i,M_c,R)$ is the probability that i packets select the first channel and s packets among them succeed to transmit with M_c channels and R receivers. The term $P(s|n,i,M_c,R)$ can be recursively derived by

$$P(s|n,i,M_c,R) = \begin{cases} S_{s|n,M_c-1,R} & \text{, for } i=0 \\ P_s(n)S_{s-1|n-1,M_c-1,R-1} + \\ (1-P_s(n))S_{s|n-1,M_c-1,R-1} & \text{, for } i=1 \\ P_s(n)P_c(i)S_{s-1|n-i,M_c-1,R-1} + \\ \{1\text{-}P_s(n)P_c(i)\}S_{s|n-i,M_c-1,R-1} & \text{, for } 2 \le i \le n \end{cases} \tag{5}$$

where $P_s(n)$ is the probability that all of the bit errors in a received packet are corrected by using FEC codes, which is given in Eq. (2). Though mobile stations transmit their packet at a same slot, the time of packet arrival at base station may differ each other. The base station, therefore, can capture a packet. In Eq. (5), $P_c(i)$ is the probability that one packet among i simultaneously arrived packets is successfully captured by the receiver.

In Eq. (5), the term for i=0 is the probability that s packets have to be successfully transmitted over the remaining M_c-1 channels and the R receivers because none of n mobile stations selected the first channel. The second term, for i=1, is the case that only one packet select the first channel. In this case, if bit errors of a received packet are successfully corrected by FEC code, s-1 packets among the remaining packets must be successfully transmitted over the remaining channels. Otherwise, s packets among the remaining packets must be successfully transmitted over the remaining M_c-1 channels. The third term is the case that two or more mobile stations transmit their packet over an arbitrary first channel. In this case, if only one packet can be captured by the mobile station receiver and can be corrected by a FEC code, we can consider it as a successfully received packet. Thus, s-1 packets among the remaining packets must be successfully transmitted over the remaining channels.

The initial conditions for $S_{s|n,Mc,R}$ are given by

$$\begin{array}{ll} \text{for } M_c \ge 0 \text{ and } R \ge 0, & S_{0|0,M_c,R} = 1, S_{1|0,M_c,R} = 0 \\ \text{for } n \ge 0 \text{ and } R \ge 0, & S_{0|n,0,R} = 1, \mathrm{S}_{1|\mathrm{n},0,\mathrm{R}} = 0 \\ \text{for } M_c \ge 1 \text{ and } R \ge 1, & S_{0|1,M_c,R} = 1\text{-}P_s(1), \\ & S_{1|1,M_{c,R}} = P_s(1) \\ \text{for } n \ge 2 \text{ and } R \ge 1, & S_{1|n,1,R} = P_s(n) \cdot P_c(n), \\ & S_{0|n,1,R} = 1 - P_s(n) \cdot P_c(n) \\ \text{for } s > Min\{n, M_c, R\}, & S_{s|n,M_c,R} = 0 \end{array} \tag{6}$$

The probability $P_c(i)$ is given by

$$P_c(i) = \begin{cases} 1 & \text{, for } i = 1 \\ Q^i & \text{, for } i \ge 2 \\ 0 & \text{, otherwise} \end{cases} \tag{7}$$

where i is the number of packets to be transmitted simultaneously over the same channel, and Q is the capture ratio[14].

Once the probability P_{jk} is obtained, the steady state probability π_i that i mobile stations are in a contending state is derived as [15]

$$\pi_i = \sum_{j=0}^{M} \pi_j P_{ji} \quad \text{, and } \sum_{i=0}^{M} \pi_i = 1 \tag{8}$$

The performance measure of the proposed protocol is the system throughput. The system throughput S, which is defined as the average number of packets transmitted in a slot, can be obtained as follows:

$$S = \lambda \left(M - \sum_{i=0}^{M} i\pi_i \right) \tag{9}$$

IV. NUMERICAL RESULTS

In this section, some numerical results obtained by the analytical method presented in Section III are shown. At first, it shows how the system throughput of the proposed protocol can be affected by the bit error rate. In this analysis, the number of spreading code channels M_c, the number of receivers R, and the transmission permission probability P_r are assumed as 3, 3, and 0.1 respectively.

