Performance Analysis for a Slotted CDMA Multiservice System*

CDMAマルチサービスシステムの性能評価

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Abstract: This paper proposed a CDMA-slotted ALOHA system, in which all transmitters used the same PN sequence but with different chip phases and packets can be captured because of the autocorrelation property of PN sequence. Then its channel throughput and some performance parameters with different number of receivers in base station are analyzed. The effects of wireless link quality on parameters such as packet dropping probability, average delay are discussed for some types of services. Analysis and simulation results show that the maximum channel throughput of this system is much greater than pure S-ALOHA system and multiservices can be supported with guaranteed QoS.

Key words: CDMA, Slotted ALOHA, Throughput, Capture.

I. Introduction

The requirement for broadband services brings the demand on the third generation mobile communication system which should be able to interface to fixed broadband network such as B-ISDN using ATM transmission, and support multi-services. It is important to select an efficient multi-access scheme which can meet the QoS requirements of every service and adapt the best to dynamic traffic in wireless multimedia communication, and CDMA, which is characterized by statistical multiplexing a same frequency bandwidth and has the advantages of high utilization of frequency bandwidth, is such a radio access technique[1].

S-ALOHA is a natural choice for a packet system with the slot size being equivalent to a packet.If combination of spread spectrum with S-ALOHA is used, the packets which are transmitted simultaneously may be captured because of the correlation property of the spreading sequence, so that the throughput of the system can increased greatly[2]. In this paper, a CDMA-slotted ALOHA system is proposed which has a potentiality of providing efficient wireless packet communications while preserving the random access capability, and the advantages of CDMA, in combination with the simplicity offered by S-ALOHA, make this scheme attractive.

There are a few schemes for a CDMA system. For example, different spreading codes can be used by different users[2]. But in this scheme, the receiver unit in center station must monitor and perform the acquisition of signals on multiple code channels. Another scheme is that users use different chip phases of the same spreading sequence. Because of auto-correlation property of PN sequence, the signal over each channel is separated after being despreaded. Then the receiver unit only needs to monitor one code channel so that the complexity of receiver unit is reduced. At the same time, fast acquisition can be realized more easily. Being different from the first scheme, Collisions may be occured in this scheme. An efficient method is to add random delay before transmission to reduce the collision probability.

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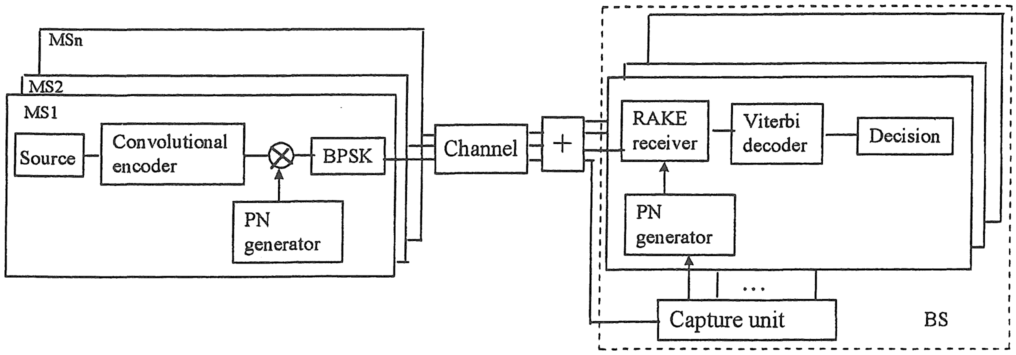


Fig.1 The structure of the system

In this system, the transmission errors are caused by collision and interference.

In the paper, section II describes the system models. Then the channel throughput is calculated in section III. A few QoS parameters are analyzed for some types of services with and without ARQ in section IV. In section V, simulation results for the performance of the proposed system are presented. In the end, conclusion is made in section VI.

II. System models

The structure of the system is shown in Fig.1. The system has a centric structure with a base station (BS) located in the center of a cell and mobile stations (MSs) distributed around it. Every MS produces packets with fixed length, and gets system synchronous information from the BS's broadcasting signal. Before a packet is to be transmitted, the MS generates a random number R_n according to a certain random method. The transmitting moment is R_n $(0 \le R_n \le M-1)$ chip duration(T_c) later than the beginning of a slot and the PN sequence is delayed correspondingly so that the chip phase of PN sequence used by every user may be different. The transmitting time is shown in Fig.2.

