Performance of Slotted Asynchronous CDMA Using Controlled Time of Arrival

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***Abstract*—A slotted asynchronous (SA) code-divison multiple-access communication scheme controlling the time of arrival is proposed for distributed spread-spectrum packet radio networks where the transmission range is limited as in an indoor wireless system. In this scheme, each terminal can send its packet randomly at any one of N_w possible time instants, equally spaced over one period of direct-sequence spread-spectrum signals. Such transmissions initiated at different time instants can be resolved because of high time resolution of wide-band signals if the channel delays associated with multipath are small due to limited transmission range. Quasi-synchronous distributed networks are considered to allow timing drift among terminals and also reflect wireless multiple-access channels, in which common-transmitter-based (C-T) and receiver–transmitter-based (R–T) spreading-code assignments are adopted to permit a contention mode only for the header portion. Throughput is evaluated under the spread ALOHA assumption on collision events and also by reflecting the effect of the MAI in the header detection process. Theoretical results show that the combination of the SA scheme with C-T assignment results in more significant improvement than the case of R–T assignment, and also the former provides the benefit of the efficient usage of spreading codes in a code-limited environment.**

***Index Terms*— Direct-sequence spread-spectrum, distributed networks, slotted asynchronous CDMA, MAI, spread ALOHA, spreading-code assignments.**

I. Introduction

GENERALLY, the operation and performance of packet radio networks using spread-spectrum signals depend on multiple-access schemes and spreading-code assignments. As for the multiple-access schemes, various forms of multiple access have been proposed for conventional packet radio networks, which can be mainly divided into two types of ALOHA and carrier sense [1], [2]. Typically, carrier sense assures higher channel efficiency than ALOHA in case of narrow-band signaling, but carries a somewhat different meaning for spread-spectrum systems. By sensing the common carrier, each terminal in the narrow-band system detects whether other terminals within hearing range from its destination are transmitting. On the other hand, in the spread-spectrum system, carrier sense may be used for checking whether the destined terminal is in idle state (because the system basically provides multiple-access capability). Here, each idle terminal is trying to lock onto other transmissions and decode the address of a packet, thereafter observing the channel status in the network [3]. Thus, carrier sense causes a lot of burden on each terminal unless every terminal in the system shares a single spreading code.

As for the spreading-code assignments, Sousa and Silvester proposed hybrid types of assignments, i.e., common-transmitter-based (C-T) and receiver–transmitter-based (R–T) assignments for distributed spread-spectrum packet radio networks [4]. They considered a mini-slotted code-division multiple-access (CDMA) packet radio network with orthogonal signature codes and synchronous transmissions in which the effect of multiple-access interference (MAI) can be safely neglected. In this case, the C-T assignment results in poor throughput performance because two headers in the R–T assignment collide only when they are intended for the same terminal. In reality, there exists some timing drift among terminals in distributed networks even with a universal time reference, which is often transformed into quasi-synchronous networks. Also, wireless multiple-access channels cause different multipath fading characteristics among terminals so that synchronous orthogonal code channels are not easily allowed. Here, we are concerned with such network conditions in which the collision event and the effect of MAI on throughput are jointly investigated for both code assignments.

Spread-spectrum signals [5] possess the property of high time resolution after passing through the correlator/matched-filter receiver. By exploiting this property, we propose a slotted asynchronous (SA) CDMA scheme for wireless data networks with small radius. Here, "SA" is intended to properly resolve collisions during the header portion in a contention mode, while CDMA assures collision-free for the data portion because of channel orthogonalization. The proposed SA scheme can adjust the transmission time of a packet by randomly choosing any one of N_w time instants, equally spaced over one period of direct-sequence (DS) spread-spectrum signals. As far as the channel delays associated with multipath are small, it controls the time of arrival such that those packets transmitted at different time instants can be resolved even though they

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are using the same spreading code. As for the multiple-access scheme, we consider SA CDMA using controlled time of arrival (SA/CTOA), and adopt the C-T and R–T assignments for the spreading-code assignment.

The purpose of this research is to enhance channel efficiency of the C-T assignment by combination with the SA/CTOA multiple-access scheme under the quasi-synchronous distributed networks. Typically, a small processing gain is used in wireless local communications due to limited system bandwidth and, hence, there exist a small number of spreading codes with well-defined correlation properties. However, the potential number of users in wireless data networks is considerably larger than the active number of users involved in either transmission or reception. Therefore, in such a code-limited environment, the use of the C-T assignment is preferable in view of the efficient usage of spreading codes.[1] We here demonstrate that the C-T assignment yields an acceptable throughput performance compared to the R–T assignment when the SA/CTOA multiple-access scheme is employed.

This paper is organized as follows. In Section II, we describe the system model with necessary assumptions, and also the two different types of spreading-code assignments to be used. Section III outlines the proposed SA/CTOA scheme along with definitions on collision and success events. In Section IV, the general expression for throughput is derived using the Markov chain model and combinatorial theory. Theoretical results are provided in Section V with simulation results for validation. Finally, we summarize the contents and draw conclusions in Section VI.

II. System Description

An indoor wireless system or packet radio system with small radius shows the characteristics of a channel whose propagation delay and multipath delay spread are relatively short. We consider a distributed single-hop system exhibiting such channel characteristics with uniform traffic in which a terminal is equally likely to transmit to all other terminals within hearing range and direct-sequence spread-spectrum signals are employed for high time resolution. A mini-slotted system [4] is assumed so that a slot size is equal to the header length of a packet while the data packet occupies a number of slots, and each terminal is operated in a half-duplex mode, which allows either transmission or reception in a given time.

We assume synchronous transmission at the slot level, but quasi-synchronous at the bit time level to properly reflect some timing delays even though all terminals use a universal time reference. Thus, they must achieve fine synchronization by searching for a synchronization sequence contained in the header and also identify the beginning of a packet. Related to this, we can use the code-matched filter whose impulse response is adjustable by a desired code, its filter output is sampled at a chip rate or even higher rate, and then construct a data file that includes a number of sequences of signal samples or only noise samples. These sample sequences are compared

[1] The C-T scheme needs a smaller number of codes for a given number of users, about half as many for the R–T scheme.

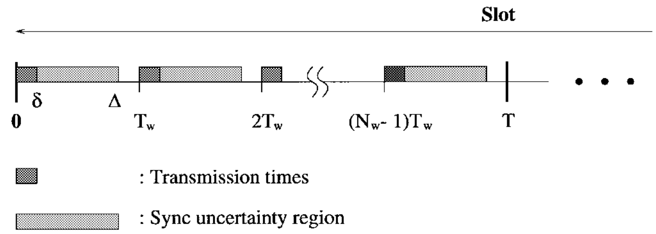

Fig. 1. Timing diagram for adjusting the transmission time in SA/CTOA.

with a special sequence in the header to detect the presence of a packet addressed to a required terminal. Refer to [6] regarding detailed packet processing.

Here, we consider the hybrid C-T and R–T assignments in which each terminal changes a despreading code for reception of the data packet after an initial header is correctly received. Thus, the header preceding a packet contains a destination address and also a source address, in which the former is utilized to verify synchronization of a special sequence, while the latter enables us to dynamically switch to the despreading code corresponding to a source. A packet consists of the special sequence, followed by the address, and then followed by real data. For convenience, we denote the length of a packet by some integer value $L = T_p/T_s$, which is normalized by a slot time T_s. Note that the data packet contains $L-1$ minipackets, each of length one.

In the C-T assignment, a particular ith terminal uses the common spreading code C^c for encoding the header while its unique transmitting code C_i^t is employed for encoding the data packet. Hence, while all idle terminals continue to monitor C^c, the destined terminal tries to lock onto the packet transmission and identify its source address, and then decodes the data packet using C_i^t. For the R–T assignment, a particular ith terminal is assigned two distinct spreading codes; one is used for receiving the header, namely, its unique receiving code C_i^r, the other is the transmitting code C_i^t, which is used for encoding the data packet. In the spreading-code assignments [4], it is required that each terminal has the information about $\{C^c\} \cup \{C_i^t\}_{i=1}^K$ and $\{C_i^r, C_i^t\}_{i=1}^K$, and these codes can be generated by using a programmable code generator.

