A Fast UWB Timing Acquisition Scheme with Robustness to Multiple Access Interference

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Abstract— **The major challenges confronted in the timing acquisition for Ultra-wideband (UWB) communication systems are enormous search space, extremely low signal power and the heavy multiple access interference (MAI) environments. Since the acquisition methods with the conventional preamble structure suffer severe performance degradation in the presence of interference, we will present a novel preamble structure in this paper where the preambles for different users have unequal symbol durations. The proposed structure associated with any acquisition algorithm can improve the accuracy of timing estimation and shorten the acquisition time significantly for multi-user systems, which will be demonstrated by both theoretical analyses and simulation results.**

I. INTRODUCTION

Ultra-wideband communications have recently drawn great attention in academic and industrial society for their attractive features such as immense spread spectrum gain, large multiple-access capability, high multi-path fading immunity, low probability of detection and interception, low-cost implementation and so on [1]. In order to gain the unique merits of UWB radio, timing acquisition is one of the most critical issues.

In most of the systems, timing acquisition is achieved by transmitting a training sequence (*i.e.* preamble) at the beginning of each data burst. As for UWB communication systems, to reach reliable synchronization performance, the training sequence is usually very long. In UWB systems, the large search space due to the fine resolution of ultra-short pulse leads to a long acquisition time. Moreover, the relatively low transmission power, which is further scattered onto multipath components, calls for transmitting repeated symbols in the preamble field and averaging received signals in these symbols to achieve an acceptable the acquisition performance [1–4]. In multiple access systems, low cross-correlation time-hopping (TH) codes are employed, much longer TH codes are often necessary for the preamble to mitigate MAI in the acquisition stage [5]. As a result, the excessive long training sequence not only makes the system susceptive to time jitter or time-varying channel, but also increases the collision probability among the signals from multiple users, which will reduce the network efficiency significantly.

The acquisition performance can be improved by designing better preambles and synchronization algorithms. Recent studies focus on achieving fast acquisition through more effective search strategies [6–8] and preamble structures to reduce the search space [5,9,10]. In order to increase the timing estimation accuracy in low Signal-to-Noise Ratio (SNR) conditions, several candidate pseudo noise (PN) codes for preamble are compared in [11], optimal estimation criteria are investigated in [2,3,12], and efficient energy capture methods are developed in [4, 8]. These methods are mainly designed for single user systems, and are not capable of suppressing MAI. Several methods [3, 4, 6] take into account the MAI led to by the data from interfering users, but they suffer considerable performance degradation when the interference is from preamble field of other users, since the preamble is generally composed of many repeated symbols. Furthermore, unlike in traditional spread spectrum systems, the training sequences in UWB systems are so long that there is large preamble collision probability, thus the influence from them cannot be neglected. In order to prevent dramatic performance loss in multi-user systems, it is indispensable to study an acquisition scheme having robustness to various MAI, especially interference caused by preambles from other users.

The purpose of this paper is to design a new preamble structure where the symbol duration of each user is unequal. Any synchronization algorithm with this preamble structure can increase Signal to Interference-and-Noise Ratio (SINR) as well as reduce the required preamble length, simply by averaging the received signals in the preamble field. The acquisition performance with the proposed preamble structure is evaluated by SINR after averaging, and further demonstrated by simulations with performance metric of the false detection probability (FDP) and bit error rate (BER).

This paper is organized as follows. Section II describes the signal models. Section III presents the designed preamble structure and Section IV derives the SINR after averaging. The simulations are shown in Section V, and conclusions are provided in the last section.

