Detection of TR-UWB by Recursion in Dense Multipath

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***Abstract*—For the ultra-wideband (UWB) communication, the Rake receiver could efficiently collect the spread energy from the diversity of channel environment. Unfortunately, the overload of correlator is too huge to retain the diversity gain, and the channel estimation and timing acquisition are hard to achieve. Therefore, a suboptimal solution for UWB transmission was proposed by using transmitted-reference (TR), for which neither complex channel estimation nor pulse information is needed. From the noisy-template (NT) of TR-UWB, the correlator could efficiently detect information data but the NT is strongly affected by noise. We can improve the NT by the approach that averages all TR's as the averaged NT (ANT) during the reasonable delay, with only half of the transmission rate. Moreover, the ANT should be constrained by the quasi-static period of channel. For this reason, we propose an algorithm for the situation of the short quasi-static period of channel. Based on our algorithm, the finite data could be taken and decided as pilots, like TR's, by a discriminator with a threshold. Further, the modified clustered channel estimation (MCCE) [8] gives the improvement of performance by the regional autocorrelation decision. The proposed algorithm is verified by the error probability analysis and the simulations. With only a few TR's and low complexity buffer, we could obtain good error performance in the uncorrelated rapid-varying dense multipath.**

***keywords*: Transmitted-Reference, Ultra-Wideband, Recursion, Autocorrelation, Discriminator.**

I. Introduction

For the short distance transmission, ultra-wideband (UWB) system could sustain the requirement of bandwidth for high quality communication. The high resolution of dense multipath of the UWB channel creates the benefit of high diversity. However, the Rake receiver could obtain the advantage only if the channel and timing estimations work well. Nevertheless, for the Rake receiver it is not an easy way to grasp narrow pulse precisely for the timing acquisition and support a number of correlators with the associated tap estimation. For the sake of low complexity, the suboptimal transmitted-reference (TR) or autocorrelation receiver was proposed. The TR-UWB [1]-[4] will take the reference/piloted information to detect the data information if the channel within the duration of reference and data information remains constant. Moreover, for the TR-UWB the condition of symbol time synchronization is better than the Rake receiver that has narrowed UWB pulses. Once the channel remains quasi-static for a long time, the improved noisy-template (NT) could be the average of referred information that depends on what leading delay they could tolerate. Although the averaged NT (ANT) is directly perceived, however, it is also the optimal solution of generalized likelihood ratio test (GLRT) under the situation of no channel and timing information [2] [5].

Accordingly, [6] mentions that the ANT could be adaptively updated if the quasi-static channel varies correlatedly with the previous channel response (CR). And [7] gives that by the non-zero mean property of pulse position modulation (PPM), the symbol of pulse amplitude modulation (PAM) could first be detected by NT from the referred PPM, and then vice verse. After the ANT is obtained, under the reasonable delay and computation, the ANT could support data detection and update iteratively [6]-[7]. However, if the quasi-static period of channel is short and uncorrelated between CR's, then the performance will degrade due to the loss of restraining the noise effect.

For the uncorrelated CR's and channel of short quasi-static period, the number of TR's should be restricted. However, this degrades the performance of symbol-by-symbol iterative NT update. In this paper, we consider such channel of short quasi-static period. The receiver makes effort to discriminate the finite information data by the temporal TR's (TTR's) which supports for the improvement of NT. We can improve the NT, however, by recursively updating TTR under the reasonable delay and buffer space. By the proposed algorithm, with less TR's we could obtain the same performance as the situation with more TR used, which reduces the transmission rate. Moreover, the little gain from the tail of CR could be neglected if the channel statistical property has known [9]. However, the valuable tap is worth to select, and the modified clustered channel estimation (CCE) [8] will assist the tap selection as the regional autocorrelation detection.

The rest of this paper is organized as follows. In Section II we give a brief introduction of TR-UWB and the restriction of ANT. Section III shows the detailed mechanism in recursion and discriminator of our algorithm, and gives the error probability analysis that could verify our result. The complexity reduction and tap selection are also shown in this section. We show the simulation results that could confirm our idea and design in Section IV. Finally, we conclude this paper in Section V.