III. SA/CTOA Multiple Access

The timing diagram is shown in Fig. 1 for adjusting the transmission time of a packet. Let us denote the starting time of a slot by zero, and T indicates one period of direct-sequence spread-spectrum signals. N_w possible time instants are equally spaced over $[0, T)$, namely, at

$$t_i = \{t : iT_w \le t < iT_w + \delta\}, \qquad i = 0, 1, \cdots, N_w - 1 \quad (1)$$

where δ accounts for the timing drift existing among terminals in distributed networks even though the transmission time is set to one of N_w time instants in a given slot. Hence, the terminals are somewhat synchronized in the frame of T_w s with some timing drift. Here, the timing drift δ should be less than T_w, which is given by $T_w = T/N_w$ and satisfies the condition

$$T_w > \Delta = (\delta + \tau_{\max} + T_m). \quad (2)$$

Thus, the spacing T_w between adjacent time instants t_i and t_{i+1} may be established such that the total time delay Δ includes the timing drift δ, maximum propagation delay $\tau_{\max}$, and multipath delay spread T_m.

The proposed SA scheme to be able to control the time of arrival at the receiver is a kind of spread ALOHA [7] in which if each terminal has a packet to send, it chooses one, say t_i, of N_w time instants $\{t_i\}_{i=0}^{N_w-1}$ with equal probability and starts the packet transmission at t_i in a slot. The packet signal transmitted at t_i passes through a multipath channel and arrives at the receiver within the time range $[iT_w, iT_w + \Delta]$, which corresponds to the uncertainty time region for synchronization. At the receiver, if we are using the code-matched filter with a chip-rate (T_c^{-1}) sampling, there are N_w data files to be used in searching for a special sequence of length N_h in the header, which are formed by the signal samples in successive N_w time windows $[iT_w + nT, iT_w + \Delta + nT], i = 0, 1, \cdots, N_w - 1$ for $n = 0, 1, \cdots, N_h - 1$. Each data file consists of $G = \lfloor \Delta/T_c \rfloor + 1$ sample sequences ($\lfloor x \rfloor$ denotes the greatest integer not exceeding x) where the jth sequence of the ith data file contains N_h samples at $iT_w + jT_c + nT$, $n = 0, 1, \cdots, N_h - 1$ for given $0 \le i \le N_w - 1$ and $0 \le j \le G - 1$. This implies that a total of GN_hN_w post data processing is required to acquire symbol sync and also know the exact beginning of a packet. When the condition $T_w > \Delta$ is satisfied, the signal samples existing in a time window do not interfere with signals belonging to the other time windows. Thus, it is possible to achieve synchronization in the corresponding data file, and then decode the source address of a packet.

In order to evaluate throughput performance of the proposed SA/CTOA scheme, we make the spread ALOHA assumption such that *collision may occur when two or more headers using the same spreading code are transmitted at the same time instant in a slot*. If two headers encoded by the same spreading code are transmitted at the same time instant from different terminals with possible timing drift, it is unlikely of the destined terminal to correctly receive the header since there exists a strong correlation between these two header signals with relatively small time offset, especially for a multipath channel. Thus, the spread ALOHA assumption on collision events may be justified with this observation. Along with this assumption, we further assume that if there are one or more collision-free packets at the destined terminal, it receives anyone that is randomly selected out of such packets. For a collision-free packet, it is assumed that *the packet is successfully received if its header is correctly received by detecting a special sequence of length N_h in the presence of the MAI caused by concurrent transmissions*. Thus, unsuccessful transmission occurs when the header of a packet collides with other headers or incorrectly received because of the MAI even with no collision, otherwise, the destined terminal is not idle. In addition, we assume that the effect of the MAI on reception of the data packet [6] can be mitigated by the use of forward-error-correction coding. To further reduce the MAI caused by unsuccessful attempts, we may adopt acknowledgments for transmissions [8], but their effect is not reflected in our analysis for distributed networks because of computational difficulties.

For a system with small time delay Δ, the period of spread-spectrum signals can be set to $T = T_b$, a bit time, while a M-ary spread-spectrum signal with $T = T_b \log_2 M$ may be used for a system with relatively large Δ.

IV. Throughput Analysis

We introduce a Markov chain model in evaluating throughput of the SA/CTOA scheme employing hybrid spreading-code assignments. In case of a fixed packet length, the number of states is quite large and the analysis is intractable. For this reason, we assume a variable length of a packet with geometric distribution [4], which leads to a Markov chain model with fewer states because of the memoryless property. Then the length L of a packet is distributed as

$$\Pr[L = l] = (1-q)q^{l-1}, \qquad l = 1, 2, \cdots. \tag{3}$$

Thus, the average packet length is given by $\bar{L} = 1/(1-q)$ and the average length of the data packet becomes $\bar{L} - 1$. When a terminal is in idle state or transmitting a last minipacket at the $(t-1)$th slot, we assume that it starts the packet transmission with probability p at the beginning of the tth slot.

Once a terminal transmits a packet, it continues to send the remaining data packet of length $L - 1$, regardless of the preceding header being correctly received or not. Likewise, if a terminal correctly receives the header of a packet in the presence of the MAI, it is in the receiving mode during the subsequent $L - 1$ slots. Thus, every terminal in the network remains in any one of the following four states, namely: 1) successful transmission state; 2) unsuccessful transmission state; 3) receiving state; and 4) idle state. Note that the number of terminals in successful transmission state is equal to that in receiving state. In order to look into the network of finite K users, it is required to know the number n_1 of terminals with successful transmissions and the number n_2 of terminals with unsuccessful ones. If we denote the network state by $z(t) = (n_1, n_2)$, then the state space of $z(t)$ is given by $Z = \{(n_1, n_2) \mid n_1 \ge 0,\ n_2 \ge 0,\ 0 \le 2n_1 + n_2 \le K\}$. Thus, the number of states in the Markov chain model becomes

$$|Z| = \left(K - \left\lfloor \frac{K}{2} \right\rfloor + 1\right)\left(\left\lfloor \frac{K}{2} \right\rfloor + 1\right). \tag{4}$$

This number can be approximated to $K^2/4$ for large K. The Markov chain is irreducible and, hence, there exists the stationary distribution $\{\pi(m,n) \mid (m,n) \in Z\}$. If the transition matrix of Markov chain is denoted by $\mathbf{P}$, the stationary probabilities $\{\pi(m,n)\}$ can be obtained by solving

$$\pi = \pi\mathbf{P}, \qquad \sum_{(m,n)\in Z} \pi(m,n) = 1 \tag{5}$$

where π is a row vector with its element $\pi(m,n)$ for all $(m,n) \in Z$.