II. SIGNAL MODELS

In UWB impulse radio (IR) multiple access systems, each symbol is transmitted over N_f frames of the duration T_f, with one pulse $p(t)$ per frame. The pulse duration T_p is usually at the nanosecond scale. To separate users, for the user k, TH code $\{c_i^k\}_{i=0}^{N_f-1}$ provides an additional shift $c_i^k T_c$ ($c_i^k \in [0, N_c-1]$) to each pulse, where T_c denotes chip duration and one frame consists of $N_c = T_f/T_c$ chips. The transmit signal waveform in a symbol duration before modulation is $p_s^k(t) = \sum_{i=0}^{N_f-1} p(t - iT_f - c_i^k T_c)$, which usually has equal duration $T_s = N_f T_f$ and is normalized to have unit energy $\int_0^{T_s} |p_s^k(t)|^2 dt = 1$ in the existing systems [13]. In this

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study, we consider that the symbol duration of different users is unequal, which is expressed by T_s^k. To distinguish our duration-unequal preamble structure, we will call the duration-equal structure as the conventional structure in the context. The transmitted UWB waveform of the user k is

$$u^k(t) = \sqrt{\varepsilon^k} \sum_{n=-\infty}^{\infty} a_n^k p_s^k(t - nT_s^k - b_n^k \xi), \qquad (1)$$

where ε^k expresses transmission energy per symbol, $a_n^k \in \{\pm 1\}$ and $b_n^k \in \{0, 1\}$ represent the modulation information in pulse amplitude modulation (PAM) and pulse position modulation (PPM), respectively, and ξ is the PPM modulation index, *i.e.* the time difference between the two modulated positions.

For the user k, signal $u^k(t)$ propagates through L^k resolvable UWB channel paths with attenuations α_l^k and delays τ_l^k. Define the relative delay of the lth path as $\tau_{l,0}^k = \tau_l^k - \tau_0^k$. In multipath channels, the correct timing area is not a specific position. Instead, it is a range of $[0, \tau_{\max}^k]$, where $\tau_{\max}^k = \tau_{L^k,0}^k$ is the maximum delay spread. Then the composite receive signature waveform is $g_s^k(t) = \sum_{l=0}^{L^k-1} \alpha_l^k p_s^k(t - \tau_{l,0}^k)$. To avoid the inter-symbol interference (ISI), we consider $T_f > \tau_{L^k-1,0}^k + \xi$, then $g_s^k(t) = 0$ when $t \notin [0, T_s^k)$.

When N_u transmitters are active in the multiple-access systems, the received signal can be expressed by

$$r(t) = \sum_{k=1}^{N_u} \sqrt{\varepsilon^k} \sum_{n=-\infty}^{\infty} a_n^k g_s^k(t - nT_s^k - \phi_n^k) + n(t), \qquad (2)$$

where $\phi_n^k = \tau_0^k + b_n^k \xi$ represents the relative delay within the nth symbol of user k. $n(t)$ is the zero-mean Gaussian noise with double-sided power spectral density (PSD) $N_0/2$.

Let user d be the desired user, then the desired preamble signal $s(t) = \sqrt{\varepsilon^d} \sum_{n=-\infty}^{\infty} g_s^d(t - nT_s^d - \phi_n^d)$, and the total interference from other $N_u - 1$ users $I(t) = \sum_{k=1,k\neq d}^{N_u} I^k(t)$, where $I^k(t) = \sqrt{\varepsilon^k} \sum_{n=-\infty}^{\infty} a_n^k g_s^k(t - nT_s^k - \phi_n^k)$.

According to the type of interference source, the modulation information of $I^k(t)$ is listed in Table I. In the following context, we will call ① as preamble interference, ② and ③ as data interference.

III. PREAMBLE DESIGN AND ACQUISITION SCHEME

Starting from a normal method of increasing SNR for the acquisition stage, we will point out the problem of the conventional preamble structure when the preamble interference exists, and propose a novel preamble structure in this section.