In Fig.2, the Syn. header can be a short PN sequence used by capture unit in BS to perform

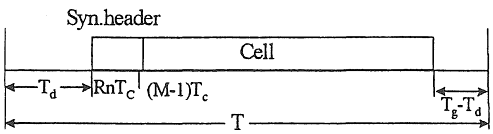


Fig.2 Slot width, cell width, and guard interval (uplink)

PN acquisition and recognize the transmission. T_d is random delay and T_d=R_nT_c. The width of a slot T will be made larger than the packet width by a guard interval T_g.

There are a few receivers in the BS which have RAKE structure to receive the signals transmitted by different users. If more than one MS transmit packet in a slot, it is possible that some MSs' packets can be acquired by the capture unit in the BS using matched filters when correlation peaks of the multipath signals of these stations do not overlap. A short PN sequence (Syn.header) attached to a packet is transmitted firstly. When this sequence puts into the matched filter, correlation peak will be output. Then the transmission timing of the MS can be determined according to the correlation peak, and one of the receivers in BS is assigned to trace and receive signals of this MS. In multipath channel, it is possible that several correlation peaks are obtained for the signal of a mobile station. If the correlation peaks are in the multipath spread range that the receiver can resolve, the receiver takes these correlation peaks as one MS's signal and receive them by diversity.

The following conditions are assumed for further analysis.

1) The total number of users is large enough that packet arrival process can be modeled by a Poisson distribution.
2) Offer load G is defined as the average number of packets occurring during a time slot.
3) The power of the received signals are equal for all users by ideal power control scheme.
4) The minimum multipath delay the RAKE receiver can resolve is 1/w, and w is the signal's bandwidth. In spread spectrum system,

it is a chip duration. And the receiver can resolve the multipaths in the range of [0, $(L-1)T_c$].

5) If the correlation peaks of multiple stations' signals are overlapped, the packet can not be received correctly.

6) The system has negligible propagation delay and perfect acknowledgements from the receivers.

7) Forward error correction (FEC) and cyclic redundancy check (CRC) are used to increase transmission reliability and detect the transmission errors.

III. The channel's throughput

In Fig.3, a MS transmits a packet each time. At T_0 moment, which is DT_c duration later than the slot start moment and D is an integer, the *i*th MS transmits a packet. If there are some other

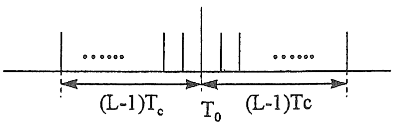


Fig.3 The time relation of transmitted data on a multipath

MSs which transmit packets in the interval [max{$T_0-(L-1)T_c$, 0}, min{$T_0+(L-1)T_c$, $(M-1)T_c$}], overlap occurs. Because the moment a MS transmits a packet is uniformly distributed over [0, $(M-1)T_c$], the probability that another MS transmits in this interval, i.e., the correlation peaks of the despreaded signals of another MS and the ones of *i*th MS's signals overlap and both packets can not be recovered successfully, is

$$p_i(D)=\begin{cases}\frac{2L-1}{M}, & L-1\le D\le M-L\\ \frac{L+D}{M}, & 0\le D\le L-2\\ \frac{M-D+L-1}{M}, & M-L+1\le D\le M-1\end{cases} \qquad (1)$$

If there are N+1 packets to be transmitted in a slot T, the probability that the correlation peaks of other N MSs' packets and *ith* MS's packet do not overlap, is

$$p(N)=\sum_{D=0}^{M-1}\left[1-p_i(D)\right]^N\frac{1}{M}\ge\left[1-\frac{2L-1}{M}\right]^N \qquad (2)$$