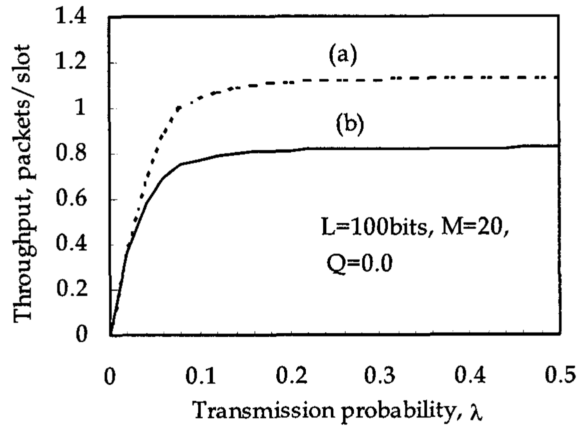

Fig. 6 Throughput comparison between the error free channel and the erroneous channel : (a) error free channel, (b) erroneous channel (Eb/N0=6dB, N=20dB, r=1.0).

Fig. 6 shows the system throughput in the case of the error free channel (a) and the erroneous channel without forward error correction (b). For simplicity, the capture capability is not considered in this comparison (i.e., Q=0.0). Since the multiple access interferences will increase along with the increase of the offered traffic load, the bit error rate in the received packet will also increase, and the packet success probability $P_s(n)$ will decrease. So the erroneous channel condition results in lower system throughput than the error free channel conditions. By comparing the curve (b) of Fig. 6 with the curve that indicated as FEC coding rate r=1.0 of Fig. 7, it is manifest that the capture capability of the base station improve the system throughput.

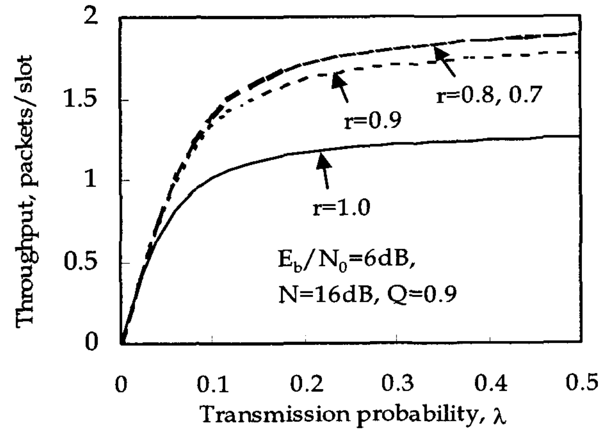

Fig. 7 System throughput according to the FEC coding rates (Eb/N0=6dB, N=16dB, Q=0.9).

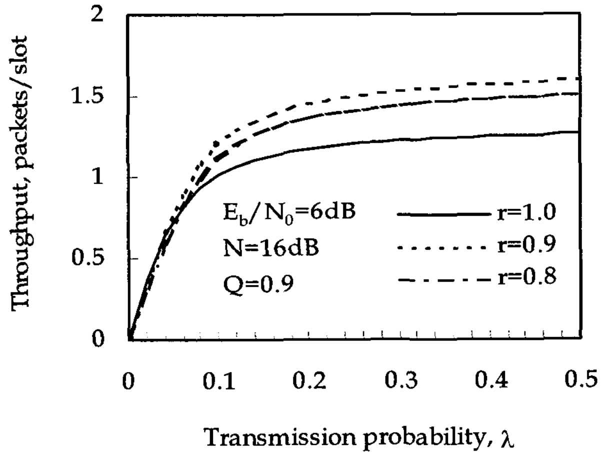

Fig. 8 User Throughput (Eb/N0=6dB, N=16dB, Q=0.9).