A. A Normal Approach to Enhance SNR

By making use of the repeated signal structure in the preamble field, SNR can be increased simply by averaging the received signal over several symbol durations. The received signal after being averaged over N successive symbols is

$$\bar{r}(t) = \frac{1}{N} \sum_{m=0}^{N-1} r(t + mT_s^d) = \bar{s}_N(t) + \sum_{\substack{k=1 \\ k \neq d}}^{N_u-1} \bar{I}_N^k(t) + \bar{n}_N(t), \qquad (3)$$

TABLE I

THE MODULATION INFORMATION OF INTERFERENCE

Sign	Interference source	Modulation Information
①	Preamble	$a_n^k = 1, b_n^k = 0$
②	PAM Data	$a_n^k \in \{\pm 1\}$, $b_n^k = 0$
③	PPM Data	$a_n^k = 1$, $b_n^k \in \{0, 1\}$

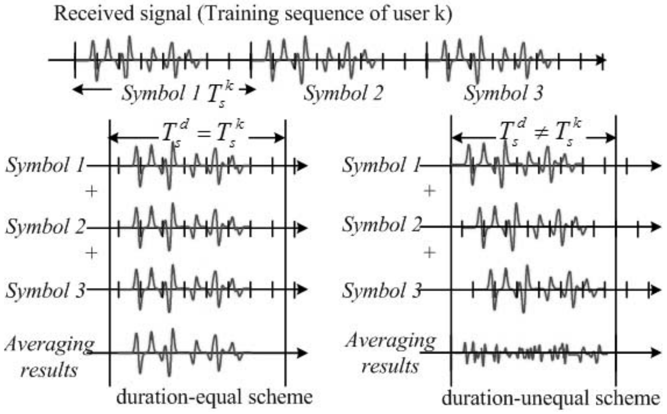

Fig. 1. Averaging results of interference preambles for two schemes.

where $t \in [0, T_s^d)$, $\bar{s}_N(t)$, $\bar{n}_N(t)$, and $\bar{I}_N^k(t)$ represent the desired signal, noise and the interference signal from the user k after averaging, respectively, and

$$\bar{s}_N(t) = \frac{\sqrt{\varepsilon^d}}{N} \sum_{m=0}^{N-1} \sum_{n=-\infty}^{\infty} g_s^d(t - (n-m)T_s^d - \tau_0^d). \qquad (4)$$

Since $g_s^d(t) = 0$ when $t \notin [0, T_s^d)$, the possible non-zero summands in (4) are associated only with either $n = m$ or $n = m - 1$, so (4) becomes

$$\begin{aligned} \bar{s}_N(t) &= \frac{\sqrt{\varepsilon^d}}{N} \left\{ \sum_{m=0}^{N-1} g_s^d(t - \tau_0^d) + \sum_{m=-1}^{N-2} g_s^d(t + T_s^d - \tau_0^d) \right\} \\ &= \sqrt{\varepsilon^d} \tilde{g}_s^d(t, \tau_0^d), \end{aligned} \qquad (5)$$

where $\tilde{g}_s^k(t, \tau) = \{g_s^k(t - \tau) + g_s^k(t + T_s^d - \tau)\}$, $t \in [0, T_s^d)$ is a circularly-shifted (by τ) version of $g_s^k(t)$, $k \in [1, N_u]$.

Considering the signal in $t \in [0, T_s^d)$, (4) and (5) imply that the desired signal remains unchanged, and the signal power does not vary after averaging. The noise variance, however, becomes only $1/N$ of its original value. Therefore, under the interference-free condition, the averaging operation can increase SNR to improve the acquisition performance effectively.

B. Preamble Design

According to (3), the averaging operation is carried out over the received signals with the symbol duration of the desired user. In the conventional preamble structure, the symbol durations are equal for all users, hence the symbols of preamble interference have identical polarities and positions. As shown in Fig.1, the power of preamble interference will not vary

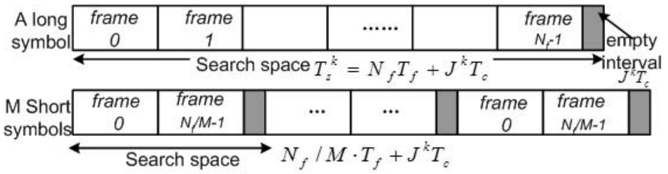

Fig. 2. New training symbol with smaller search space than the original one.

after averaging. Therefore, in this structure, averaging can only increase SNR rather than Signal-to-Interference Radio (SIR).