II. System Model

We now introduce the signal model based on the assumption of channel with finite quasi-static period. For the general TR-UWB, the information data symbols follows the reference symbols which are transmitted periodically. Once the ANT is used, these reference symbols could be anywhere due to location independence, and the system performance depends on the total energy from reference symbols [3]. Therefore, an equivalent TR-UWB has the minimum delay of ANT when all reference symbols locate in the front of data symbols. We can express the received signal as

$$\begin{aligned} y(t) = & \sum_{i=0}^{L_{tr}-1} \sqrt{E_a} g(t - iT_s) \\ & + \sum_{j=0}^{L-L_{tr}-1} \sqrt{E_a} a_j g\left(t - (L_{tr} + j)T_s\right) + n(t) \\ = & \sum_{i=0}^{L_{tr}-1} y_T(t - iT_s) + \sum_{j=0}^{L-L_{tr}-1} y_D(t - jT_s), \end{aligned} \quad (1)$$

where $g(t) \triangleq p(t) * h(t)$ is the convolution of the UWB pulse $p(t)$ and the CR. We assume the pulse width be T_p, and $h(t) = \sum_{k=0}^{L_{cr}-1} \alpha_k \delta(t - \tau_k)$, with the kth tap delay τ_k and amplitude α_k. The noise $n(t)$ is a zero-mean white Gaussian process with the two-sided power spectral density $N_0/2$. Here we call one frame in TR-UWB a symbol and denote the symbol time as T_s, which is large enough to avoid the interference between consecutive symbols. For the pulse amplitude modulation (PAM) with information symbol $a_j = \pm 1$, the averaged power of a UWB symbol is E_a. In the above $y(t)$ is a packet with L_{tr} reference symbols that are transmitted within the quasi-static period of channel.

Once y_T is received, the ANT could be resolved as

$$\begin{aligned} \hat{g}(t) = & \frac{1}{L_{tr}} \sum_{i=0}^{L_{tr}-1} y_T(t - iT_s) \\ \Rightarrow \ \hat{\mathbf{g}} = & \sqrt{E_a}\mathbf{g} + \frac{1}{L_{tr}} \sum_{i=0}^{L_{tr}-1} \mathbf{n}_i \\ = & \sqrt{E_a}\mathbf{g} + \frac{\mathbf{n}'}{L_{tr}}, \end{aligned} \quad (2)$$

where we represent the samples of $\hat{g}(t)$ with sampling period $T_{sam} = \frac{T_s}{K}$ by the vector $\mathbf{g} \in \mathbb{R}^K$, and $\mathbf{n}_i$ and $\mathbf{n}'$ are noise vectors. We assume that the bandwidth $W \triangleq \frac{1}{T_{sam}}$ is large enough to completely receive the UWB signal. The signal-to-noise ratio (SNR) of ANT is easily obtained by $SNR_t \triangleq \frac{E\{||\sqrt{E_a}\mathbf{g}||^2\}}{E\{||\frac{\mathbf{n}'}{L_{tr}}||^2\}} = \frac{E_a E_g L_{tr}}{K(\frac{N_0}{2})} = \frac{SNR_h}{K} L_{tr}$, where $E_g \triangleq ||\mathbf{g}||^2$. Accordingly, the autocorrelation detector with $\hat{\mathbf{g}}$ has the error probability

$$P_e = \mathbf{Q}\left(\frac{E\{r_D\}}{\sqrt{var\{r_D\}}}\right) = \mathbf{Q}\left(\sqrt{\frac{L_{tr}\ SNR_h}{1 + L_{tr} + \frac{K}{SNR_h}}}\right), \quad (3)$$

