A New UWB Synchronization Scheme Using Multipath Components Jointly

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***Abstract*— In ultra-wideband (UWB) systems, conventionally, the synchronization is to align time phases of a locally generated template and any of multipath components to within an allowable range. However, the synchronization with a low-power multipath component could incur significant performance degradation in receiver operation (e.g., detection) after the synchronization. On the other hand, the synchronization with a high-power multipath component can improve the performance in receiver operation after the synchronization. Generally, the first one among multipath components has the largest power. Thus, the synchronization with the first path component can make better performance than that with a low-power component in receiver operations after the synchronization. Based on which, we first propose an optimal decision rule based on a maximum likelihood (ML) approach, and then, develope a simpler suboptimal decision rule for selecting the first path component. Simulation results show that the optimal and suboptimal decision rules have better performance than the conventional decision rule in UWB multipath channels.**

***Index Terms*— UWB, multipath component, synchronization, optimal decision rule, suboptimal decision rule**

I. Introduction

Ultra-wideband (UWB) systems are high data rate systems using short pulses with a relatively large bandwidth [1], [2] and aim to low power transmission. Thus, UWB systems can be applicable to wireless personal area network (WPAN) and many researches have been studied. For those application of UWB systems, the data must be demodulated correctly, and for the successful demodulation, the synchronization must be achieved essentially. Therefore, the synchronization is one of the most important steps for UWB systems.

Since UWB signals have low power, UWB systems require a long preamble and have wider search space than the conventional communication systems [3]. Thus, UWB systems spend longer time than the conventional communication systems in synchronization process. To reduce the synchronization time in UWB systems, conventionally, the synchronization is defined as aligning time phases of a locally generated template and any of received multipath components to within an allowable range, and using this definition, many synchronization schemes are studied to reduce the synchronization time [4]-[9]. These schemes can reduce the synchronization time effectively, however, since each multipath component has different power, they cannot guarantee good performance in receiver operations after the synchronization. The synchronization with a low-power multipath component could incur significant performance degradation in receiver operations (e.g., detection) after the synchronization. Generally, the first one among multipath components has the largest power. In other words, the synchronization with the first path component can make better performance than that with a low-power component in receiver operations after the synchronization.

In this paper, we define the synchronization as aligning time phases of a template and the first path component, and propose the associated synchronization decision rules. First, an optimal decision rule is proposed based on a maximum-likelihood (ML) approach. However, since the optimal decision rule requires channel information, it is difficult to implement. Thus, a simpler suboptimal decision rule is developed. The simulation results show that the proposed decision rules provide a substantial performance improvement over the conventional decision rule.

This paper is organized as follows. Section II describes the system model. In Section III, the optimal and suboptimal decision rules are proposed, and in Section IV, we introduce the conventional decision rule. Section V presents the simulation results over several channel models and Section VI concludes this paper.

II. System Description

A. Signal Model

In this paper, we consider a direct-sequence (DS)-UWB system in the institute of electrical and electronics engineers (IEEE) 802.15.3a channel model. In the synchronization process, we assume that an unmodulated signal is transmitted. Then, the transmitted signal in a DS-UWB system can be expressed as

$$s(t) = \sqrt{E_c} \sum_{i=1}^{N_c} c_i p(t-(i-1)T_c), \qquad (1)$$

where E_c is the signal energy; $c_i \in \{1, -1\}$ is the ith chip of a pseudo noise (PN) code with a period of N_c chips; T_c is the chip duration; $p(t)$ is the second derivative Gaussian pulse with a duration of T_c, which is the most widely used pulse model for UWB system; and can be expressed as [4], [9]

$$p(t) = \sqrt{\frac{4}{3t_\psi\sqrt{\pi}}}\left(1-\left(\frac{t}{t_\psi}\right)^2\right)\exp\left(-\frac{1}{2}\left(\frac{t}{t_\psi}\right)^2\right), \qquad (2)$$

where t_ψ is the effective time width of the pulse duration.

The received signal $r(t)$ can be expressed as

$$r(t) = s(t) * h(t) + w(t) \tag{3}$$

where $*$ denotes the convolution operation, $h(t)$ is the channel impulse response, and $w(t)$ is an additive white Gaussian noise (AWGN) process with zero mean and one-sided power spectral density N_0.