To solve this problem, we propose a new preamble structure where the symbol duration of each user is unequal. Since the repeated period of the preamble interference (*i.e.* symbol duration of interfering user T_s^k) is different from the interval for averaging (*i.e.* symbol duration of desired user T_s^d), the training symbols from other users have different positions. Thus, averaging will reduce the interference power by eliminating some pulses with opposite polarity.

Changing symbol duration is easy to implement. For instance, we can insert an empty interval of $J^kT_c(J^k \neq J^l, \forall k, l \in [1, N_u], k \neq l)$ between symbols, then the symbol duration of user k becomes $T_s^k = T_s + J^kT_c$.

For the consistence of the signal structure, we can make the symbols in the data field have identical durations to those in the preamble field.

The large search space is another issue in the UWB acquisition stage. To speed up the acquisition process, a short TH code is usually employed for preamble. In the conventional structure, when MAI exists, the fast acquisition performance often deteriorates due to its poor capability of suppressing MAI. Whereas, with the proposed structure, by replacing the original long training sequence by M new repeated TH codes as Fig. 2, there will be no sacrifice of performance in the presence of MAI. Since the search space is M times smaller than that before, the acquisition time can be shortened efficiently. Through the analysis in the next section, we will show that the proposed structure can effectively deal with the issues caused by low SNR, large search space and multi-user interference at the same time.

C. Synchronization Algorithm

The proposed preamble structure can perform well by combining with any acquisition algorithm when MAI exists. Without loss of generality, we will employ maximum likelihood (ML) timing acquisition method proposed in [3] to illustrate our new structure. In the ML method, the output of a correlation of the local template with the received signal after averaging, is combined with equal gain and the length of maximum delay spread, so the estimate of timing is obtained by

$$\hat{\tau}_0^d = \arg \max_{\tau \in [0, T_s^d)} \left\{ \sum_{l=0}^{L^d-1} |\psi((lT_c - \tau) \mod T_s^d)|^2 \right\}, \quad (6)$$

where $\psi(t) = \int_0^{T_s^d} \bar{r}_N(\gamma) p_s^d((t-\gamma) \mod T_s^d) d\gamma$ is the output of the sliding correlator.

IV. PERFORMANCE ANALYSIS

Since we will study the influence of preamble structure on acquisition performance rather than the performance of synchronization method itself, we select the SINR after averaging as the performance metric.

Define P_s, P_n and P_I^k as the power of the desired signal, noise and interference from the user k, and $\overline{P}_{s,N}$, $\overline{P}_{n,N}$ and $\overline{P}_{I,N}^k$ as the power of those after averaging, respectively. Then the SINR after averaging over N consecutive symbols is

$$\overline{SINR} = \frac{\overline{P}_{s,N}}{\overline{P}_{n,N} + \sum\limits_{\substack{k=1,\\ k \neq d}}^{N_u} \overline{P}_{I,N}^k} = \frac{P_s}{\frac{P_n}{N} + \sum\limits_{\substack{k=1,\\ k \neq d}}^{N_u} \eta_N^k P_I^k}, \quad (7)$$

where $\eta_N^k = \overline{P}_{I,N}^k / P_I^k$ is defined as the processing gain over interference from user k by averaging.

Similar to the desired signal, the interference caused by the user k after the N times averaging is

$$\begin{aligned} \bar{I}_N^k(t) &= \frac{\sqrt{\varepsilon^k}}{N} \sum_{m=0}^{N-1} \sum_{n=-\infty}^{\infty} a_n^k g_s^k(t - (nT_s^k - mT_s^d) - \phi_m^k) \\ &= \frac{\sqrt{\varepsilon^k}}{N} \sum_{m=0}^{N-1} a_m^k \tilde{g}_s^k(t, \lambda_m^k) + \zeta, \end{aligned} \quad (8)$$

where $t \in [0, T_s^d)$, $\lambda_m^k = m(T_s^k - T_s^d) + \phi_m^k$ represents the relative shift of user k's mth symbol in averaging, $k \in [1, N_u]$, and $\zeta = \sqrt{\varepsilon^k}/N \cdot \{a_{-1}^k g_s^k(t - \lambda_{-1}^k) + a_N^k g_s^k(t - \lambda_N^k)\}$.