A. C-T Assignment

Collision will occur when two or more packets are transmitted at the same time instant in a slot (because this scheme shares a common spreading code among users for encoding the header). Let us define $p_{kl,mn}$ as the transition probability from (k,l) state to (m,n) state, which is given by

$$\begin{aligned} p_{kl,mn} &= \Pr[\Gamma_{kl,mn}] \\ &= \Pr[z(t)=(m,n) \mid z(t-1)=(k,l)]. \end{aligned} \tag{6}$$

Here, $\Gamma_{kl,mn}$ indicates an event of the transition $(k,l) \rightarrow (m,n)$ having occurred. To derive the transition probability, we consider an event $C_{i,j}$ that some i of k terminal pairs involved in successful transmission and reception, and some j of l terminals in unsuccessful transmission are completing their packet transmissions and changing into idle state at the beginning of tth slot. From the geometric distribution of (3), the probability of such event occurring is given by

$$\Pr[C_{i,j}] = \binom{k}{i}\binom{l}{j}(1-q)^{i+j}q^{k+l-(i+j)} \tag{7}$$

where $\binom{m}{n}=0$ for $m<0$, $n<0$ or $n>m$ and, otherwise, $m!/(m-n)!n!$. By the law of total probability, the transition probability $p_{kl,mn}$ can be written as

$$p_{kl,mn} = \sum_{i=0}^{k}\sum_{j=0}^{l} \Pr[\Gamma_{kl,mn} \mid C_{i,j}] \cdot \Pr[C_{i,j}]. \tag{8}$$

We know that there are $K_I = K - 2(k-i) - (l-j)$ idle terminals at the beginning of the tth slot. Thus, to have the transition from (k,l) state to (m,n) state, $\mu = m-(k-i)$ terminal pairs of them should change into successful transmission and receiving states, respectively, and also $\nu = n-(l-j)$ terminals of them change into unsuccessful transmission state. In computing the number of ways of doing this, we must consider the states of all terminals in the network and the channel activity at the same time because the state of a terminal is affected by the states and channel activity of other terminals.

Given a set T_I consisting of K_I idle terminals, only the number $\mu+\nu$ of terminals will start the packet transmission at the tth slot. For derivation of $p_{kl,mn}$, we should properly designate the time instants $\{t_i\}$ at which they start to transmit their packets, and the destinations of their packets. First, the set T_I is partitioned into four sets, i.e., a set T_X of transmitting terminals, a set T_R of receiving terminals, a set T_F of still idle terminals even with collision-free packets (not received), and a set T_C of idle terminals with collided packets or not destined, whose size are given by $|T_X| = \mu+\nu$, $|T_R| = \mu$, $|T_F| = \lambda \le \nu$, and $|T_C| = K_I - 2\mu - \nu - \lambda$. The number of ways of doing such partitions is

$$M(K_I,\mu,\nu,\lambda) = \binom{K_I}{\mu+\nu}\binom{K_I-\mu-\nu}{\mu+\lambda}\binom{\mu+\lambda}{\mu}. \tag{9}$$

Now, we assume that only the $\mu+\lambda$ terminals in $T_R \cup T_F$ observe collision-free transmissions, finally the μ terminals in T_R leading to success. We apply combinatorial theory, especially the principle of inclusion and exclusion [9], to derive the number of ways of designating all possible transmission times and destinations of those packets belonging to T_X in order to make the event $\Gamma_{kl,mn}$ occur. Let us define this number of ways by $N_{C-T}(K_I,\ \mu,\ \nu,\ \lambda)$, which is derived in Appendix A as follows:

$$\begin{aligned} &N_{C-T}(K_I,\mu,\nu,\lambda) \\ &\quad= \sum_{\mathbf{n}\in\Psi} \frac{(\mu+\lambda)!}{\prod_e (b_e!)} \cdot \binom{N_w}{S_{\mu+\lambda}} S_{\mu+\lambda}! \\ &\qquad \cdot \frac{(\mu+\nu)!}{(\mu+\nu-S_{\mu+\lambda})!\prod_{d=1}^{\mu+\lambda}(n_d!)} \sum_{g=0}^{f}(-1)^g\binom{f}{g} \\ &\qquad \cdot \binom{N_w-S_{\mu+\lambda}}{g} g!(K_I-\mu-\nu)^g \\ &\qquad \cdot [(N_w-S_{\mu+\lambda}-g)(K-1)]^{f-g}. \end{aligned} \tag{10}$$

Here, $\mathbf{n} \triangleq (n_1,n_2,\cdots,n_{\mu+\lambda})$, n_d indicates the number of collision-free packets destined to the dth terminal in $T_R \cup T_F$, $S_{\mu+\lambda} = \sum_{d=1}^{\mu+\lambda} n_d$, $f = |T_X| - S_{\mu+\lambda} = \mu+\nu-S_{\mu+\lambda}$, and $\Psi = \{(n_1,n_2,\cdots,n_{\mu+\lambda}) \mid n_d \le n_{d+1}, 1 \le n_d \le \nu-\lambda+1, \mu+\lambda \le S_{\mu+\lambda} \le \mu+\nu\}$. The element n_d of $\mathbf{n} \in \Psi$ is listed in an ascending order due to the condition $n_d \le n_{d+1}$, and b_e is equal to the number of the eth largest elements among $\{n_d\}$.

A terminal in T_R will be changed into the receiving mode by correctly receiving the header of a collision-free packet in the presence of the MAI. Note that the MAI results from the $\mu+\nu-1$ interferers using the common code and the $(k-i)+(l-j)$ interferers using the transmitting codes, summing to total $m+n-1$ interferers. Conditioned on the event $C_{i,j}$, the transition probability from (k,l) state to (m,n) state can be expressed by

$$\begin{aligned} &\Pr[\Gamma_{kl,mn} \mid C_{i,j}] \\ &\quad= \sum_{\lambda=0}^{\nu} p^{\mu+\nu}(1-p)^{K_I-(\mu+\nu)} \cdot [P_h(\mu+\nu,m+n)]^{\mu} \\ &\qquad \cdot [1-P_h(\mu+\nu,m+n)]^{\lambda} \cdot \left(\frac{1}{(K-1)N_w}\right)^{\mu+\nu} \\ &\qquad \cdot M(K_I,\mu,\nu,\lambda) \cdot N_{C-T}(K_I,\mu,\nu,\lambda) \end{aligned} \tag{11}$$

where the detection probability $P_h(\alpha,\gamma)$ incorporating timing acquisition[2] at the code-matched filter is derived in Appendix B as follows:

$$P_h(\alpha,\gamma) \cong \frac{1}{GN_w}\sum_{l=0}^{GN_w-1}[1-P_f(\alpha,\gamma)]^l P_d(\alpha,\gamma) \tag{12}$$

assuming envelope sequence detection for the DS/binary phase shift-keying (BPSK) modulation in the header. In the above, $P_f(\alpha,\gamma)$ is the false alarm probability that occurred before a correct sampling time, at which a special sequence in the header is detected with the probability $P_d(\alpha,\gamma) =$

[2] The second-order effect is ignored that results from two or more collision-free headers in a slot.

$\mathbf{E}\{P_d(\alpha, \gamma \mid \epsilon)\}$. Here, ϵ is the normalized sync time offset that is uniformly distributed in $[0, 1/2]$ for a chip-rate sampling, $\mathbf{E}$ denoting the expectation with respect to ϵ. Therefore, substitution of (7) and (9)–(11) upon (8) yields

$$\begin{aligned} p_{kl,mn} = &\sum_{i=0}^{k}\sum_{j=0}^{l}\sum_{\lambda=0}^{\nu}\binom{k}{i}\binom{l}{j}(1-q)^{i+j}q^{k+l-(i+j)} \\ &\cdot p^{\mu+\nu}(1-p)^{K_I-(\mu+\nu)}[P_h(\mu+\nu, m+n)]^{\mu} \\ &\cdot [1-P_h(\mu+\nu, m+n)]^{\lambda}\left(\frac{1}{(K-1)N_w}\right)^{\mu+\nu} \\ &\cdot \binom{K_I}{\mu+\nu}\binom{K_I-\mu-\nu}{\mu+\lambda}\binom{\mu+\lambda}{\mu} \\ &\cdot \sum_{\mathbf{n}\in\Psi}\frac{(\mu+\lambda)!}{\prod_e(b_e!)}\cdot\binom{N_w}{S_{\mu+\lambda}}S_{\mu+\lambda}! \\ &\cdot \frac{(\mu+\nu)!}{(\mu+\nu-S_{\mu+\lambda})!\prod_{d=1}^{\mu+\lambda}(n_d!)} \\ &\cdot \sum_{g=0}^{f}(-1)^g\binom{f}{g}\binom{N_w-S_{\mu+\lambda}}{g}g!(K_I-\mu-\nu)^g \\ &\cdot [(N_w-S_{\mu+\lambda}-g)(K-1)]^{f-g}. \end{aligned} \tag{13}$$