Because the arrival rate of packets is based on the Poisson process with offered load G packets/slot, the probability that N packets arrive in a slot is

$$R_N(G)=G^N\exp(-G)/N!. \qquad (3)$$

At the beginning of every slot, we assume that there are N+1 packets generated from MSs, and at most K packets are captured by the K receivers in BS. For a packet, the other N packets are considered to be interference. Defining $P_c(N)$ as the probability that a packet is captured and recovered successfully with N interfering packets, and the averaged throughput S of the channel is the average number of packets received successfully per time slot which is given by

$$S(G)=\sum_{N=0}^{\infty}R_{N+1}(G)P_c(N)\cdot\min(N+1,K). \qquad (4)$$

In our CDMA S-ALOHA system, if the multi-access interference is not considered and AWGN is ignored, then $P_c(N)=p(N)$ and S(G) can be expressed as

$$S(G)\ge\sum_{N=0}^{\infty}\frac{G^{N+1}}{(N+1)!}\exp(-G)\left(1-\frac{2L-1}{M}\right)^N\cdot\min(N+1,K) \qquad (5)$$

In practical system, the multi-access interference should be considered, then, $P_c(N)$ must be modified. But the modification to $P_c(N)$ should be decided according to system design.

We consider a system with multipath fading channel and maximal ratio combiners. The half-rate convolutional coding of constraint length 9 and soft decision Viterbi algorithm are used as FEC to increase the reliability of transmission. A Gaussian approximation can be used for multi-access interference. Then if the processing gain is R and N simultaneous transmissions, and the energy of a bit is E_b, the SNR after despreading of each transmission is

$$\gamma_b(N)=\frac{E_b}{N_0+E_b\frac{N-1}{R}} \qquad (6)$$

Let $P_I(N)$ be the probability of the event that there is no error in the decoded packet, then

$$P_c(N)=p(N)\cdot P_I(N) \qquad (7)$$

We derive $P_I(N)$ from the first-event error probability P_u whose upper bound is[5]

$$P_u(\gamma_b)\le\sum_{d=d_{free}}^{\infty}a_dP_2(d) \qquad (8)$$

where a_d denotes the number of paths of distance d from the all-zero path and in AWGN channel,

$$P_2(d) = Q\left(\sqrt{2r \cdot \gamma_b d}\right) \quad (9)$$

where r is the coding rate.

While in fading channels, when the maximal ratio combiner is used, using the similar method as in [5], we can get that for fast fading channel and deep interleaving,

$$P_2(d) = \left[\tfrac{1}{2}(1-\mu(d))\right]^{Ld} \sum_{k=0}^{Ld-1} \binom{Ld-1+k}{k} \left[\tfrac{1}{2}(1+\mu(d))\right]^k \quad (10)$$

with $$\mu(d) = \sqrt{\frac{r\bar{\gamma}_c}{1+r\bar{\gamma}_c}} \quad (11)$$

where $\bar{\gamma}_c$ is the average SNR per channel and $\bar{\gamma}_c = \gamma_b E(\alpha_l^2)$, and $\{\alpha_l\}_{l=1}^{L}$ represent the attenuation factors for the L multipaths.

For a packet of length of B, $P_I(N)$ is bounded by P_u

$$P_I(N) \geq \left[1 - P_u(\gamma_b(N))\right]^B \quad (12)$$

For slow fading channel, we assume that $\{\alpha_l\}_{l=1}^{L}$ are constants during a packet interval and we can obtain the lower bound of P_I as follows

$$P_I(N) > \int_0^\infty \left[1 - \sum_{d=d_{free}}^{\infty} a_d Q\left(\sqrt{2r\gamma_b d}\right)\right]^B p_s(\gamma_b) d\gamma_b \quad (13)$$

with

$$p_s(\gamma_b) = \frac{1}{(L-1)!\,\bar{\gamma}_c^L} \gamma_b^{L-1} \exp(-\gamma_b/\bar{\gamma}_c) \quad (14)$$

where $p_s(\gamma_b)$ is the probability density function of a chi-square-distributed random γ_b with 2L degrees of freedom.

Then, the throughput is

$$S(G) > \sum_{N=0}^{\infty} R_{N+1}(G) \cdot \left(1 - \tfrac{2L-1}{M}\right)^N P_c(N) \cdot \min(N+1, K) \quad (15)$$

IV. Analysis of Performance parameters

1. For services without ARQ

For this kind of services, those packets with errors are passed on to the user unaltered and the lost packets may be blanked or replaced by interpolations between successive valid data blocks. They always have higher priorities. After they have accessed the channel initially, slots and chip phases are reserved for it periodically. The transmission errors are mainly due to AWGN, interference caused by other users and multipath fading. No overlap of correlation peaks occurs and multi-access interference must be controlled in an acceptable level.