where $r_D^j \triangleq \hat{\mathbf{g}}^T \mathbf{y}_D(t - jT_s),\ j = 0, \cdots, L - L_{tr} - 1$. The analyzed and simulated results are shown in Fig. 2, with the definition of lower bound corresponding to $L_{tr} = \infty$. When L is short, it is worth to consider the ratio of L_{tr} and $L'_d \triangleq L - L_{tr}$, and L should be constrained by the quasi-static period of channel. We can improve the TR performance by making use of the detected data symbols and adding it to the TTR's. The resulted new ANT is

$$\begin{aligned} \hat{\mathbf{g}}' = & \frac{1}{L}\left(\sum_{i=0}^{L_{tr}-1} y_T(t - iT_s) + \sum_{j=0}^{L'_d-1} \check{a}_j y_D(t - jT_s)\right) \\ = & \sqrt{E_a}\frac{L_{tr} + L_c - L_e}{L}\mathbf{g} + \frac{1}{L}\sum_{i=0}^{L-1} \check{a}_{i-L_{tr}} \mathbf{n}_i \\ = & \sqrt{E_a}\frac{L - 2L_e}{L}\mathbf{g} + \frac{1}{L}\mathbf{n}' = \sqrt{E_a}\frac{L'}{L}\mathbf{g} + \frac{1}{L}\mathbf{n}', \end{aligned} \quad (4)$$

where $\check{a}_j$ is the temporally detected data by $sign\{r_D^j\}$ with $\hat{\mathbf{g}}$, and $\check{a}_j = 1$ if $j < 0$. We denote by L_c and L_e the numbers of corrects and errors, respectively, in the packet y_D. Then the improved NT, $\hat{\mathbf{g}}'$, have the $SNR_{t'}$

$$\begin{aligned} SNR_{t'} \triangleq & \frac{E\{||\sqrt{E_a}\frac{L'}{L}\mathbf{g}||^2\}}{E\{||\frac{1}{L}\mathbf{n}'||^2\}} \\ = & \frac{SNR_h}{K}\frac{(L - 2L_e)^2}{L} = \frac{SNR_h}{K}\frac{L'^2}{L}. \end{aligned} \quad (5)$$

If $SNR_{t'} > SNR_t$, we have

$$G \triangleq \frac{(L - 2L_e)^2}{L} = \frac{(L_{tr} + L'_d(1 - 2P_e^D))^2}{L_{tr} + L'_d} > L_{tr}, \quad (6)$$

where P_e^D is the error probability in packet y_D. However, it is impractical to have

$$\lim_{L'_d = \infty} G \simeq L,\ with\ P_e^D \approx 0 \quad (7)$$

except for the situation of higher SNR and longer quasi-static period of channel. For the above reasons, in the next section we will develop an efficient algorithm with low density of pilots, and validate it by the analytical error probability.

III. Efficient Algorithm

The extra gain from G is constrained by L and P_e^D, in which L is determined by the UWB channel. Although we can apply the error-corrected coding to reduce P_e^D, we do not consider this approach in this paper. Therefore, under the condition of finite-length L, we propose an algorithm that utilizes part data symbols of $y_D(t)$ as TTR's such that P_e^D could be reduced. Fortunately, we can apply a discriminator with the threshold such that we can utilize the correctly detected data symbols from $y_D(t)$ to improve the NT. The procedures of the algorithm is stated in the following, according to the Mode-A of Fig. 1.

Algorithm:

1) Set a threshold T_h such that if $|r_D^j| \geq T_h$ then $j \in D_c \cup D_e$, otherwise, $j \in D_r$. Where the initial ANT is assumed as $\hat{\mathbf{g}}$ in (2) at the first recursion.
2) Complete the above step from $j = 0$ to $j = L'_d - 1$.
3) Refer symbols belonging to $D_c \cup D_e$ as pilots or TR's, and replace the previous ANT with $\hat{\mathbf{g}}'$, as in (4), where $j \in D_c \cup D_e$.
4) Go around the above three steps if we could improve the template, with the initial ANT replaced by the new $\hat{\mathbf{g}}'$ in each recursion. Otherwise, go to the next step.