Finally, by solving (5) with (13), we derive the stationary probabilities $\{\pi(m,n)\}$, and then throughput can be evaluated as

$$\beta = \sum_{(m,n)\in Z} m\pi(m,n) \quad \text{minipackets/slot.} \tag{14}$$

B. R–T Assignment

The possibility of collision in the R–T assignment will be lower than that in the C-T assignment since collision may occur when two or more packets are transmitted at the same time instant t_i in a slot and are also destined to the same terminal. Note that there exist the same total $m+n-1$ interferers generating the MAI for both assignments, except the $\mu+\nu-1$ interferers using the receiving codes, which affects reception of a collision-free packet. Similar to the C-T assignment, conditioned on the event $C_{i,j}$, we first evaluate the number $N_{R\text{–}T}(K_I, \mu, \nu, \lambda)$ of ways of designating all possible transmission times of those packets belonging to T_X, and their destinations for the event $\Gamma_{kl,mn}$. The number $N_{R\text{–}T}(K_I, \mu, \nu, \lambda)$ is derived in Appendix C as follows:

$$\begin{aligned} &N_{R\text{–}T}(K_I, \mu, \nu, \lambda) \\ &= \sum_{\mathbf{n}\in\Psi}\frac{(\mu+\lambda)!}{\prod_e(b_e!)}\cdot\frac{(\mu+\nu)!}{(\mu+\nu-S_{\mu+\lambda})!\prod_{d=1}^{\mu+\lambda}(n_d!)}\cdot\prod_{d=1}^{\mu+\lambda}N(n_d) \\ &\quad\cdot\sum_{g=0}^{f}(-1)^g\binom{f}{g}\binom{(K_I-2\mu-\nu-\lambda)N_w}{g}g! \\ &\quad\cdot[(K_I-\mu-\lambda-1)N_w-g]^{f-g} \end{aligned} \tag{15}$$

where all parameters have the same meaning as in (10), but the element n_d of $\mathbf{n}$ indicates the number of packets destined to the dth terminal in $T_R \cup T_F$ regardless of collisions, and

$$N(n_d) = \sum_{v=1}^{\min(N_w, n_d)}(-1)^{v-1}\binom{N_w}{v}\binom{n_d}{v}v!(N_w-v)^{n_d-v}. \tag{16}$$

Conditioned on the event $C_{i,j}$, the transition probability $\Pr[\Gamma_{kl,mn} \mid C_{i,j}]$ from (k,l) state to (m,n) state has the expression in (11) with $N_{C-T}(K_I, \mu, \nu, \lambda)$ replaced by $N_{R-T}(K_I, \mu, \nu, \lambda)$. Now, combining this with (8) yields the following transition probability $p_{kl,mn}$:

$$\begin{aligned} &p_{kl,mn} \\ &= \sum_{i=0}^{k}\sum_{j=0}^{l}\sum_{\lambda=0}^{\nu}\binom{k}{i}\binom{l}{j}(1-q)^{i+j}q^{k+l-(i+j)} \\ &\quad\cdot p^{\mu+\nu}(1-p)^{K_I-(\mu+\nu)}[P_h(\mu+\nu, m+n)]^{\mu} \\ &\quad\cdot [1-P_h(\mu+\nu, m+n)]^{\lambda}\left(\frac{1}{(K-1)N_w}\right)^{\mu+\nu} \\ &\quad\cdot \binom{K_I}{\mu+\nu}\binom{K_I-\mu-\nu}{\mu+\lambda}\binom{\mu+\lambda}{\mu}\cdot\sum_{\mathbf{n}\in\Psi}\frac{(\mu+\lambda)!}{\prod_e(b_e!)} \\ &\quad\cdot \frac{(\mu+\nu)!}{(\mu+\nu-S_{\mu+\lambda})!\prod_{d=1}^{\mu+\lambda}(n_d!)}\cdot\prod_{d=1}^{\mu+\lambda}N(n_d) \\ &\quad\cdot \sum_{g=0}^{f}(-1)^g\binom{f}{g}\binom{(K_I-2\mu-\nu-\lambda)N_w}{g}g! \\ &\quad\cdot [(K_I-\mu-\lambda-1)N_w-g]^{f-g}. \end{aligned} \tag{17}$$

Hence, throughput can be evaluated in (14) after obtaining the stationary probabilities $\{\pi(m,n)\}$ through (5) and (17).

C. Special Case ($\bar{L}=1,\ T_p=T_s$)

Each terminal is assumed to generate a packet of fixed length and operate in a slotted mode with $T_s=T_p$. In this case, the Markov chain model is of no use because the network state at the $(t-1)$th slot does not affect that at the tth slot. All K terminals at the beginning of every slot remain in idle state and, hence, throughput is simply given by the average number of active transmitter–receiver pairs during a slot whose transmissions are correctly received in the presence of the MAI.

First, using the transition probability derived in the C-T assignment, we find the probability distribution $f_M(m)$ of active terminal pairs, i.e.,

$$\begin{aligned} &f_M(m) \\ &= \Pr[z(t)=(m,n), n\in\{0,1,\cdots,K-2m\} \\ &\quad \mid z(t-1)=(0,0)] \\ &= \sum_{n=0}^{K-2m}[p_{00,mn}]_{q=0}, \qquad \text{for } m=0,1,\cdots,\min\left(N_w, \left\lfloor\frac{K}{2}\right\rfloor\right) \end{aligned} \tag{18}$$

where $[p_{00,mn}]_{q=0}$ corresponds to the transition probability in (13) when $q=0$ ($\bar{L}=1$). Thus, the probability distribution

$f_M(m)$ becomes

$$f_M(m) = \sum_{n=0}^{K-2m} \sum_{\lambda=0}^{n} p^{m+n}(1-p)^{K-(m+n)} \cdot [P_h(m+n,0)]^m [1 - P_h(m+n,0)]^\lambda \cdot \left(\frac{1}{(K-1)N_w}\right)^{m+n} \binom{K}{m+n} \binom{K-m-n}{m+\lambda} \cdot \binom{m+\lambda}{m} \cdot N_{C-T}(K,m,n,\lambda). \tag{19}$$

Therefore, throughput of the SA/CTOA scheme using the common spreading code can be evaluated as

$$\beta = \sum_{m=0}^{\min(N_w, \lfloor \frac{K}{2} \rfloor)} m f_M(m). \tag{20}$$

Similarly, using $p_{kl,mn}$ derived in the R–T assignment, the probability distribution $f_M(m)$ can be expressed by (18) and (19) for $m = 0, 1, \cdots, \lfloor K/2 \rfloor$ with $N_{C-T}(K_I, \mu, \nu, \lambda)$ replaced by $N_{R-T}(K_I, \mu, \nu, \lambda)$. Thus, when the SA/CTOA scheme is employing, the receiver-based spreading code, throughput is simply given by (20) with $\min(N_w, \lfloor K/2 \rfloor)$ replaced by $\lfloor K/2 \rfloor$.

V. Results

Under the SA/CTOA multiple-access scheme, throughput is evaluated as a function of N_w and $\bar{L}$ for both the C-T and R–T assignments. To show the effect of the MAI, the Barker sequence of $N_h = 13$ was chosen as a special sequence in the header, while the m-sequence for the common code[3] and Gold sequences for the receiving and transmitting codes [10]. The reason for using Gold sequences is that the number of spreading codes is limited (e.g., six for $N = 31$) in the case of the m-sequences because of a small processing gain. The Barker sequence is cyclic shifted to generate different patterns for N_w time windows, which aims at reducing the MAI caused by the headers located in adjacent windows. Table I shows the threshold level $\bar{\kappa}_h = \kappa_h / N_h$ depending on the code assignments for given N_w and Δ, and also the mean-square values $\bar{\sigma}^2_{I_h} = \sigma^2_{I_h}/N_h$, $\bar{\sigma}^2_{I_d} = \sigma^2_{I_d}/N_h$, which are calculated as the average per user per bit for evaluation of $P_h(\alpha, \gamma)$. Note that the mean-square values are getting worse for the R–T assignment with shortened m-sequences from a long m-sequence of period 1023.