B. Channel Model

IEEE 802.15.3a channel model has the following discrete impulse response [2], [9], [10].

$$h(t) = \sum_{l=1}^{L} \sum_{k=1}^{K} \alpha_{k,l} \delta(t - T_l - \tau_{k,l}). \tag{4}$$

where L and K denote the numbers of clusters and multipaths within one cluster, respectively; $\delta(t)$ is the Dirac-delta function; $\alpha_{k,l}$ and $\tau_{k,l}$ are the channel coefficient and time delay, respectively, of the kth path of the lth cluster; and T_l is the time delay of the lth cluster. $\alpha_{k,l}$ can be rewritten as a product of ± 1 and a log-normal random variable $\beta_{k,l}$, and T_l and $\tau_{k,l}$ are Poisson distributed. The distributions of clusters and paths can be expressed as

$$\Pr(T_l | T_{l-1}) = \Lambda \exp[-\Lambda(T_l - T_{l-1})] \tag{5}$$

and

$$\Pr(\tau_{k,l} | T_{(k-1),l}) = \lambda \exp[-\lambda(\tau_{k,l} - T_{(k-1),l})], \tag{6}$$

where Λ and λ are the mean arrival rates of the cluster and path, respectively. The multipath intensity profile is defined as

$$E[\alpha_{k,l}^2] = \Omega_0 e^{-T_l/\Gamma} e^{-\tau_{k,l}/\gamma}, \tag{7}$$

where Γ and γ are decay factors of the cluster and path, respectively, and Ω_0 is the mean power of the first path component.

For mathematical tractability, we set the path interval equal to chip duration [7], [11], [12]. Thus, the channel model is rewritten as

$$h(t) = \sum_{j=1}^{L_p} \alpha_j \delta(t - (j-1)T_c - \tau), \tag{8}$$

where L_p $(= LK)$ is the number of paths; α_j is the channel coefficient of the jth path; and τ is the channel propagation delay. In a UWB channel, L_p is generally close to infinity; however, many paths have negligible low-power. Therefore, the total number of paths can be redefined as the number of paths within 10dB from the largest path [2], [11]. Thus, the channel model is rewritten as

$$h(t) = \sum_{j=1}^{Q} \alpha_j \delta(t - (j-1)T_c - \tau), 1 \le Q \le L_p, \tag{9}$$

where Q is the total number of paths within 10dB from the largest path.

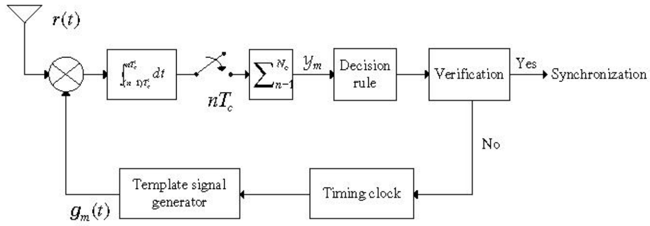


Fig. 1. A UWB synchronization system structure.

C. System Structure

Fig. 1 shows a UWB synchronization system structure, where $g_m(t)$ is the template signal given by

$$g_m(t) = \sum_{n=1}^{N_c} c_n p(t - (n+m-1)T_c), \quad m \in \{0, 1, 2, \cdots, N_c - 1\}. \tag{10}$$

In Fig. 1, y_m is the correlator output which can be expressed as

$$y_m = \sum_{n=1}^{N_c} \left(\int_{(n-1)T_c}^{nT_c} r(t) g_m(t) dt \right). \tag{11}$$

y_m is used as the test statistic of the synchronization system, which determines whether the synchronization is achieved or not with the decision rule.

III. Proposed Decision Rules

A. Distribution of Correlator Output

As shown in (7), the first path component generally has the largest power. Based on which, we propose novel decision rules for selecting the first path component using ML approach.

First, in order to know the distribution of y_m, we calculate the mean and variance of y_m. (11) is rewritten as follow

$$\begin{aligned} y_m &= \int_0^{N_c T_c} r(t) g_m(t) dt \\ &= \sqrt{E_c} \int_0^{N_c T_c} \sum_{i=1}^{N_c} \sum_{n=1}^{N_c} \sum_{j=1}^{Q} \alpha_j c_i c_n \\ &\quad \cdot p(t - (i+j-2)T_c - \tau) \\ &\quad \cdot p(t - (n+m-1)T_c) dt \\ &\quad + \int_0^{N_c T_c} n(t) c_n p(t - (n+m-1)T_c) dt. \end{aligned} \tag{12}$$