When N is large enough, ζ in (8) can be ignored, then the interference power after averaging is obtained by

$$\begin{aligned} \overline{P}_{I,N}^k &= \frac{1}{T_s^d} \int_0^{T_s^d} |\bar{I}_N^k(t)|^2 dt \\ &= \frac{\varepsilon^k}{N^2 T_s^d} \mathbf{E}\left\{ \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} a_m^k a_n^k \int_0^{T_s^d} \tilde{g}_s^k(t, \lambda_m^k) \tilde{g}_s^k(t, \lambda_n^k) dt \right\} \\ &= \frac{\varepsilon^k}{N^2 T_s^d} \int_0^{T_s^d} |g_s^k(t)|^2 dt \cdot \mathbf{E}\left\{ \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} a_m^k a_n^k \rho_{m,n} \right\}, \end{aligned} \quad (9)$$

where $\mathbf{E}\{*\}$ represents the expectation operation, $\rho_{m,n}^k = R(\lambda_m^k, \lambda_n^k)$ is the normalized correlation coefficient between $\tilde{g}_s^k(t, \lambda_m^k)$ and $\tilde{g}_s^k(t, \lambda_n^k)$, $R(\tau)$ is the normalized auto-correlation function of $\tilde{g}_s^k(t, \tau)$, in which $\lambda_m^k = m\triangle_{k,d} + \tau_0^k + b_m^k \xi$, $\triangle_{k,d} = T_s^k - T_s^d = (J^k - J^d)T_c$, which is the difference of symbol duration between the user k and d, $k \neq d$.

When $T_s^k >> \Delta_{k,d}$, T_s^k can be approximated as T_d^k, then the interference power before averaging becomes $P_I^k = \varepsilon^k / T_s^k \cdot \int_0^{T_s^k} |g_s^k(t)|^2 dt \approx \varepsilon^k / T_s^d \cdot \int_0^{T_s^d} |g_s^k(t)|^2 dt$. Hence, the processing gain over interference from the user k introduced by averaging is

$$\eta_N^k = \frac{\overline{P}_{I,N}^k}{P_I^k} = \frac{1}{N^2} \cdot \mathbf{E}\left\{ \sum_{m=0}^{N-1} \sum_{n=0}^{N-1} a_m^k a_n^k \rho_{m,n}^k \right\}. \quad (10)$$

Since $\tilde{g}_s^k(t, \tau)$ is a spread spectrum signal, it is reasonable to assume that $\tilde{g}_s^k(t, \tau)$ has the ideal auto-correlation function,

TABLE II

THE RATIO OF INTERFERENCE POWER AFTER AND BEFORE AVERAGING

Interference type	Duration-equal	Duration-unequal
Preamble	1	$\frac{1}{N}$
PAM Data	$\sum_{l=0}^{N} \frac{1}{2^N} \binom{N}{l} \frac{(N-2l)^2}{N^2}$	$\frac{1}{N}$
PPM Data	$\sum_{l=0}^{N} \frac{1}{2^N} \binom{N}{l} \frac{(N-l)^2+(l)^2}{N^2}$	$\frac{1}{N}$

which is independent on the pulse $p(t)$, then the normalized correlation coefficient is

$$\rho_{m,n}^{k} = \delta((m-n)\Delta_{k,d} + (b_m^k - b_n^k)\xi). \tag{11}$$

Shown in Table I, consider the modulation information and the characteristic of preamble structure, we can obtain the processing gain η_N^k with various interference sources from (11) and (10). Due to the lack of space, we summarize the developed results in Table II. It is shown that the proposed structure has identical processing gain for all types of interferences, and is more robust to interference than the conventional structure.