First, throughput β of the C-T assignment is plotted in Figs. 2 and 3 for several values of N_w ($\Delta = 5$ if $N_w \le 5$, but $\Delta = 2$ if $N_w = 10$) when $K = 12$, $N = 31$, and $\bar{L} = 5$, 20. Here, nonperfect header capture reflects the effect of the MAI, while perfect header capture ignores the MAI. We see that β increases in proportion to N_w because of lower possibility of collision. It is also observed that for fixed N_w, throughput is enhanced with increased $\bar{L}$, while as $\bar{L}$ increases, the performance gain resulting from increased N_w is relatively reduced. This is because throughput is mainly dependent on collision events for small $\bar{L}$ and N_w, but for large $\bar{L}$ and N_w, it depends on the number of potential transmitter–receiver pairs. In reality, there exist unsuccessfully received packets even though they are collision-free since their destined terminals are not in idle state. It is shown that the effect of the MAI in the C-T assignment is not so significant because of lower values of autocorrelation sidelobes, namely, $\bar{\sigma}^2_{I_h}$ compared to the

[3]The better autocorrelation property of the m-sequence can be exploited for the common code.

TABLE I
THE NORMALIZED MEAN-SQUARE VALUES ($\bar{\sigma}^2_{I_h}$, $\bar{\sigma}^2_{I_d}$) AS THE AVERAGE PER USER PER BIT FOR $\alpha = 6$ AND $\gamma = 11$, AND THERSHOLD LEVEL $\bar{\kappa}_h$ AT $P_f(\alpha, \gamma) = 10^{-6}$ IN (35) (ASSUMED THE WORST CASE OF $\gamma = 12$, AND $\alpha = 2$) REFLECTING THE CODE ASSIGNMENTS AS A FUNCTION OF N_w AND Δ ($N_h = 13$, $N = 31$, NO SAMPLES PER CHIP = 10, SIMULATION RUNS = 5000 SLOTS). (a) C-T ASSIGNMENT. (b) R–T ASSIGNMENT

N_w	Δ	$\bar{\sigma}^2_{I_h}$	$\bar{\sigma}^2_{I_d}$	$\bar{\kappa}_h$
1	5	–	7.654x10^{-3}	0.442
2	5	1.303x10^{-2}	8.926x10^{-3}	0.495
5	5	7.638x10^{-3}	1.032x10^{-2}	0.502
1	2	–	5.917x10^{-3}	0.388
2	2	8.821x10^{-3}	8.818x10^{-3}	0.474
5	2	6.556x10^{-3}	9.664x10^{-3}	0.483
10	2	1.053x10^{-3}	1.034x10^{-2}	0.473

(a)

N_w	Δ	$\bar{\sigma}^2_{I_h}$	$\bar{\sigma}^2_{I_d}$	κ_h
1	5	1.981x10^{-1}	8.010x10^{-3}	0.798
2	5	8.520x10^{-2}	9.060x10^{-3}	0.745
5	5	3.072x10^{-2}	1.025x10^{-2}	0.590
5	5	*4.929x10^{-2}	*1.221x10^{-2}	*0.658
1	2	7.030x10^{-2}	6.247x10^{-3}	0.657
2	2	6.342x10^{-2}	8.527x10^{-3}	0.671
5	2	2.182x10^{-2}	9.436x10^{-3}	0.542
10	2	1.076x10^{-2}	1.026x10^{-2}	0.514

(b)

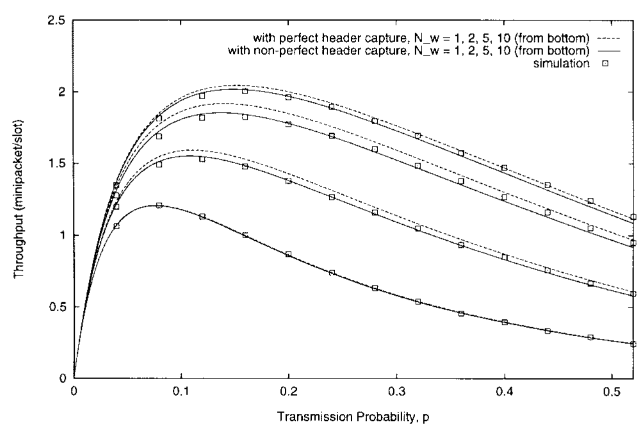

Fig. 2. Throughput β of the SA/CTOA using C-T assignment when $K = 12$, $N = 31$, and $\bar{L} = 5$ ($\Delta = 5$ if $N_w \le 5$, but $\Delta = 2$ if $N_w = 10$).

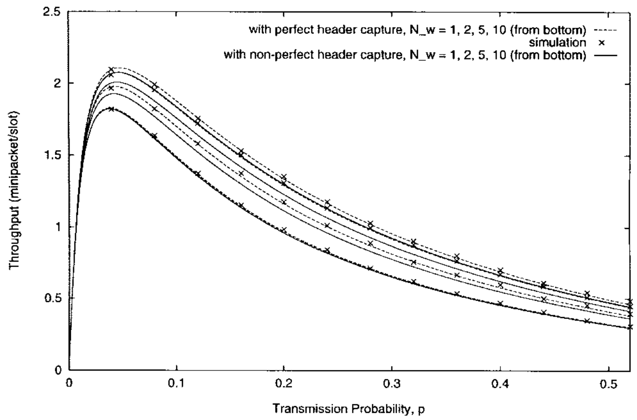

Fig. 3. Throughput β of the SA/CTOA using C-T assignment when $K = 12$, $N = 31$, and $\bar{L} = 20$ ($\Delta = 5$ if $N_w \leq 5$, but $\Delta = 2$ if $N_w = 10$).

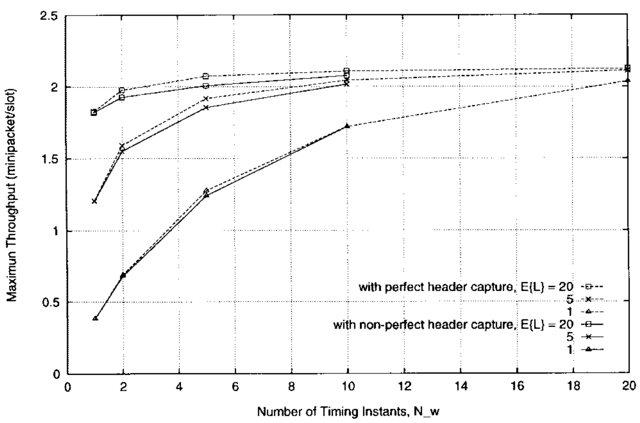

Fig. 4. Maximum throughput versus N_w and $\bar{L}$ for the SA/CTOA using C-T assignment (only perfect header capture for $N_w > 10$).

R–T assignment. As N_w increases, the MAI generated from the headers is getting reduced while the MAI from the data packets increased, thus, the combined effect on throughput is slightly pronounced for $N_w = 5$. In case of $N_w = 1$ (assumed perfect header capture), we can check our numerical results to exactly coincide with those in [4], and simulation results for $\bar{L} = 5$, 20 are well in accord with numerical results, both assumed nonperfect and perfect header captures, respectively. In addition, the behavior of saturation in β can be noticed through Fig. 4, which depicts maximum throughput versus N_w and $\bar{L}$.