(12) is rewritten according to phase difference of received

and template signal (i.e. $\tau - mT_c$), which can be expressed as

$$y_m = \begin{cases} N_c\sqrt{E_c}\alpha_1 + w'(t), & \tau - mT_c = 0 \\ N_c\sqrt{E_c}\alpha_2 + w'(t), & \tau - mT_c = T_c \\ \vdots & \vdots \\ N_c\sqrt{E_c}\alpha_j + w'(t), & \tau - mT_c = (j-1)T_c \\ w'(t), & \tau - mT_c = jT_c \\ \vdots & \vdots \\ w'(t), & \tau - mT_c = (N_c-1)T_c \end{cases} \quad (13)$$

$$w'(t) = \int_0^{N_cT_c} w(t)c_n p(t-(n+m-1)T_c)dt, \quad (14)$$

where $w'(t)$ is the noise component of the correlator output, of which variance is N_cN_0.

Then, the probability density function (pdf) of the correlator output corresponding to the jth path component can be written as

$$f_j(y_m) = \frac{1}{\sqrt{2\pi N_cN_0}}\exp\left(-\frac{(y_m - N_c\sqrt{E_c}\alpha_j)^2}{2N_cN_0}\right), \quad (15)$$

where $N_c\sqrt{E_c}\alpha_j$ is the mean of the jth path component. And, the pdf of the correlator output which does not correspond to any of the path components can be written as

$$f_0(y_m) = \frac{1}{\sqrt{2\pi N_cN_0}}\exp\left(-\frac{y_m^2}{2N_cN_0}\right). \quad (16)$$

B. Proposed Decision Rules

To derive the optimal decision rule, we use all correlator outputs corresponded to all delays of template signal. The set of correlator outputs can be denoted as

$$y = [y_0, y_1, \cdots, y_{N_c-1}]^T, y_i = y_{(i \bmod N_c)}. \quad (17)$$

Then, the pdf of y, given that $\tau = mT_c$, can be expressed as

$$f(y|m) = \prod_{b=0}^{N_c-1} f_0(y_b)\prod_{j=1}^{Q}\frac{f_j(y_{m+j-1})}{f_0(y_{m+j-1})}. \quad (18)$$

Since τ is uniformly distributed, the optimal decision rule Λ_o based on ML approach can be expressed as

$$\Lambda_o(m) = \arg\max_{0\le m\le N_c-1} f(y|m). \quad (19)$$

In (19), we can remove the term which is not dependent on m. Then, (19) is rewritten as

$$\Lambda_o(m) = \arg\max_{0\le m\le N_c-1}\prod_{j=1}^{Q}\frac{f_j(y_{m+j-1})}{f_0(y_{m+j-1})}. \quad (20)$$

From (15) and (16), (20) becomes

$$\Lambda_o(m) = \arg\max_{0\le m\le N_c-1} \exp\left(\sum_{j=1}^{Q} -\frac{(y_{m+j-1} - N_c\sqrt{E_c}\alpha_j)^2}{2N_cN_0} + \frac{y_{m+j-1}^2}{2N_cN_0}\right). \quad (21)$$

In (21), we can remove the terms which are not dependent on m and constant. Then, the optimal decision rule can be expressed as

$$\Lambda_o(m) = \arg\max_{0\le m\le N_c-1}\sum_{j=1}^{Q} y_{m+j-1}\alpha_j, \quad (22)$$

which is the optimal decision rule to select the first path component in UWB channel. However, as shown in (22), the optimal decision rule requires information on channel coefficient $\{\alpha_j\}_{j=1}^{Q}$. Thus, the optimal decision rule is difficult to implement.

The channel coefficients can be divided into values and signs. The signs of channel coefficients can be expressed as specific sequence which is consisted of 1 and -1. Thus, the signs of channel coefficients affect the performance of (22) significantly. However, since we do not have sign information of channel coefficients, we will ignore effects of the signs by using absolute operation, so that we can have the simple suboptimal decision rule Λ_s. The suboptimal decision rule can be expressed as

$$\Lambda_s(m) = \arg\max_{0\le m\le N_c-1}\sum_{j=1}^{Q}|y_{m+j-1}|, \quad (23)$$

which can select the first path component without channel information.

IV. Conventional Decision Rule

In the conventional scheme, the synchronization is defined as aligning time phases of a template and any of multipath component, and the associated statistic is $|y_m|$. The conventional scheme is based on comparison between $|y_m|$ and threshold. Thus, when the system performs the synchronization with new synchronization definition, if τ is smaller than mT_c, the conventional scheme hardly use all statistics.