V. SIMULATION RESULTS

In this section, we will validate our analysis and compare the acquisition performance of the proposed structure with that of the conventional structure through Monte-Carlo simulations for various interferences, SNR, averaging times and the length of TH codes applied for preamble. The acquisition performance is measured by the false detection probability, while the ML algorithm presented in [3] is employed. The false detection is defined as the timing estimation error $\Delta\tau = |\hat{\tau}_0^d - \tau_0^d|$ being larger than the maximum delay spread $\tau_{\max}^d$. The CM (channel model)1 [14] is employed as the UWB multipath channel, in which the $\tau_{\max}$ is almost 50ns. To further illustrate the influence of timing error on system performance, we also evaluate the BER for a system with PAM modulation and partial Rake (PRake) receiver with 10 fingers.

In all the simulations, the $p(t)$ is chosen as a typical pulse function (*e.g.* the second derivative of a Gaussian) with width $T_p = 1$ns. In addition, we select the frame and chip interval as $T_f = 100$ns and $T_c = 1$ns, respectively. The length of TH code $N_f = 12$. In the conventional structure, the symbol duration of each user is equal to $T_s^k = T_s = 1.2\mu$s. By contrast, in the proposed structure, $J^k = k$, then $T_s^k = T_s + kT_c$, $k \in [1, N_u]$. Quadratic Congruence codes [15] are considered as the TH codes in (1) due to their good characteristics of auto-correlation and cross-correlation. Consider that there are 10 interfering users ($N_u = 11$) with equal powers, and the SIR of a single user is 0dB, then the total SIR becomes -10dB. To separate the impact of timing error on the BER from that of the data field interference, suppose that the data field of the desired user is interference-free in the simulations.

Fig. 3 illustrates the processing gain versus the averaging times N. It is obvious that the numerical results (legend *(N)*) agree well with the simulations (legend *(S)*). As shown in Fig. 3, the processing gains with the proposed structure are all identical for various interferences, while the gains with the conventional structure vary with the interference types. The capability of the duration-equal structure to suppress interference is only 0dB for preamble interference and no more than 3dB for PPM data interference, while it grows when N increases for PAM data interference. Furthermore, its best performance is the same as that of the purposed structure.

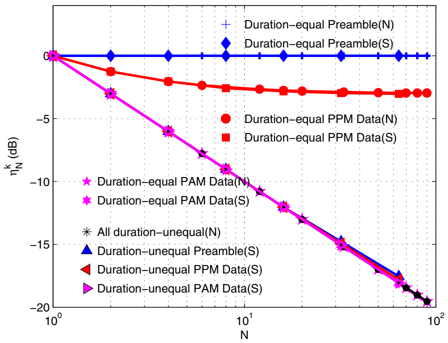

Fig. 3. The processing gain $\eta_N^k \sim$ averaging times N

Figs. 4∼6 show the impact of preamble interference on the acquisition performance of different preamble structures, which are illustrated by the SINR after averaging, the FDP and BER, respectively, where the results without interference are taken for reference. In Fig. 6, legend *PAM* denotes the performance of coherent PAM demodulation, which shows the upper bound of the BER performance, the difference between other results and *PAM* reflects the influence of the timing error.

In the interference-free condition, the performance of acquisition and demodulation can be improved by increasing either the averaging times or the SNR. However, the SINR is hard to be further increased through these methods when preamble interference exists. Hence, the FDP and BER curves for the conventional structure arrive at an error floor. Whereas, in the same scenario with the proposed structure, the SINR after averaging can be increased. As a result, both acquisition and demodulation performance can be improved with the increment of the average times. Moreover, these performance is close to the results without any interference when the averaging times is large enough. These results reveal that the developed scheme is able to suppress interference remarkably merely by the averaging operation.