Fig. 7 and Fig. 8 show the system throughput according to the various FEC coding rates. It is assumed that M=20, L=100 bits, M_c=3, R=3, and Q=0.9. And for the bit error condition in the physical layer, the E_b/N_0 and the processing gain are assumed as 6dB and 6dB, respectively. When the FEC coding rate r decreases to 0.9, the system throughput increases about 40% as compared with r=1.0. And when r=0.8, the increase in the system throughput approaches to about 48%. As illustrated in Fig. 7, if the length of FEC code field in a packet is large sufficiently to correct many bit errors, the overall system throughput might be increased. But the user throughput, which is the throughput of the user data, is decreased as shown in Fig. 8 due to the packet overhead by the FEC code.

Fig. 9 shows the system throughput according to the processing gain of CDMA system and the FEC coding rates. The processing gain of the dashed lines is assumed as 16dB, and the others as 10dB. In general, the bit error rate of CDMA system with the low processing gains increases more than the higher one. So, it results in the degradation of the system throughput. When the processing gain N is 16dB and the FEC coding rate r is 0.8, the system performance is improved about 48% as compared with the no FEC coding. But in the case of N=10dB, there is about 110% increases in the throughput. So, from Fig. 9, it is manifest that the FEC coding in the data link control layer might be necessary for improving the system throughput, especially in the lower processing gain systems.

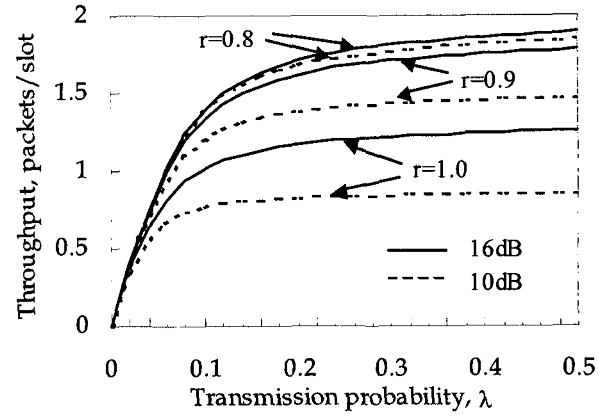

Fig. 9 System throughput according to the processing gain (Eb/N0=6dB, Q=0.9).

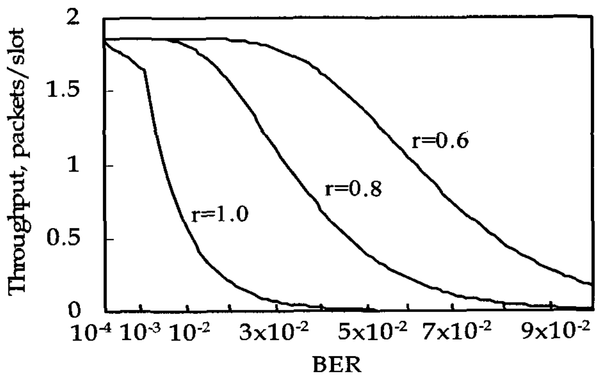

Fig. 10 System throughput vs. BER (λ=0.394, Q=0.9).

The maximum achievable throughput and the optimum FEC coding rates in the various BER conditions are depicted in Fig. 10. The ARQ scheme may be sufficient to achieve the maximum throughput under the bit error conditions of lower than 10^{-4}. But as expected, this figure shows that the FEC scheme at the DLC layer is necessary to improve the throughput as the BER increases.

V. CONCLUSIONS

In this paper, the slotted CDMA_ALOHA protocol with hybrid ARQ scheme is proposed for a medium access control protocol in the wireless CDMA networks. The proposed protocol combines the characteristics of the slotted ALOHA, code division multiple access (CDMA), and the hybrid ARQ. By combining the hybrid ARQ scheme to the slotted CDMA_ALOHA protocol, it should reduce the number of retransmissions. Therefore, the proposed protocol can increase the system throughput and keep the bit error rate of the wireless link low when the channel experiences heavy traffic.

The main feature of the proposed protocol is the utilization of the forward error correction (FEC) capability to correct errors that appear after the CDMA dispreading of the packets. The base station does not need to ask so often for retransmission of erroneous packets. It will request for retransmission only when the FEC capability is exceeded.

Throughout the numerical results, it is observed that the bit error rate by the multiple access interferences affects the system performance. It is also investigated that the forward error correction scheme can significantly improve the system throughput performance.

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