In this paper, for a comparison with the proposed decision rules, we make the following decision rule which can use all statistics, based on the statistic of [9] and refer to it as the conventional decision rule:

$$\Lambda_c(m) = \arg\max_{0\le m\le N_c-1}|y_m|. \quad (24)$$

The conventional decision rule determines whether the largest $|y_m|$ is the first path component or not. However, since the statistic of the conventional decision rule depends on only one path component, if the first path component does not have the largest power, the system hardly achieves the synchronization.

V. Simulation Results

In this section, we compare the performance of the optimal, suboptimal, and conventional decision rules in terms of the probability of false synchronization defined as the probability that statistic selected by decision rule is not the first path component. Also, we compare the bit error rate (BER) performance of cases of the synchronization with the first path component

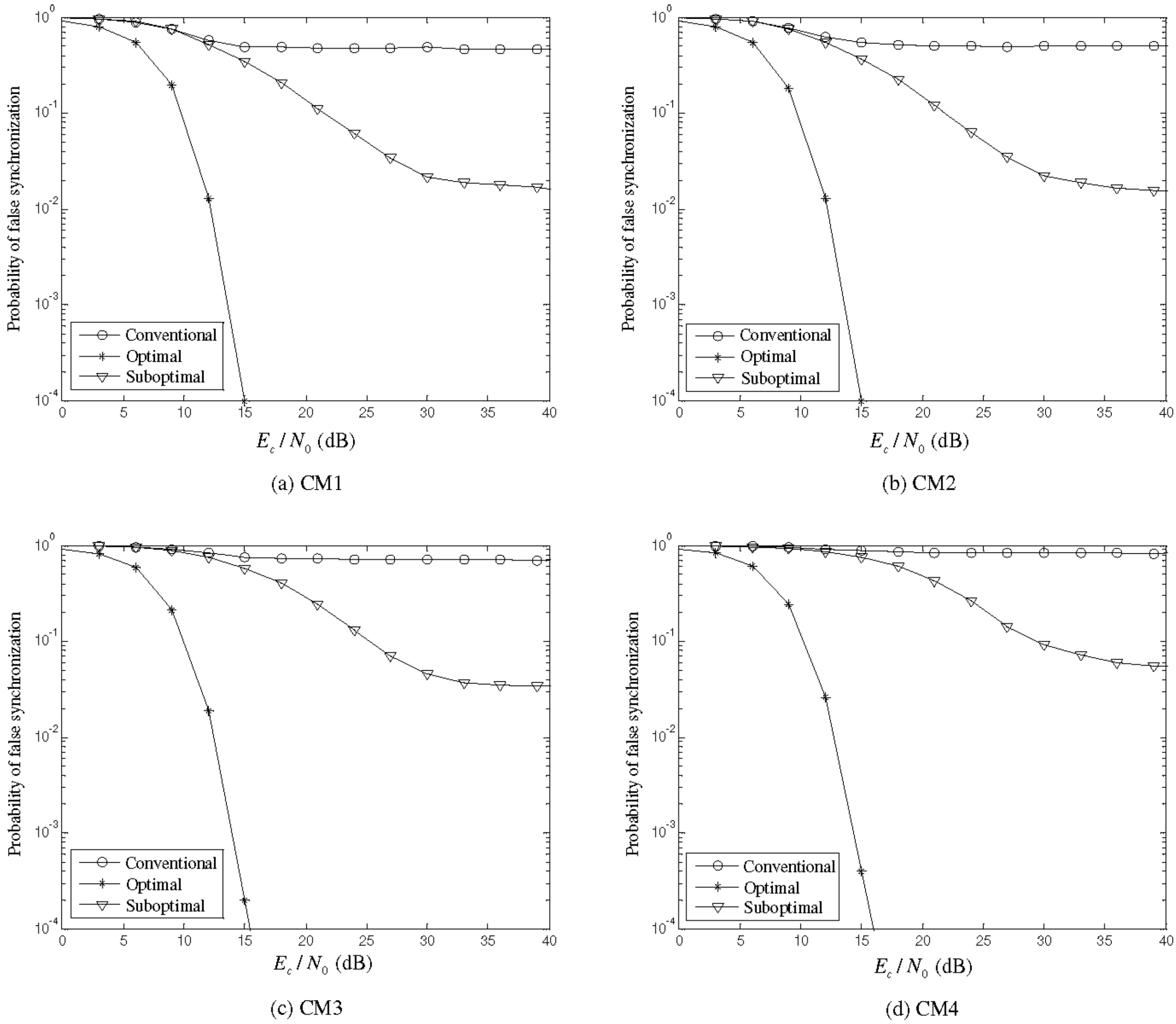


Fig. 2. Probability of false synchronization of the conventional, optimal, and suboptimal decision rules in the IEEE 802.15.3a channel model.

and that with one among multipath components. We define the signal to noise ratio (SNR) as E_c/N_0 and use PN code with a period of 255 chips and a chip duration of 0.5 ns.