We discuss the packet dropping probability for this kind of services. If CRC shows that the received packet is erroneous, the packet is dropped. From (12), we can get the dropping probability P_{drop} as follows.

$$P_{drop} = 1 - P_I(N) \leq 1 - \left[1 - P_u(\gamma_b)\right]^B \quad (16)$$

This probability is a function of average SNR which is affected by the number of users transmitting simultaneously. According to the requirement for the packet dropping probability, the maximum number of users in a slot can be determined.

2. For services with ARQ

In this case, we assume that the channel is accessed in a burst manner. If the transmission is not successful because of overlap of correlation peaks or transmission errors, retransmission occurs after some delay until acknowledgement is received, or the packet is discarded if the expiration time is exceeded.

The important measure of performance is the delay which shows the required time of successfully delivering a packet in the system. In our system, the propagation delay is negligible and delay is mainly due to the number of retransmissions of erroneous packets. If there are N users which transmit packets in a same slot, the probability for one of the users to be transmitted successfully is $P_c(N-1)$. The delay of a packet is

$$D = \sum_{i=2}^{\infty} \left(\sum_{j=2}^{i} d_j\right) \left[\prod_{j=1}^{i-1} \left[1 - P_c(m_j - 1)\right]\right] P_c(m_i - 1) \quad (17)$$

where d_i ($i>1$) is the time interval between ($i-1$)th and ith transmission and $d_1=0$, m_i is the number of transmitted packets at the ith transmission moment.

Consider the situation that the transmission time scale is organized in frames with duration of T_f, each containing a fixed number of time slots. The failed packets are retransmitted in the next frame. So the delay between two successive transmission is T_f, i.e. $d_i = T_f$. The average probability that a packet is accepted for once transmission is

$$\overline{P_t}(G) = \sum_{N=1}^{\infty} R_N(G) \cdot \frac{P_c(N-1) \cdot \min(N,K)}{N} \tag{18}$$

Then the average delay of a packet is

$$\overline{D(G)} = E(D) = \sum_{i=2}^{\infty} (i-1)T_f \cdot \left[1-\overline{P_t}(G)\right]^{i-1} \cdot \overline{P_t}(G) = \frac{1-\overline{P_t}(G)}{\overline{P_t}(G)} T_f \tag{19}$$

V. Simulation results

In simulation, the processing gain is 32 and the packet is consisted of an wireless ATM cell (54 bytes)[6], and is encoded by half-rate convolutional coding of constraint length 9. AWGN is ignored. The RAKE receiver uses the maximal ratio combiner and soft decision Viterbi Algorithm. The simulation results of throughputs for one receiver are shown in Fig.4. In the figures of following, L is the number of multipaths and assume that every multipath has equal intensity.

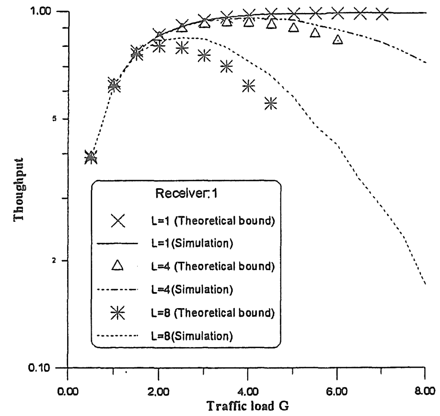


Fig.4 channel throughput with one receiver

When the theoretical bounds are calculated, the sum of the infinite items has to be replaced by the sum of limited items which causes large error for low SNR(SNR<3dB). So when the traffic load is high, the differences between simulation results and theoretical bounds are a little larger. The simulation results are above the theoretical lower bounds.