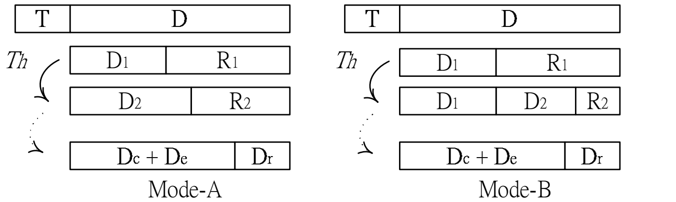

Fig. 1. Transmission Mode

5) Finally, the detector by the correlator has $\hat{a}_j = sign\{r_D^j \triangleq \hat{\mathbf{g}}'^T \mathbf{y}_D(t - jT_s)\}$, with $j \in D \triangleq D_c \cup D_e \cup D_r$.

After the Kth recursion, data symbols that satisfy $|r_D^j| \geq T_h$ will be located at set $D_c \cup D_e$, otherwise, they are in D_r. For $D_c \cup D_e$, if $sign\{r_D^j\} = a_j$ then j belongs to D_c; otherwise, $sign\{r_D^j\} \neq a_j$, and j is in D_e. Obviously, these three set do not have intersection, and the lengths $L'_d = |D|$ and $L_d = |D_k \triangleq D_c \cup D_e|$, which is in the kth recursion, $k = 1, \cdots, K$, as well as the remanent set $R_k \triangleq D - D_k$, referring to Fig. 1. For the sake of simplicity, we will set $L_{tr} = |T|$, $L'_d = |D|$, and $L = |D + T|$ through our paper.

Accordingly, the detector at step5 of the algorithm has

$$\begin{aligned} r_D^j &= \hat{\mathbf{g}}'^T \mathbf{y}_D(t - jT_s) \\ &= \left(\sqrt{E_a}\frac{L'}{L}\mathbf{g} + \frac{\mathbf{n}'}{L}\right)^T \left(\sqrt{E_a}a_j\mathbf{g} + \mathbf{n}_j\right) \\ &= E_a E_g a_j \frac{L'}{L} + \sqrt{E_a}\frac{L'}{L}\mathbf{g}^T\mathbf{n}_j + \frac{\sqrt{E_a}a_j}{L}\mathbf{n}'^T\mathbf{g} + \frac{1}{L}\mathbf{n}'^T\mathbf{n}_j \\ &= S + N_1 + N_2 + N_3, \ j \in D, \end{aligned} \tag{8}$$

where $E\{N_1^T N_3\} = E\{N_2^T N_3\} = 0$, and

$$E\{N_1^T N_2\} = \begin{cases} 0 & \text{if } j \in D_r, \\ E_a E_g \frac{L'}{L^2}\frac{N_0}{2} \approx 0 & \text{if } j \in D_c, \\ -E_a E_g \frac{L'}{L^2}\frac{N_0}{2} \approx 0 & \text{if } j \in D_e, \end{cases}$$

that the N_1, N_2, and N_3 have joint Gaussian distribution due to the properties of UWB channel h, [10], and noise $\mathbf{n}$. For the situation that $a_j = 1$ but $\hat{a}_j = -1$, the error probability (PAM case)

$$\begin{aligned} P_e &= P(\hat{a}_j = -1 | a_j = +1) \\ &= P(\hat{a}_j = -1 | a_j = +1 \in D_r) + P(\hat{a}_j = -1 | a_j = +1 \in D_c) \\ &+ P(\hat{a}_j = -1 | a_j = +1 \in D_e) \\ &= (1 - P_p) Q\left(\frac{\mu_s}{\sqrt{\sigma_{n_1} + \sigma_{n_2} + \sigma_{n_3 \in D_r}}}\right) \\ &+ P_p(1 - P_e^D) Q\left(\frac{\mu_s + \mu_{n_3 \in D_c}}{\sqrt{\sigma_{n_1} + \sigma_{n_2} + \sigma_{n_3 \in D_c}}}\right) \\ &+ P_p P_e^D \left(1 - Q\left(\frac{|\mu_s + \mu_{n_3 \in D_e}|}{\sqrt{\sigma_{n_1} + \sigma_{n_2} + \sigma_{n_3 \in D_e}}}\right)\right) \\ &= (1 - P_p)P^r + P_p(1 - P_e^D)P^c + P_p P_e^D P^e, \end{aligned} \tag{9}$$