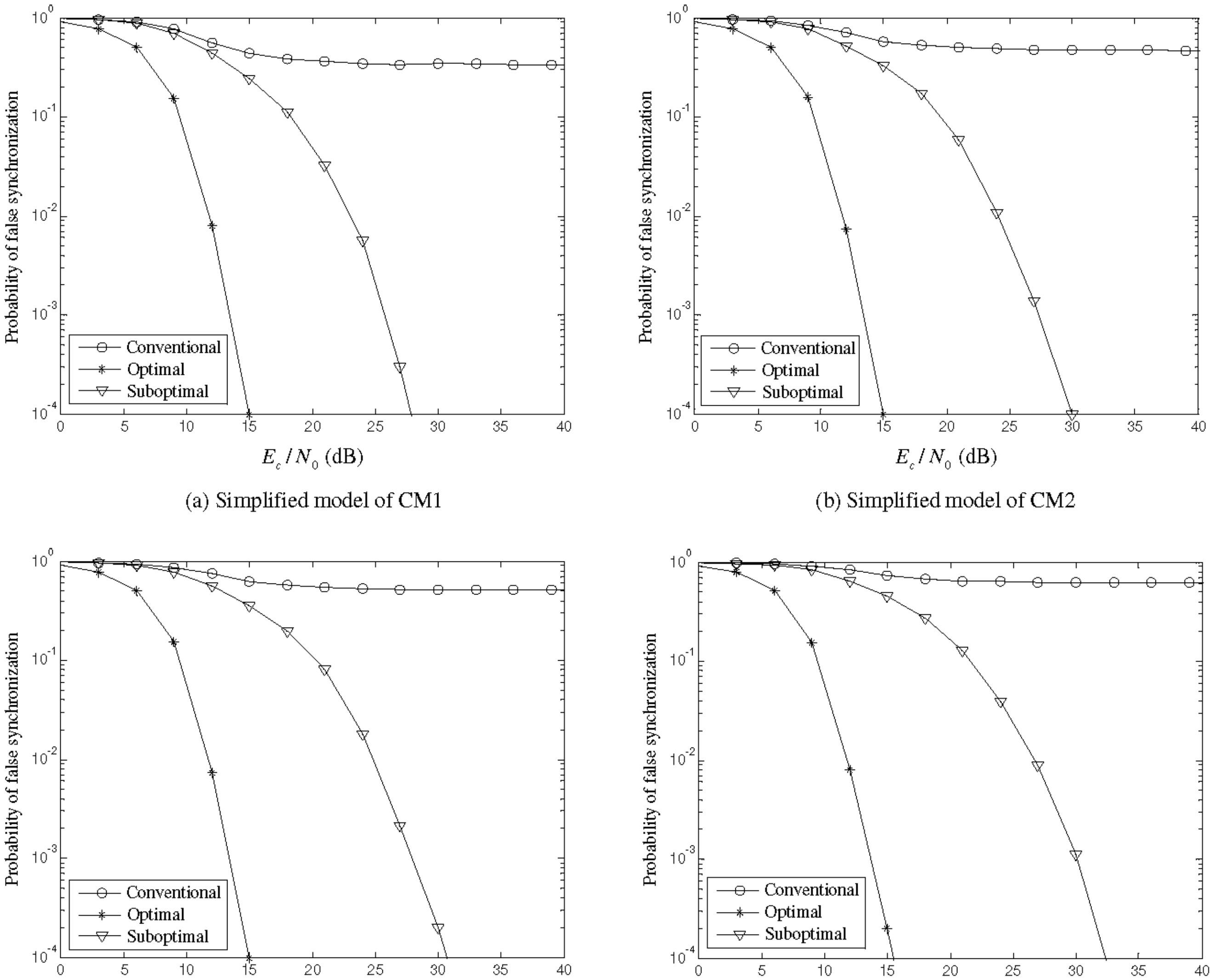
In IEEE 802.15.3a standard, the channel environments is classified 4 models (CM1, CM2, CM3, CM4) with existence of line-of-sight (LOS) and distance of the transmitter and receiver [11]. We simulated the synchronization process on each of IEEE 802.15.3a channel models (4) and its simplified models (9). The channel parameters are shown in Table 1. To confirm that the synchronization with the first path component and that with the any of multipath components, the demodulation process was simulated on CM1 model to represent other channel models.

