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On Throughput Estimation of CDMA Unslotted ALOHA System for Random Access Networks

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Abstract: We employ the Simplified Improved Gaussian Approximation (SIGA) to estimate the performance of a connectionless-type CDMA packet communication system. In this system, a user's station can asynchronously and randomly transmit, making performance analysis hard due to the fluctuation of interfering users. We address this performance hardness by simulating a real world setting of the unslotted ALOHA network. Our simulation provides means of observing and reporting the system's specifications and performance under diverse boundaries.

Key words: SIGA, throughput, offered load, unslotted network

INTRODUCTION

Wireless communication systems are becoming pervasive with the growth of wireless communication. A Code Division Multiple Access (CDMA) ALOHA, which is a connectionless-type of CDMA packet communication system, has drawn much attention for wireless data communications because of features such as random access capability, potential for capacity performance and low peak power transmission (Okada *et al*., 2002; Morrow and Lehnert, 1992; Wang *et al*., 2003, 2004).

Most of the throughput analyses of random access, CDMA systems are based on slotted or circuit switched systems. In a slotted system, the transmission time is divided into slots, which consist of a packet interval time and a guard time. All users must synchronize their transmission to the beginning of their slots. The system performance only depends on the number of interfering packets (or users) within a slot (Wang *et al*., 2004).

Unslotted systems are easy to implement because they do not require synchronization. However, its performance analysis is extremely difficult due to the fluctuation of interfering users within the packet interval. Most of the performance analysis of unslotted ALOHA depends on perfect capture since the packet with a larger power can survive during packets collision, while the number of interference is assumed to be constant. This is known as capture effect (Yin and Li, 1990).

This study presents a throughput capacity estimation technique for unslotted random access networks. To achieve this, the use of the Bit Error Rate (BER) probability for CDMA systems is adopted and appropriately modified. It is expected that the present method, which takes into account the system link quality will provide a more accurate analysis for the unslotted systems.

THE SYSTEM MODEL

Traffic model: Figure 1 shows the system model of CDMA unslotted ALOHA system. This consists of a single hub station and an unspecified number of user stations. Each user station transmits a packet hub station by one hop. In this study, we only consider uplink packet access. Each packet has a fixed length and contains a data block sequence of L_d bits. The offered load, G, is defined as the average number of packet generated during one data duration, i.e.,

$$T = \frac{L_d}{R_d}$$

where:
R_d = The data rate

The offered load corresponds to the traffic intensity of the generated data. The throughput, Th, also defined as the average number of successful packets during one data duration is our main performance measure.

Transmitter/receiver structure: The transmitter structure and channel model is shown in Fig. 2. The Binary Phase Shift Keying (BPSK) is assumed as the modulation

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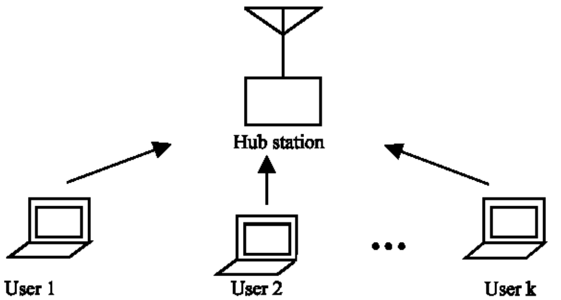

Fig. 1: System model of a CDMA unslotted ALOHA system

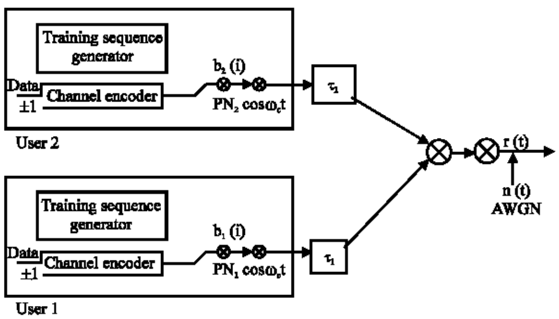

Fig. 2: The transmitter structure and channel model

scheme. A data block sequence (channel encoded and termination bits to the initial state) is employed as a channel coding technique. A preamble sequence of L_t bits is added to the coded data sequence, so the whole packet length is:

$$L = L_t + \frac{(L_d + L_z)}{R_c} \text{ bits}$$

where:
R_c = The code rate
L_z = The number of termination bits

Each packet's sequence is then spread with a uniquely assigned random signature sequence of length N chips.