Next, Figs. 5 and 6 show β of the R–T assignment as a function of N_w ($\Delta = 5$ if $N_w \leq 5$, but $\Delta = 2$ if $N_w = 10$) when $K = 12$, $N = 31$, and $\bar{L} = 5$, 20. It is obvious that throughput is slightly improved with increased N_w in case of perfect header capture, but the MAI generated from the headers greatly deteriorates throughput for small N_w, unlike the C-T assignment. This is because the R–T assignment has the worse MAI effect caused by the Gold sequences relative to the best common m-sequence, especially for the Barker sequence in the header. As N_w further increases up to ten, the cyclic-shifted Barker sequences located in different windows can be treated like random data and, hence, $\bar{\sigma}^2_{I_h}$ approaches $\bar{\sigma}^2_{I_d}$. Note that β of the R–T assignment ($N_w = 1$) without the MAI is roughly comparable to that of the C-T assignment reflecting the MAI with increased $N_w = 10$. Similarly, we

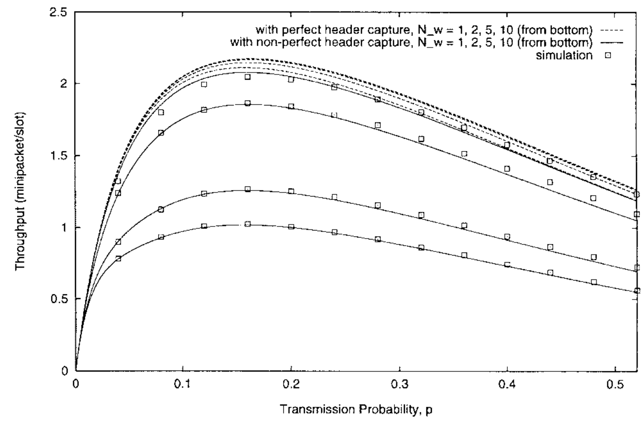

Fig. 5. Throughput β of the SA/CTOA using R–T assignment when $K = 12$, $N = 31$, and $\bar{L} = 5$ ($\Delta = 5$ if $N_w \leq 5$, but $\Delta = 2$ if $N_w = 10$).

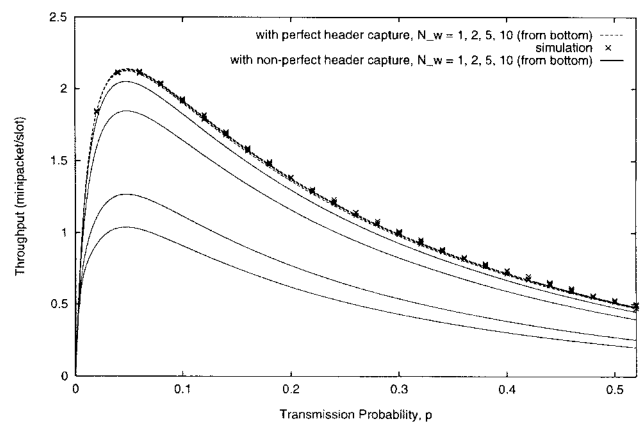

Fig. 6. Throughput β of the SA/CTOA using R–T assignment when $K = 12$, $N = 31$, and $\bar{L} = 20$ ($\Delta = 5$ if $N_w \leq 5$, but $\Delta = 2$ if $N_w = 10$).

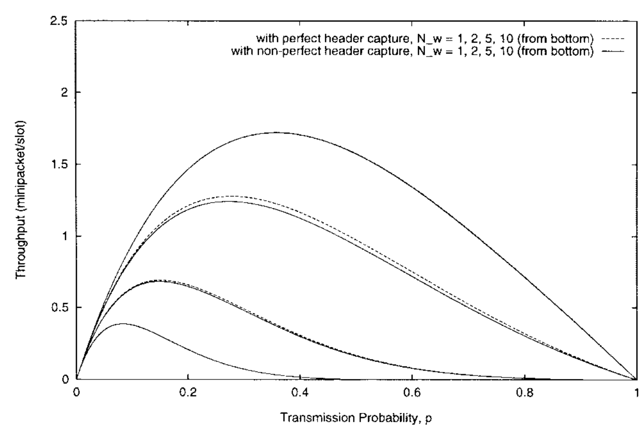

Fig. 7. Throughput β of the SA/CTOA using common code when $K = 12$, $N = 31$, and $\bar{L} = 1$ ($\Delta = 5$ if $N_w \leq 5$, but $\Delta = 2$ if $N_w = 10$).

can compare numerical results of $N_w = 1$ with those in [4], and simulation results for $\bar{L} = 5$, 20 with numerical results.

For the special case of $\bar{L} = 1$ and $T_p = T_s$, the SA/CTOA scheme greatly enhances throughput β in Figs. 7 and 8 as N_w increases. The performance improvement is more significant in case of a common spreading code compared to a receiver-based spreading code. Especially the common-code SA/CTOA scheme with $N_w = 1$ (assumed perfect header capture) is

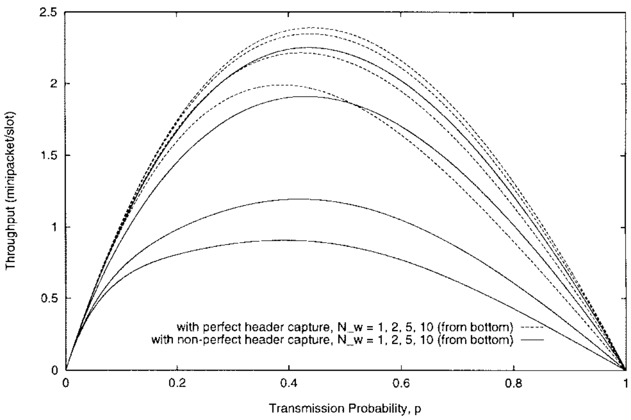

Fig. 8. Throughput β of the SA/CTOA using receiver-based code when $K = 12$, $N = 31$, and $\bar{L} = 1$ ($\Delta = 5$ if $N_w \leq 5$, but $\Delta = 2$ if $N_w = 10$).

equivalent to slotted ALOHA so that β approaches $e^{-1} \cong 0.368$ packets/slot as $K \to \infty$.

VI. Summary and Conclusion

We have proposed a novel multiple-access scheme for quasi-synchronous distributed networks with some timing drift and limited transmission range, which results in small propagation delay and delay spread in a multipath fading channel. This scheme exploits the property of high time resolution offered by direct-sequence spread-spectrum signaling, which permits the receiver to discern simultaneously arrived packet signals with sufficient time offsets. By randomly selecting any one of N_w possible time instants, the proposed scheme can be classified as SA, while the time of arrival can be controlled to locate in an unoccupied time window if the transmission time is solely selected. We refer to it as SA CDMA using controlled time of arrival (SA/CTOA).

It was demonstrated that the C-T assignment combined with the proposed SA/CTOA has superiority over the previous C-T assignment without SA/CTOA [4], and also roughly exhibits a comparable performance to the previous R–T assignment [4], which ignores the MAI ($N_w = 1$). This implies that the C-T assignment can be preferably adopted instead of the R–T assignment when the SA/CTOA scheme is considered since the former provides the advantage of the efficient usage of spreading codes in a code-limited environment. In addition, we observed that the MAI generated from the headers slightly deteriorates throughput for the C-T assignment, while in the case of the R–T assignment, its effect is rather significant for small N_w. Also, the performance improvement becomes saturated as N_w and $\bar{L}$ increase, and with small $N_w = 5$, most of this can be achieved when $K = 12$, $N = 31$, and $\bar{L} > 5$. Based on this observation, the SA/CTOA scheme may be applied to distributed spread-spectrum networks without causing any large system complexity and also extra overhead to maintain rough synchronization among terminals by allowing more timing offset δ.

Appendix A
Derivation of $N_{C-T}(K_I, \mu, \nu, \lambda)$ in (10)

Given the set T_I is partitioned into (T_X, T_R, T_F, T_C), we designate all possible transmission times and destinations for each terminal belonging to T_X to make the event $\Gamma_{kl,mn}$ occur. The number of such mappings can be expressed by

$$N_{C-T}(K_I, \mu, \nu, \lambda) = |\{\langle s, (t_s, d_s)\rangle : s \in T_X \text{s.t } \Gamma_{kl,mn} \text{ occurs}\}| \quad (21)$$

where $(t_s,\ d_s)$ denote the transmission time and destination for a terminal s belonging to T_X.