Fig. 2 shows the probability of false synchronization of the decision rules in each IEEE 802.15.3a channel model. As shown in Fig. 2, the proposed decision rules have better performance compared with the conventional decision rule. Since the optimal decision rule uses channel information, it has the best performance. On the other hand, since the suboptimal decision rule does not use channel information, it demonstrates some performance degradation compared with the optimal decision rule. From CM1 to CM4, as increase of channel complexity, the proposed decision rules have some

TABLE I

PARAMETERS OF IEEE 802.15.3A CHANNEL MODELS.

Channel model	Λ(1/ns)	λ(1/ns)	Γ	γ
CM1 (LOS, 0~4m)	0.0233	2.5	7.1	4.3
CM2 (NLOS, 0~4m)	0.4	0.5	5.5	6.7
CM3 (NLOS, 4~10m)	0.0667	2.1	14	7.9
CM4 (Extreme NLOS, 0~4m)	0.0667	2.1	14	21



(a) Simplified model of CM1

(b) Simplified model of CM2

(c) Simplified model of CM3

(d) Simplified model of CM4

Fig. 3. Probability of false synchronization of the conventional, optimal, and suboptimal decision rules in the simplified UWB channel model.

performance degradation.

Fig. 3 shows the probability of false synchronization of the decision rules in simplified UWB channel models. As shown in Fig. 3, the proposed decision rules have better performance compared with the conventional decision rule. Similarly as in IEEE 802.15.3a channel models, as channel complexity increases, the proposed decision rules have some performance degradation. The performance difference of the conventional and proposed decision rules increases as SNR increases.

In demodulation process, we use the rake receivers with 4 and 8 fingers. And we choose 4 and 8 path components from the path component selected by the decision rule and following path components, according to path amplitude. To modulate the data, we use the binary pulse amplitude modulation (PAM). Fig. 4 shows the BER performance of cases of the synchronization with the new synchronization definition (selecting the first path component) and that with the conventional synchronization definition (selecting any of multipath components). As shown in Fig. 4, when the system synchronizes with the first path component, it has better BER performance than that with any of multipath components. The BER performance difference increases as SNR increases.

VI. Conclusion

In this paper, we have newly defined the synchronization on UWB system and have proposed the optimal and suboptimal decision rules for selecting the first path component. Simulation results have shown that the proposed decision rules have better synchronization performance than the conventional decision rule. The optimal decision rule has the best performance, however, it requires channel information. On the other hand, since the suboptimal decision rule does not require the channel

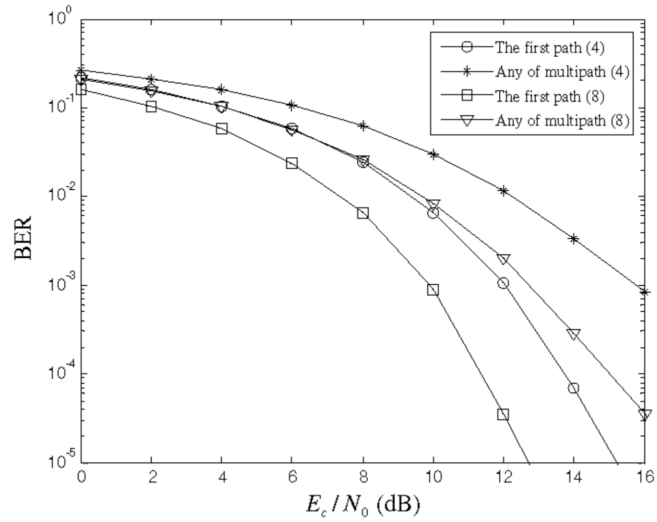


Fig. 4. BER performance of cases of synchronization with the first path component and any of multipath components.

information, it has slight performance degradation compared with the optimal decision rule. The performance difference of the conventional and proposed decision rules increases as SNR increases. Also, we have shown that the synchronization with the first path component can improve BER performance compared with that with the any of multipath components.

ACKNOWLEDGMENTS

This work was supported by the Korea Research Foundation Grant funded by the Korean Government (MOEHRD, Basic Research Promotion Fund) (KRF-2007-331-D00295).

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