where $P_p \triangleq E\{\frac{L_d}{L'_d}\}$, and the P_e^D is the error probability of the packet y_D, whose symbols belong to $D_c \cup D_e$. Both of them are variables of T_h. For $a_j = 1$, the details of the mean value and variance are shown in (11) at the top of the next page. However, the error performance will be dominated from $P_p P_e^D P^e$ due to the strong interference μ_{n_3}, where $\mu_s + \mu_{n3 \in D_e}$ must be less zero. Particularly, at low SNRs, the item $P^c \approx 0$ and $P^e \approx 1$. Therefore, the approximated error probability

$$P_e \approx (1 - P_p)P^r + P_p P_e^D. \tag{10}$$

Although the close-form of P_e^D and P_p are not easily obtained, the exhausted search could be applied. Consider the scenario with finite L and $L_{tr} = 10$, the simulation by $L'_d = 100$ is shown in Fig. 3, for which the same threshold value is assigned through $k = 1$ to K, where $K = 2$. The results show that the performance of our algorithm outperforms much the upper bound, which is obtained by setting $L_{tr} = 10$ in (3). However, the mismatch between simulation and analysis appears for larger threshold value T_h and high SNR due to the destruction of discriminator that comes from the accuracy loss of zero-mean Gaussian approximation.

Accordingly, the computational delay in Mode-A (see Fig. 1) is $K * L'_d$. In fact, once the $\hat{\mathbf{g}}'$ results in better performance at the kth recursion, the set R_k could support for the next improvement of ANT. When the set R_k becomes smaller, the corresponding computational delay reduces. For this reason, the Mode-B of Fig. 1 is the mode that performs the same error rate comparing to the transmission with Mode-A. The results will be shown in Section IV. The details of algorithm is the same as Mode-A, except that the step2 should be modified as

- Go from $j = 0$ until $j = L'_d - 1$ in step1 at the first recursion. After that, the searching region will be constrained to $j \in R_k$ with $k = 1, \cdots, K - 1$.

In terms of (4)-(7), even the quasi-static length of channel is long enough, the overhead of computation is infeasible to have further improvement. For the trade-off between performance and complexity under the available of the longer quasi-static channel, the packet $y(t)$ ahead of L still supports for the improvement of $\hat{\mathbf{g}}'$ in our proposed algorithm, and the correlator makes decision on r_D^j, with $j = L_{tr}, \cdots, L + L_{ext} - 1$. The extended packet with length L_{ext} is constrained by the quasi-static channel with length $L + L_{ext}$. That is the length of quasi-static channel is equal to $L + L_{ext}$. Once it is available, the definition of P_p should be altered by $P_p = \frac{L_d}{L'_d + L_{ext}} \approx 0$ if L_{ext} is long enough. This makes (9) have the domination of G by the reason

$$\begin{aligned} P_e &\approx P^r \\ &= Q\left(\sqrt{\frac{G \ SNR_h}{1 + G + \frac{K}{SNR_h}}}\right), \end{aligned} \tag{12}$$

in terms of different threshold value T_h. This result has the similar phenomenon comparing with (3). In other words, our proposed algorithm with less pilots has the same performance as (3) with $L_{tr} = G$. The result will be shown in the next section.