First, order the terminals in $T_R \cup T_F$ like $1, 2, \cdots, \mu+\lambda$. We note that the $\mu+\nu$ packets from T_X will be transmitted in the tth slot, and one of n_d collision-free packets destined to the dth terminal in $T_R \cup T_F$ is randomly selected for reception. Thus, all possible combinations of $(n_1, n_2, \cdots, n_{\mu+\lambda})$ take the form

$$\Psi' = \{(n_1, n_2, \cdots, n_{\mu+\lambda}) \mid 1 \leq n_d \leq \nu - \lambda + 1, \\ \mu + \lambda \leq S_{\mu+\lambda} \leq \mu + \nu\}. \quad (22)$$

Given $(n_1, n_2, \cdots, n_{\mu+\lambda}) \in \Psi'$, we denote such terminals in T_X by A_d that are associated with n_d collision-free packets. Then, A_0 represents the remaining terminals belonging to T_X, except $\cup_{d=1}^{\mu+\lambda} A_d$. The number of ways of partitioning T_X into $\{A_d\}_{d=0}^{\mu+\lambda}$ becomes

$$M_{\text{part}} = \prod_{d=1}^{\mu+\lambda} \binom{\mu+\nu-S_{d-1}}{n_d} = \frac{(\mu+\nu)!}{(\mu+\nu-S_{\mu+\lambda})! \prod_{d=1}^{\mu+\lambda}(n_d!)}. \quad (23)$$

In addition, possible transmission times t_s for all $s \in \cup_{d=1}^{\mu+\lambda} A_d$ should be selected in order to avoid collisions among $S_{\mu+\lambda}$ packets destined to $T_R \cup T_F$, i.e., $t_{s_1} \neq t_{s_2} : s_1, s_2 \in \cup_{d=1}^{\mu+\lambda} A_d$ and $s_1 \neq s_2$. The number of such selections is given by $\binom{N_w}{S_{\mu+\lambda}} S_{\mu+\lambda}!$.

Next, it remains to designate possible transmission times and destinations for the $f = \mu + \nu - S_{\mu+\lambda}$ terminals belonging to A_0 so that all packets from such terminals do not collide with $S_{\mu+\lambda}$ packets and are unsuccessfully received because of collisions or their destined terminals being not idle. Let H denote the collection of all possible mappings to be able to avoid collisions with $S_{\mu+\lambda}$ packets, and H_r the collection of such mappings to satisfy that a packet from the rth terminal in A_0 is *collision-free* and its destination must be one of $K_I - \mu - \nu$ *receivable* terminals. Using the principle of inclusion and exclusion, the collection H_0 of such mappings of no packet being successfully received has the expression

$$|H_0| = |H| - \left|\bigcup_{r=1}^{f} H_r\right| \\ = |H| - \sum_{r \in A_0} |H_r| + \sum_{r_1 < r_2 \in A_0} |H_{r_1} \cap H_{r_2}| - \cdots \\ + (-1)^g \sum_{r_1 < r_2 < \cdots < r_g \in A_0} |H_{r_1} \cap H_{r_2} \cap \cdots \cap H_{r_g}| \\ + \cdots + (-1)^f \left|\bigcap_{r \in A_0} H_r\right|. \quad (24)$$

From this, we find that

$$|H_0| = \sum_{g=0}^{f}(-1)^g\binom{f}{g}\binom{N_w - S_{\mu+\lambda}}{g}g! \cdot (K_I-\mu-\nu)^g[(N_w - S_{\mu+\lambda} - g)(K-1)]^{f-g}. \quad (25)$$

By the rule of product, $N_{C-T}(K_I,\mu,\nu,\lambda)$ can be written as

$$N_{C-T}(K_I,\mu,\nu,\lambda) = \sum_{(n_1,n_2,\cdots,n_{\mu+\lambda})\in\Psi'}\binom{N_w}{S_{\mu+\lambda}}S_{\mu+\lambda}!\cdot M_{\text{part}}\cdot|H_0|. \quad (26)$$

In order to simplify computation, Ψ' is replaced by Ψ where the element n_d is ordered in an ascending order, i.e., $n_d \le n_{d+1}$. Given $(n_1,n_2,\cdots,n_{\mu+\lambda})\in\Psi$, there are $(\mu+\lambda)!/\prod_e(b_e!)$ different patterns in Ψ' so that $N_{C-T}(K_I,\mu,\nu,\lambda)$ can be rewritten as

$$N_{C-T}(K_I,\mu,\nu,\lambda) = \sum_{(n_1,n_2,\cdots,n_{\mu+\lambda})\in\Psi}\frac{(\mu+\lambda)!}{\prod_e(b_e!)} \cdot \binom{N_w}{S_{\mu+\lambda}}S_{\mu+\lambda}!\cdot M_{\text{part}}\cdot|H_0|. \quad (27)$$

Finally, (10) can be derived by substituting (23) and (25) into (27).

Appendix B
Derivation of $P_h(\alpha,\gamma)$ in (12)

Given α new packets and $\gamma-\alpha$ ongoing packets in a slot, the received signal at the baseband can be expressed by

$$\tilde{r}(t) = \sum_{n=-1}^{N_h}\sqrt{2P}\left[\sum_{k=1}^{\alpha}h_n^{(k)}c_k(t-\tau_k-nT_b)\exp(j\theta_k) + \sum_{k=\alpha+1}^{\gamma}d_n^{(k)}c_k(t-\tau_k-nT_b)\exp(j\theta_k)\right] \quad (28)$$

where P is the received signal power, $(h_0^{(k)},h_1^{(k)},\cdots,h_{N_h-1}^{(k)})$ is a special sequence of length N_h in the header for the kth user, $d_n^{(k)}$ is the kth user's random binary data, and $c_k(t)$ denotes the kth user's spreading-code waveform occupied in $[0,T_b)$. Here, the channel delay τ_k is assumed to be uniformly distributed in the interval $\cup_{i=0}^{N_w-1}[iT_w,iT_w+\Delta]\subset[0,T_b)$ and the unknown signal phase θ_k constant during the interval $[0,(N_h+1)T_b)$ with uniform distribution in $[0,2\pi)$. We note that $h_{-1}^{(k)}=0$ and $h_{N_h}^{(k)}=d_0^{(k)}$ (an address is simply treated like real data).

Suppose the first user is desired and collision-free, then its correlated output with a special sequence in the header is of the form

$$\begin{aligned}\bar{w}(\tilde{\tau}_1) &= \frac{1}{\sqrt{2P}T_b}\int_{\tilde{\tau}_1}^{\tilde{\tau}_1+N_hT_b}\tilde{r}(t)\sum_{n=0}^{N_h-1}h_n^{(1)}c_1(t-\tilde{\tau}_1-nT_b)\,dt\\ &= D(|\tau_1-\tilde{\tau}_1|,\theta_1)+\sum_{k=2}^{\alpha}I_h^{(k)}(|\tau_k-\tilde{\tau}_1|,\theta_k)\\ &\quad+\sum_{k=\alpha+1}^{\gamma}I_d^{(k)}(|\tau_k-\tilde{\tau}_1|,\theta_k)\end{aligned} \quad (29)$$