We assume that all packets are received with equal power and all data bit errors are called by the effect of Multiple Access Interference (MAI) and Additive White Gaussian Noise (AWGN). The received waveform of the k_{th} user is expressed as in Eq. 1:

$$S_k(t-\tau_k) = \sqrt{2P_x}.a_k(t-\tau_k).b_k(t-\tau_k).\cos(\omega_c t + \varphi_k) \quad (1)$$

where:
b_k (t) = The data sequence for k users
a_k (t) = The Pseudo-Noise (PN) spreading sequence for user k
τ_k = The delay of user k
P_k = The received power of user k
ω_c = The carrier frequency
ω_c = The carrier phase offset of user k

The data signal b_k (t) is a sequence of unit amplitude, positive and negative, rectangular pulses and bit period of T_b. Superimposed on the data signal is a much faster sequence of chips a_k (t), composed also of unit amplitude, positive and negative, rectangular pulses and chip period of T_c. It is assumed that the bit period is an integral multiple of the chip period such that

$$T_b = Nt_c$$

where:
N = The spreading gain

The received signal containing the desired users and the noise is given by:

$$r(t) = \sum_{k=0}^{K-1} S_k(t-\tau_k)n(t) \quad (2)$$

where, n (t) is the white Gaussian noise with 2 sided power spectral density, $N_0/2$. This signal along with the receiver is illustrated in Fig. 3.

The received signal is mixed down to base-band, multiplied by the pseudo-noise sequence of the desired user and integrated over 1 bit period by the receiver. Assuming that the receiver is delay and phase synchronized with user 0, the decision statistics for jth bit of user 0 is given by:

$$Z_0 = \int_{jT_b}^{(j+1)T_b} r(t)a_0(t)\cos(\omega_c t)dt \quad (3)$$

Mathematical expression for BER probability: Using the Gaussian Approximation (GA) described in Morrow and Lehnert (1989), the average bit error probability is given by:

$$P_b = Q\left[\bullet\sqrt{\frac{1}{\frac{1}{3N}\sum_{k}^{K-1}\frac{P_K}{P_0} + \frac{N_0}{2T_bP_0}}}\right] \quad (4)$$

where, the Q (•) function can be defined in an integral form as:

$$Q(u) = \frac{1}{\sqrt{2\pi}}\int \exp^{\left(-\frac{x^2}{2}\right)}$$

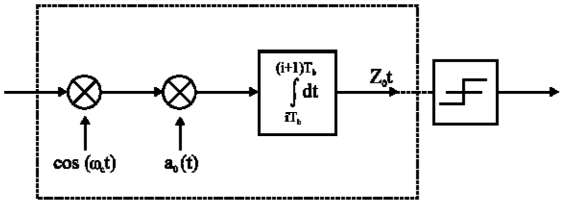

Fig. 3: CDMA receiver structure

Assuming all users has equal power:

$$P_c = Q\left[\sqrt{\frac{1}{\frac{(K-1)}{3N} + \frac{N_0}{2T_b P_0}}}\right] \quad (5)$$

If, we express the delays and phases of the interfering signals as random vectors:

$$S = (S_1, S_2, \ldots, S_k) \text{ and } \varphi = (\varphi_1, \varphi_2, \ldots, \varphi_k)$$

where:

S_k = A uniform random variable taking values in the range (0, 1)

φ_k = A uniform random variable taking values in the range (0, 2π)

Given these 2 random vectors, the variance of the multiple access interference from the kth user is found to be:

$$E[Z_k \mid S_k, \varphi_k] = N(S_k^2 - S_k + 0.5)[(1 + \cos(2\varphi_k)]$$

where:

Z_k = The variance of multiple access interference from the kth user

The total Multiple Access Interference (MAI) variance is thus,

$$\Psi = \sum_{k=2}^{K} Z_k$$

If the interference from users is identical, then, the variance, Ψ, of the MAI is given by:

$$\Psi = (K - 1)\, Z_k \text{ for some k}$$

The probability of data bit error is then approximated by:

$$P_e = Q\left[\frac{N}{\sqrt{\Psi + \frac{N_0}{2\varepsilon_b} N^2}}\right] \quad (6)$$

If the interfering signals are not chip and phase synchronous with the desired signal, then the average interference from the kth user is found by substituting and E (cos ($2\varphi_k$)), which produces:

$$E[Z_k] = \frac{N}{3} \text{ and } E[\Psi] = \frac{(K-1)N}{3}$$

The average bit error probability now becomes

$$P_e = Q\left[\frac{N}{\sqrt{\frac{(K-1)N}{3} + \frac{N_0}{2\varepsilon_b} N^2}}\right] = Q\left[\sqrt{\frac{1}{\frac{(K-1)}{3N} + \frac{N_0}{2\varepsilon_b}}}\right] \quad (7)$$

which is the standard Gaussian Approximation (GA) result. If interfering signals are chip and phase aligned with the desired signal, then E (Z_k | S_k = 0, ϕ_k = 0) and thus, results in:

$$P_e = Q\left[\frac{N}{\sqrt{(K-1)N + \frac{N_0}{2\varepsilon_b} N^2}}\right] = Q\left[\sqrt{\frac{1}{\frac{(K-1)}{N} + \frac{N_0}{2\varepsilon_b}}}\right] \quad (8)$$

which represents the worst case scenario. Using similar reasoning, interfering signals that are chip random phases have

$$P_e = Q\left[\sqrt{\frac{1}{\frac{(K-1)}{2N} + \frac{N_0}{2\varepsilon_b}}}\right] \quad (9)$$

and phase aligned interfering signals with random chip delays produce

$$P_e = Q\left[\sqrt{\frac{1}{\frac{2(K-1)}{3N} + \frac{N_0}{2\varepsilon_b}}}\right] \quad (10)$$

For a generic case, in which the received power from each user is unequal, the probability of bit error for the jth user is given by

$$P_e(j) = E\left[Q\left(\sqrt{\frac{P_j}{\frac{\sum_{k \neq j} P_k}{3N} + \frac{N_0}{2\varepsilon_b}}}\right)\right] \quad (11)$$

Using the Simplified Improved Gaussian Approximation (SIGA) (Ali *et al*., 2003), the average bit error probability becomes:

$$P_e \approx \frac{2}{3Q}\left[\sqrt{\frac{N^2}{2(\mu_4 + \frac{N_0}{2\varepsilon_b} N^2}}\right] + \frac{1}{6}\left[\frac{N^2}{2(\mu_4 + \sqrt{3\delta_\Psi} + \frac{N_0}{2\varepsilon_b} N^2}\right] \frac{1}{6}\left[\frac{N^2}{2(\mu_4 - \sqrt{3\delta_\Psi} + \frac{N_0}{2\varepsilon_b} N^2}\right] \quad (12)$$

When all users are assumed to have unit power, their mean and variance are given by:

$$\mu_\phi = \frac{N}{6}(K-1),$$

$$\delta_\phi^2 = \frac{K-1}{4}\left[\frac{23N^2}{360} + N\left(\frac{1}{20} + \frac{K-2}{36}\right) - \frac{1}{20} - \frac{K-2}{36}\right]$$

MATERIALS AND METHODS

In this section, we present the throughput estimation method for the random access CDMA system.

Throughput and link capacity: Let us consider a centralized spread spectrum system with infinite number of users, where every transmission is received with equal power and bit errors are caused by multiple access interference and thermal noise.

Outage occurs if the transmission quality drops below the required Quality of Services (QoS), i.e., packet throughput and delay. The link capacity is defined as the maximum number of active users that satisfies the allowable outage probability, Q_{allow}, which is defined as the maximum outage probability that satisfies the system's requirement. Assuming infinite number of transmissions (infinite delay is allowed before successful transmission of a packet), the throughput Th is given as:

$$Th = 1 - P(k - \lambda) \quad (13)$$

where, P (k, λ) is the average packet error rate, with k and λ being the number of interfering active users and the packet occurrence rate, respectively. The outage occurs only if the throughput is less than the required value. The outage probability Q is given by:

$$Q + Pr\,ob\,(Th < Th_{req}) \quad (14)$$

where, Th_{req} is the required throughput, defined as the minimum throughput that satisfies the required QoS.

Deriving P (k, λ): For throughput estimation, we need to obtain P (k, λ). Following the derivations in Yamazoto *et al.* (2000) and Kudoh and Adachi (2004), we assume that all the occurrence rate of the original packets are the same for all active users and is denoted by λ_0. The total packet occurrence rate, λ, is

$$1 + (packet - transmission - rate) \times \lambda_0$$

When transmit power control is used and since packet errors occur equally likely for all active users, λ becomes:

$$\lambda = \frac{\lambda_0}{1 - P(k,\lambda)} \quad (15)$$

There exist k-1 active interfering users. Now, assuming that the original and transmitted packets are randomly produced, P (k, λ) can be estimated using:

$$P(k,\lambda) = \sum_{k=0}^{K-1} P(k).\begin{pmatrix} K-1 \\ k \end{pmatrix}\lambda^k(1-\lambda)^{K-1-k} \quad (16)$$

where, P (k) is the conditional average packet error rate when k interfering packets are received and

$$\begin{pmatrix} K-1 \\ k \end{pmatrix} = \frac{(K-1)!}{k!(K-k-1)!} \quad (17)$$

is the binomial coefficient.