The simulation shows that when the traffic load is heavy, the effects of multi-access interference are obvious. We also notice that the more multipath, the greater the probability of overlap of correlation peaks, the less the maximum channel throughput, and the smaller G for the maximum throughput. When only one receiver is used in BS and the multipath are not considered (L=1), the maximum throughput is more than 98% when G is about 5.5. For L=4, 8, the maximum throughputs are about 95%, 84% respectively. So, the channel throughput of this system is much greater than 1/e (36%) For practical channel model, the signal energy is often concentrated in a few paths. When the maximal ratio combiner is used, the performance decrease caused by multipath interference is not so serious. Then the situations that multiple receivers in BS are considered. The simulation results of normalized throughput with different number of receivers are shown in Fig.5. The normalized throughput is defined as throughput divided by the spreading factor. In this figure, we can see that when the number of receivers is not very large, increasing the number of receivers can increase the maximum throughput almost proportionally, but when the number of receivers increases further, for example from 30 to 32 in this figure which is determined by processing gain and the performance of receiver, the throughput is not increased. Also, when the traffic load is high, the throughput is reduced greatly no matter how many receivers are used because of the multi-access interference. So, when the multi-access interference are serious, it is no use to utilize more receivers. According to the receiver performance and processing gain, the acceptable traffic load of the system can be determined, then the optimal number of receivers in BS can be selected. Also, the traffic load should be controlled by protocol to avoid congestion so that both receivers and channel can be utilized efficiently.

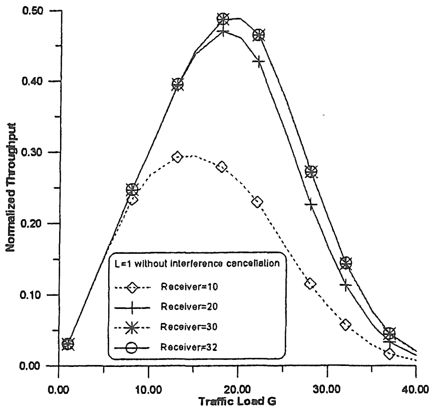
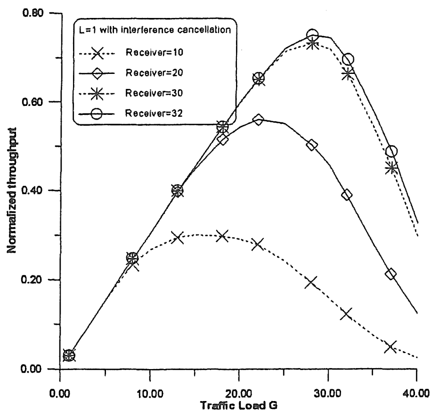
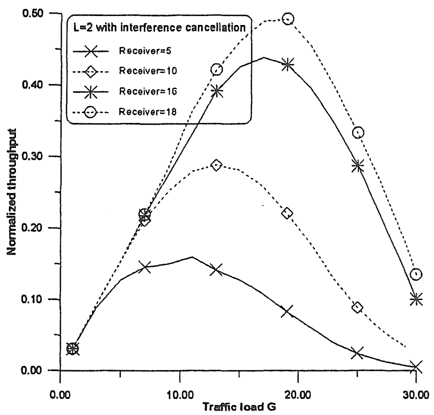


Fig.5. The normalized channel throughput with different number of receivers



(a)



(b)

Fig.6. The normalized throughput with interference cancellation

Then we use parallel interference cancellation detector which estimates and subtracts out all of the multi-access interference for each user in parallel. The results for normalized throughput are shown in Fig.6. (a), (b) respectively. The Normalized throughput can reach about 75% with 32 receivers when L=1 and 50% with 18 receivers when L=2. We focus on two type of traffic to get their performance. One type of traffic, such as voice, uses the reserved slot and chip phase of PN sequence without allowing retransmission, while the other type, such as data, accesses to the channel according to this CDMA slotted ALOHA and erroneous packets are retransmitted.

BS assigns slot and chip phase of PN sequence for each user of first type and broadcasts the assignment. No overlap of correlation peaks occurs and the transmission errors are caused by multi-access and multipath interference. BS should know system's capability beforehand with the consideration of QoS requirements. The simulation is carried out to give the packet dropping probability with different number of users transmitting packets in a same slot, as shown in Fig.7.