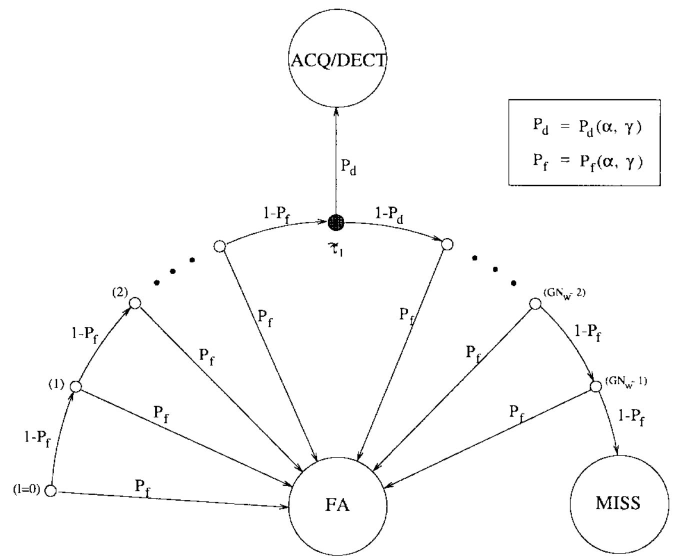

Fig. 9. Flow diagram for timing acquisition and a sequence detection in the header.

where $\tilde{\tau}_1$ is the nearest sampling instant to τ_1. In the above, the desired signal term is approximated to $D(|\tau_1-\tilde{\tau}_1|,\theta_1)\cong N_h(1-\epsilon)\exp(j\theta_1)$ for $\epsilon\triangleq|\tau_1-\tilde{\tau}_1|/T_c$. The interference term due to $\alpha-1$ new packets has the expression

$$I_h^{(k)}(|\tau_k-\tilde{\tau}_1|,\theta_k) = \frac{1}{T_b}\sum_{n=0}^{N_h-1}h_n^{(1)}\left[h_{n+l}^{(k)}f_{1,k}(|\tau_k-\tilde{\tau}_1|) + h_n^{(k)}\hat{f}_{1,k}(|\tau_k-\tilde{\tau}_1|)\right]\exp(j\theta_k) \quad (30)$$

where l is 1 for $\tau_k\le\tilde{\tau}_1$ and -1 otherwise, and the partial correlation functions $f_{1,k}(\tau)$ and $\hat{f}_{1,k}(\tau)$ are defined by $f_{1,k}(\tau)=\int_0^{\tau}c_1(t-\tau+T_b)c_k(t)\,dt$ and $\hat{f}_{1,k}(\tau)=\int_{\tau}^{T_b}c_1(t-\tau)c_k(t)\,dt$. The interference term $I_d^{(k)}(|\tau_k-\tilde{\tau}_1|,\theta_k)$ caused by $\gamma-\alpha$ ongoing packets is given by (30) with $h_m^{(k)}$ replaced by $d_m^{(k)}$ $(m=n,n+l)$.

Conditioned on ϵ, the detection probability of a special sequence in the header is defined by

$$P_d(\alpha,\gamma\mid\epsilon) = \Pr\{|\bar{w}(\tilde{\tau}_1)|\ge\kappa_h\}. \quad (31)$$

Here, κ_h denotes the threshold level for a sequence detection which can be adjusted to maintain a constant false alarm rate for given N_w and Δ. For Gaussian modeled interference, it can be approximated to [11]

$$P_d(\alpha,\gamma\mid\epsilon)\cong Q\left(\frac{N_h(1-\epsilon)}{\sigma_I(\alpha,\gamma)},\frac{\kappa_h}{\sigma_I(\alpha,\gamma)}\right) \quad (32)$$

where $Q(\cdot,\cdot)$ is the Marcum Q-function and the mean-square value $\sigma_I^2(\alpha,\gamma)$ becomes

$$\sigma_I^2(\alpha,\gamma) = (\alpha-1)\cdot\mathbf{E}\{\mathrm{Re}^2[I_h^{(k)}(|\tau_k-\tilde{\tau}_1|,\theta_k)]\} + (\gamma-\alpha)\cdot\mathbf{E}\{\mathrm{Re}^2[I_d^{(k)}(|\tau_k-\tilde{\tau}_1|,\theta_k)]\}. \quad (33)$$

Here, the mean-square values $\sigma_{I_h}^2=\mathbf{E}\{\mathrm{Re}^2[I_h^{(k)}(\cdot)]\}$ and $\sigma_{I_d}^2=\mathbf{E}\{\mathrm{Re}^2[I_d^{(k)}(\cdot)]\}$ are evaluated through simulation as a function of N_w and Δ since these values depend on the C-T and R–T assignments, and $\tau_k\in\cup_{i=0}^{N_w-1}[iT_w,iT_w+\Delta]$.

For a serial search mode in N_w time windows, the probability of timing acquisition being obtained with a sequence detection, namely, $P_h(\alpha, \gamma)$ can be derived from the flow diagram in Fig. 9 where a chip-rate sampling is assumed and the false alarm probability $P_f(\alpha, \gamma)$ is approximated to

$$P_f(\alpha,\gamma) \cong \exp\left[-\frac{\kappa_h^2}{2\left[\alpha\sigma_{I_h}^2 + (\gamma-\alpha)\sigma_{I_d}^2\right]}\right]. \quad (34)$$

APPENDIX C
DERIVATION OF $N_{R\text{–}T}(K_I, \mu, \nu, \lambda)$ IN (15)

For the R–T assignment, we note that the element n_d of Ψ denotes the number of packets destined to the dth terminal in $T_R \cup T_F$ regardless of collisions. However, at least one of n_d packets must be collision-free, i.e., the time window $[t_i, t_i+\Delta]$ at which the packet may be received is not occupied by other $n_d - 1$ packet transmissions.

Let us define P_i by a set containing all combinations of placing n_d packets into N_w time windows such that

$$P_i = \left\{ m_i = 1, \qquad \sum_{\substack{k=0\\k\neq i}}^{N_w-1} m_k = n_d - 1 \right\}$$

in which m_i is the number of packets received at the time window $[t_i, t_i + \Delta]$, $i \in I \triangleq \{0, 1, \cdots, N_w - 1\}$. Then, the number of ways of designating the transmission times of n_d packets so as to have at least one collision-free packet is equivalent to

$$\begin{aligned} N(n_d) &= \left| \bigcup_{i=0}^{N_w-1} P_i \right| \\ &= \sum_{i\in I} |P_i| - \sum_{i_1<i_2\in I} \left|P_{i_1} \cap P_{i_2}\right| + \cdots \\ &\quad + (-1)^{h-1} \sum_{i_1<i_2<\cdots<i_h\in I} \left|P_{i_1} \cap P_{i_2} \cap \cdots \cap P_{i_h}\right| \end{aligned} \quad (35)$$

where $h = \min(N_w, n_d)$. Hence, the number $N(n_d)$ can be derived as (16). Also, the number of ways of partitioning T_X into the subsets $\{A_d\}_{d=0}^{\mu+\lambda}$ is equal to M_{part} in Appendix A.

We next proceed to count the number of ways of designating possible transmission times and destinations, except $T_R \cup T_F$ to avoid overcount for the f terminals in A_0 so that all packets from such terminals are unsuccessfully received because of collisions or their destined terminals being not idle. Similarly, as in Appendix A, using the principle of inclusion and exclusion, the number H_0 of such mappings of no packet being successfully received is given by

$$\begin{aligned} |H_0| = \sum_{g=0}^{f} (-1)^g \binom{f}{g} \binom{(K_I - 2\mu - \nu - \lambda)N_w}{g} g! \\ \cdot[(K - \mu - \lambda - 1)N_w - g]^{f-g}. \end{aligned} \quad (36)$$

Hence, the number $N_{R\text{–}T}(K_I, \mu, \nu, \lambda)$ can be expressed by

$$\begin{aligned} N_{R\text{–}T}&(K_I, \mu, \nu, \lambda) \\ &= \sum_{(n_1,n_2,\cdots,n_{\mu+\lambda})\in\Psi} \frac{(\mu+\lambda)!}{\prod_e (b_e!)} \cdot M_{\text{part}} \cdot \prod_{d=1}^{\mu+\lambda} N(n_d) \cdot |H_0|. \end{aligned} \quad (37)$$

Combining (16), (23), and (36) with (37) yields (15).

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