Under no UWB pulse and channel information, however, the tail of UWB channel has less contribution, and a few clusters and rays in UWB channel will determine the performance if

$$
\begin{aligned}
&\mu_s = E\{S\} = E_a E_g \frac{L'}{L},\ \mu_{n_1} = E\{N_1\} = 0,\ \mu_{n_2} = E\{N_2\} = 0,\\
&\sigma_{n_1} = Var\{N_1\} = E_a E_g (\frac{L'}{L})^2 \frac{N_0}{2},\ \sigma_{n_2} = Var\{N_2\} = E_a E_g \frac{1}{L}\frac{N_0}{2}\\
&\mu_{n_3} = E\{N_3\} = \begin{cases} 0 & \text{if } j \in D_r,\\ \frac{1}{L}K\frac{N_0}{2} & \text{if } j \in D_c,\\ \frac{-1}{L}K\frac{N_0}{2} & \text{if } j \in D_e. \end{cases} \qquad \sigma_{n_3} = Var\{N_3\} = \begin{cases} \frac{1}{L}K(\frac{N_0}{2})^2 & \text{if } j \in D_r,\\ \frac{1}{L^2}3K(\frac{N_0}{2})^2 + \frac{1}{L}K(\frac{N_0}{2})^2 & \text{if } j \in D_c \text{ or } \ j \in D_e. \end{cases}
\end{aligned} \tag{11}
$$

the channel models are available [10]. Correspondingly, the authors [8] propose clustered channel estimation (CCE) to properly select tap for the Rake receiver with pulse information. However, the modified CCE will be applied to our TR-UWB according to the proposed algorithm. The details of CCE could be referred to [8], and we give the modified CCE (MCCE), under synchronization by

$$
\begin{aligned}
\hat{\tau} &= \arg max \sum_{j=0}^{L'_{clu}-1} \sum_{k=0}^{L'_{ray}-1} \left(\sum_{i=0}^{L_{tr}-1} z_{ik}(\hat{\tau}_j) \right)^2\\
with\ z_{ik}(\hat{\tau}_j) &= \int y_T(t - iT_s)\hat{g}'(t - \hat{\tau}_j - kT_p)dt,
\end{aligned} \tag{13}
$$

without UWB pulse and tap amplitude information. The finite taps of cluster L'_{clu} and rays L'_{ray} collect the essential diversity gain and obtain the contributed energy from regional autocorrelation detector, within timing $\hat{\tau}$. The regional decision will exclude the part of weak $\hat{g}'$ and support the better one for data detection.

IV. Numerical Results

In this section, the simulation results will be shown to validate the proposed algorithm and compare with the analytical results. For the transmission of TR-UWB, we use the pulse Gaussian-monocycle with $T_p = 1$ ns. We ignore the effect of shadowing in the CM1 channel [10], and average over the 100 channel patterns to determine the simulation results. Under the assumption of resolvable dense multipath, we apply the sampler with bandwidth $W = 10$ GHz.

An adaptive TR-UWB system that updates the NT symbol-by-symbol iteratively, like [7], which follows the data detector used for comparison. For this system the symbol-wise detection by ANT $\hat{g}$ is defined as, with $j = L_{tr}, \cdots, L-1$,

$$
\begin{aligned}
\hat{\hat{g}}_{j-L_{tr}} &= \frac{1}{j+1}(\sum_{l=0}^{L_{tr}-1} y_T(t - lT_s)\\
&\quad + \sum_{m=0}^{j-L_{tr}} \hat{\hat{a}}_m y_D(t - mT_s)),\\
with\ \hat{\hat{a}}_{j-L_{tr}} &= sign\{\hat{\hat{g}}^T_{j-L_{tr}-1} y_D(t - (j - L_{tr})T_s)\},
\end{aligned} \tag{14}
$$