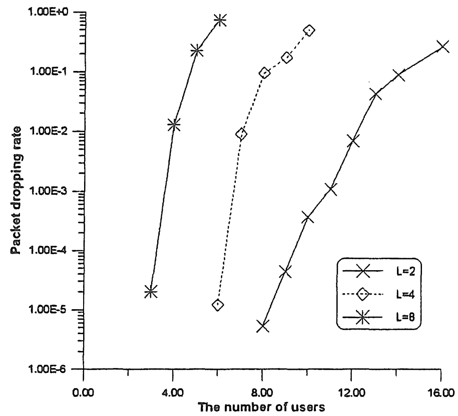
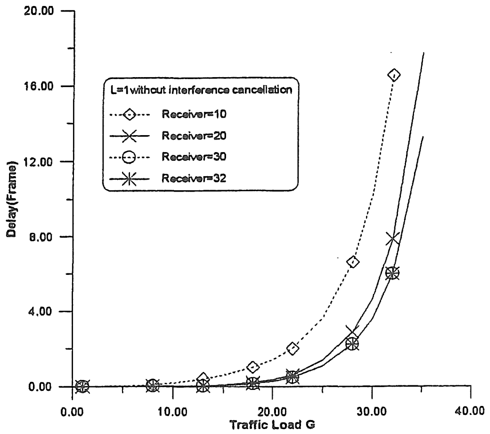


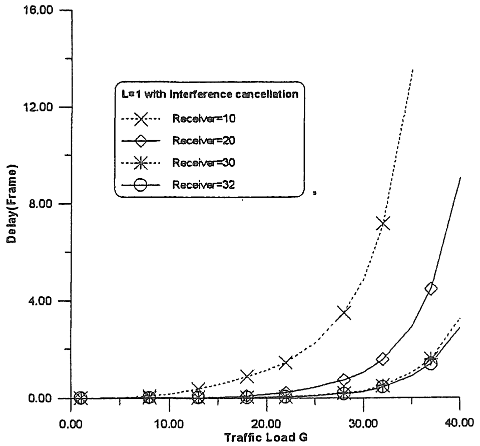
Fig.7. The packet dropping probability with different number of users in a slot

If the required packet dropping probability is 10^{-3}, the numbers of users which are allowed to transmit packet in the same slot are 11, 6, 3 respectively for L=2, L=4 and L=8. If multi-access interference cancellation is performed, these numbers can be increased further. And the number of users assigned in a slot can not be more than the number of receivers in BS.

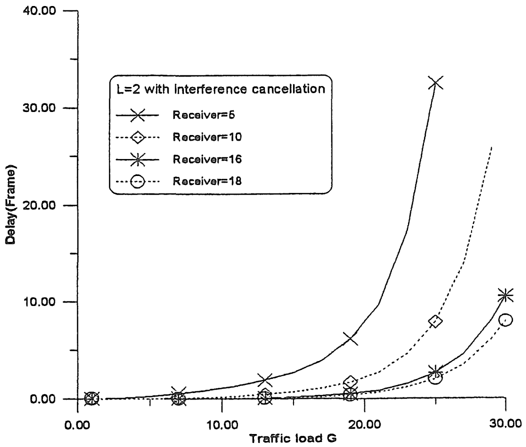
The second type of service, the average delay of a packet is considered and the simulation results are shown in Fig.8. The delay is increased with the increase of traffic load, and when the traffic load is not heavy, it is meaningless to use more receivers, while when the traffic load is high, delay is mainly determined by multiaccess interference and overlap of correlation peaks which is same as case of throughput discussed above. Also, when the traffic load reaches a point, delay is increased suddenly and quickly, i.e. congestion occurs.



(a)



(b)



(c)

Fig.8. The average packet delay with different number of receivers

From above analysis and simulations, the effects of the traffic load on the throughput and some QoS parameters can be obtained. BS can use these information to control the traffic to access the channel.

VI. Conclusion

There are great advantages when CDMA technology is used in wireless multimedia network. In this paper, a CDMA system using a kind of slotted ALOHA access method is studied and its channel throughput is calculated. Considering the effects of wireless link transmission characteristics, we also compute some performance parameters for multimedia services which have different QoS requirements. Because of the autocorrelation property of spread spectrum sequence, the channel throughput is improved greatly compared with pure S-ALOHA system. The results presented in this paper provide some useful information for future wireless broadband networks supporting multimedia applications.

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