Assuming unslotted packet transmission and a block fading (the fading stays almost constant over a packet), P (k), can be computed by

$$P(k) = 1 - \left(1 - (\overline{P_b(Y_k)}\right)^M \quad (18)$$

Where:

$\overline{P_b(Y_k)}$	=	The average Bit Error Rate (BER) when k interfering packets are received
M	=	The number of bits in a packet
$P_b(Y_k)$	=	The BER when the received signal is Y_k

We also assume coherent BPSK data modulation and that the sum of colliding packets is approximated as a Gaussian process, $P_b(Y_k)$, presented in section (2.1). Here, the energy/bit duration, ε_b/N_0 is mapped in SNR and is denoted by Y_k, Ross (2003).

RESULTS AND DISCUSSION

In this study, the system's performance is evaluated by simulating a real-world environment, using Visual Basic (VB). VB is an Object Oriented Programming Language (OOPL) suitable for scientific simulations. The operating parameters used as environment variables for the simulation are shown in Table 1.

Figure 4 shows the throughput performance as a function of load with packet size of 1062 and 809 bits, respectively. We observe that large packet size gives higher throughput, compared to small packet size, at a high SNR fixed at 8 dB.

By increasing the SNR to 10 dB, we achieve a much higher throughput as can be seen in Fig. 5. However, it

Table 1: Simulation parameters

Parameter	Value
ε_b/N_0	10|8 dB
Processing gain (N)	60
Spreading sequence	Random signature
Code Rate (R_c)	1/2|2/3
Packet size	1062|809 bits
Data packet generation	$\lambda_0 = 0.01 - 0.1$

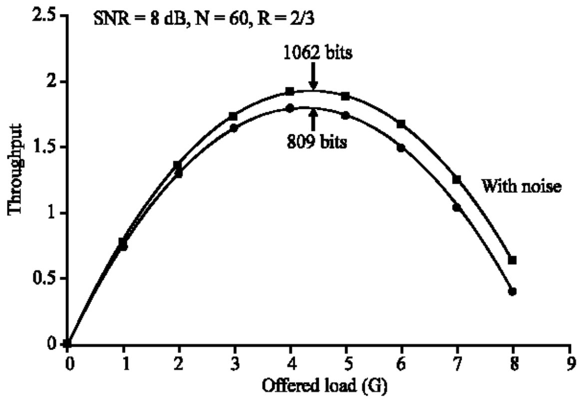

Fig. 4: Effect of noise

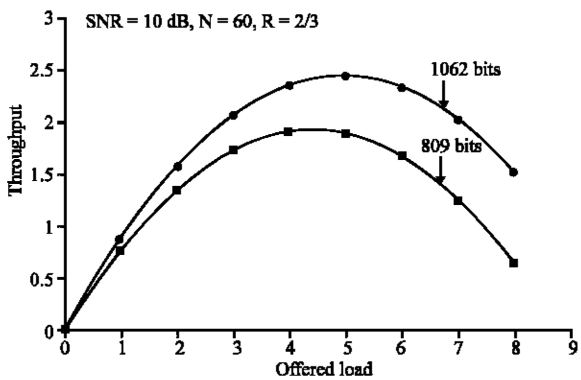

Fig. 5: Effect of SNR

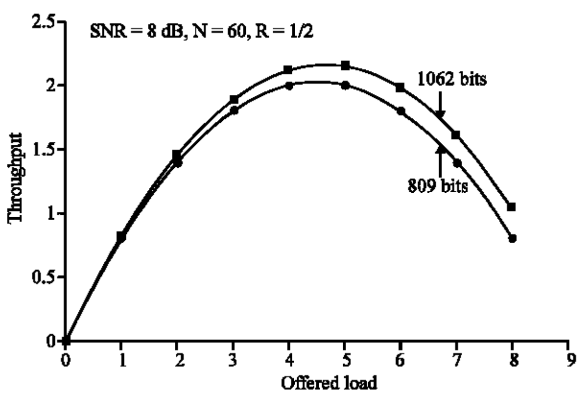

Fig. 6: Effect of code rate

does not necessarily imply that the SNR should always be variable. For instance, if we simultaneously adapt the code rate and packet length, Th_{req} is optimum regardless of the SNR value, because the code rate is adapted first to maintain $Th = Th_{req}$, thus, eliminating the effect of change. In this case, the degree of SNR would be enough for the minimum throughput that satisfies the QoS.

Shown in Fig. 6 is also a plot of throughput vs. load, but with a lower code rate of ½. From Fig. 6, we observe that choosing a low transmission rate gives a lower throughput for the system's load. It proves that high code rates are better of than low code rates.

CONCLUSION

In this study, we studied the throughput estimation of CDMA unslotted ALOHA packet communication system. Using real-world environment simulation, we attempt to characterize the communication channel conditions and study the network performance in terms of throughput, SNR, channel, load and load rate. We have shown that these factors affect throughput performance as a function of channel load by finding the optimum design parameters the system should operate at, so as to achieve excellent QoS.

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