where $\hat{\hat{g}}_{-1}$ is the same as formula (2), and the detected symbols are $\hat{a}_i \triangleq sign\{\hat{\hat{g}}_i^T y_D(t - iT_s)\}, i = 0, \cdots, L'_d - 1$. Further, for this transmission method, defined as Mode-C with no discriminator, could be recursively updated, as shown in Fig. 4. Based on the recursive processing, the upper(lower) bound is obtained with $L_{tr} = 10 (L_{tr} = \infty)$ in (3). Under $L = 110$ with $L_{tr} = 10$ and the proposed algorithm with $K = 2$, the threshold T_h for $\{D_1, D_2\}$ are $\{1.2, 0.4\}$, either on Mode-A or Mode-B. The result shows that with less buffer space, Mode-B has the same performance as Mode-A. The buffer complexity is shown at the bottom of Fig. 4, where the delay unit is given by $L'_d + \sum_{k=1}^{K-1} |R_k|$, which is less than KL'_d. For the algorithm with $K = 3$, $T_h = \{1.4, 1.2, 0.4\}$ in $\{D_1, D_2, D_3\}$, we have better performance but also high cost. According to Mode-C, it's performance is located between the upper bound and our proposed results that confirms our analysis from the restriction of TR-UWB. However, for the available of larger L and extra computation, the transmission with Mode-C is efficient.

For the extended packet available, denoted by *Ext*, this mode with $L + L_{ext} = 1000$, $L'_d = 100$ and $L_{tr} = 10$ has performance shown in Fig. 5. According to (4)-(7) and (12), the maximum of G is L that the *Ext* will close to and over the *bound* with $L_{tr} = 100$ of (3). Also, it outperforms the performance *Norm* complying with non-extended packet by Mode-B of $L_{tr} = 10$, $L'_d = 100$, and $K = 2$, which is dominated by $P_p P_e^D P^e$. Based on the same condition of *Norm*, for the *Sym-Blo* method the Mode-C combined with our proposed algorithm Mode-B to complete the symbol-block wise detection, and it has good performance but needs extra computation complexity. No matter which of these three methods is used, once applying to MCCE they have the same performance. This is because z has a good deal with $\hat{g}'$, and hence the gain G, from our proposed algorithm. For our MCCE case, the low ML computation with channel parameters $L'_{clu} = 4$, $L'_{ray} = 3$, and 12 taps assigned, is enough to capture the contributed energy.

V. Conclusion

In the matter of TR-UWB, it is feasible to fit the practical design. However, the severe channel environment will lead to some constrains that the ANT is not efficient to assist the autocorrelation detection although the GLRT has proved the ANT is worth, and somehow it is optimal under no other information. For this reason, an efficient algorithm is proposed, using the data-assisted (DA) approach to improve the NT. The MCCE takes the essential energy to improve the performance. Even the proposed algorithm will be interfered from the correlated noise, however, the analyzed conclusion shows that it is still remarkable comparing to Mode-C. Once the extended packet is available, we can reduce the interference and its performance will totally depend on the gain G. In other words, its complexity is application dependent, and the

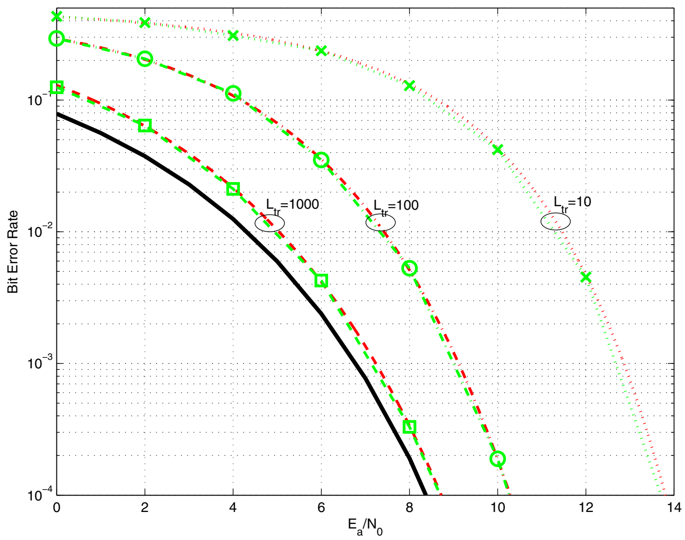

Fig. 2. The error performance of TR-UWB.