It was shown in Section III and Fig. 2 that the search space is approximately reduced to T_s/M, hence the bigger the M is, the faster the acquisition process can be achieved. In the presented preamble structure, the BER with different search space are compared in Fig. 7 when the preamble interference exists. We can find that the BER of $M = 1$ and $M = 3$ are quite close underlying the identical averaging times and SNR condition. The BER for $M = 3$ is even a little better, which is contributed by the property of the TH code. It can be concluded that the proposed structure can reduce search space thus the acquisition time, without any performance loss even when MAI exists.

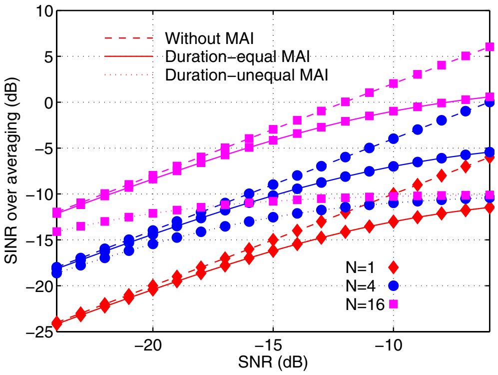

Fig. 4. $\overline{SINR} \sim SNR$ (SNR = E_b/N_0-30.8dB(spreading gain).)

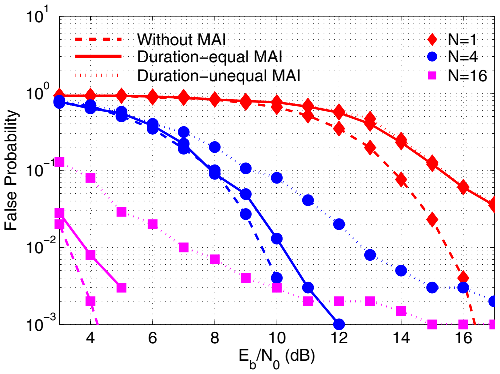

Fig. 5. False Detection Probability $\sim E_b/N_0$

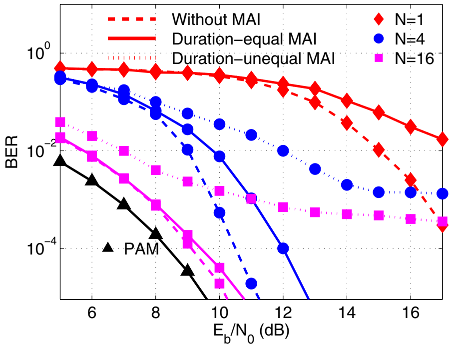

Fig. 6. $BER \sim E_b/N_0$

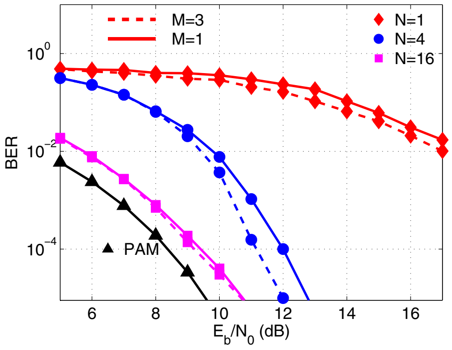

Fig. 7. $BER \sim E_b/N_0$ (search space $\approx T_s/M$.)

VI. Conclusion

In this paper, we present a new preamble structure where different users have unequal symbol durations.

Through the analysis of the SINR after averaging and the simulations, we can reach following conclusions.

1) With the conventional duration-equal structure, the irreducible power of preamble interference usually introduces significant degradation of acquisition performance, while the proposed structure can effectively mitigate interference simply by averaging.
2) Fast acquisition and robustness to MAI are hard to achieve at the same time with the conventional preamble structure, but the new structure can maintain better acquisition performance in the presence of MAI meanwhile can reduce the acquisition time.
3) The designed structure is independent of the synchronization algorithm and TH code used in preamble, thus it is able to be applied for many UWB acquisition schemes to improve their robustness to MAI.

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