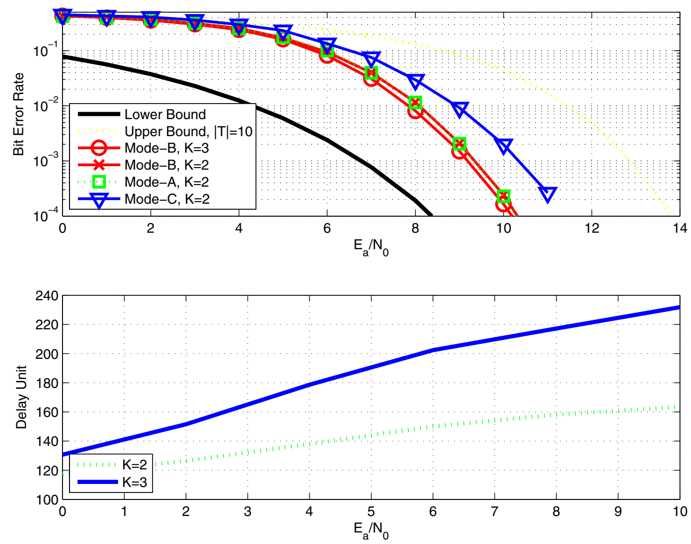

Fig. 4. The error performance of adaptive TR-UWB.

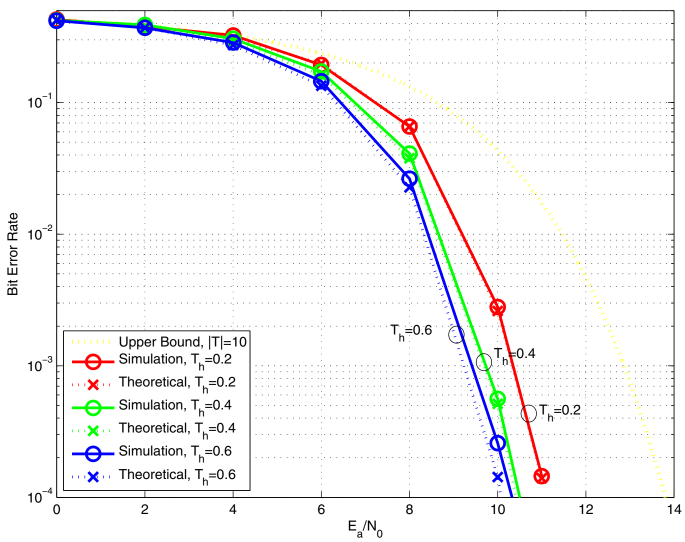

Fig. 3. The error performance of TR-UWB in Mode-A.

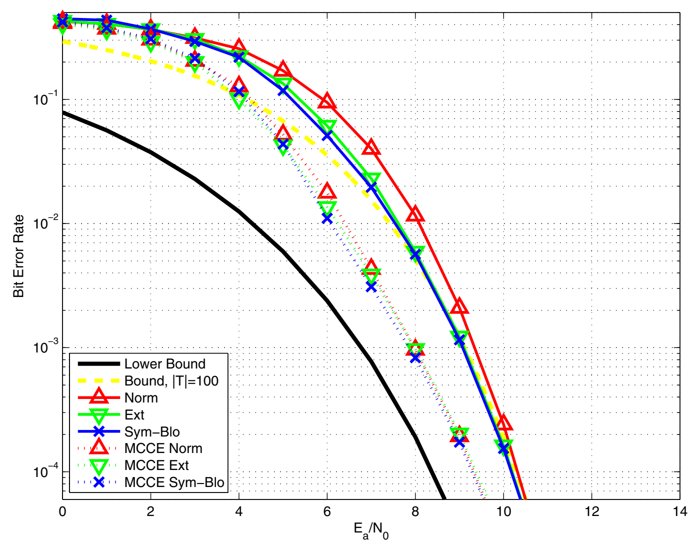

Fig. 5. The error performance of TR-UWB with MCCE.

parameters L'_d, L_{tr}, and K provide the trade-off between performance, efficiency, and buffer space.

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