Novel UWB Transmitted Reference Schemes

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***Abstract*— This paper proposes an ultra-wideband (UWB) transmitted reference (TR) signalling method to transmit and detect information in a multiuser multipath environment using a simple transceiver structure, and the single user performance is analyzed. This TR scheme is a generalized model which combines the traditional TR and differential TR techniques [5] to increase power efficiency and improve bit error probability (BEP). In addition, this novel TR scheme can transmit data using either binary or M-ary modulation. In the binary system, transmitted signals are designed so that the noise level in a correlator template can be reduced within a restrictive receiver complexity. The M-ary modulation approach with a conventional correlation receiver can enhance the BEP performance by transmitting data bits through block codes other than the repetition code. Results show that orthogonal and biorthogonal codes outperform the repetition code in the bit error probability sense.**

I. INTRODUCTION

Ultra-wideband (UWB) systems are promising because of their fine time resolution capability which can resolve many multipath signals. Instead of suffering from the multipath fading, UWB systems can obtain the multipath diversity [2]. On the other hand, an all digital UWB receiver which wants to capture energy from all the paths can be complex because of a high-sampling-frequency analog-to-digital converter (ADC), a stringent synchronization requirement, a channel estimation mechanism, and a Rake processor with many fingers. A UWB system with transmitted reference (TR) modulation has attracted attention because it can ease the synchronization requirements and acquire all the energy in the received signal by using a simple correlation receiver structure [3]. In this traditional TR system, a reference waveform is transmitted before each data-modulated waveform for the purpose of determining the current multipath channel response. The proposed *ad hoc* conventional correlation receiver uses one delay line and one correlator, which correlates the data signal with the reference, to capture all the energy in the received waveform. Then the correlator outputs are quantized and used in the decision process.

This conventional correlation receiver is easy to implement without additional channel estimation and Rake reception, and the required sampling frequency in the ADC is also reduced. But this TR modulation technique has two drawbacks. One is half of the energy is spent on transmitting references so the power efficiency is low. The other is a serious performance degradation because the template used by the correlator is noisy. Averaging several reference signals to produce a template can reduce the noise level [4], [5]. But in this simple multiple access (MA) TR system, the averaging process might need to be done using digital signal processing. In this situation, the receiver must have a high-sampling-frequency ADC, and the receiver structure is no longer ”simple”.

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In order to maintain a low-sampling-frequency receiver, only a few delays in the average process are acceptable so the correlation can still be implemented in the analog part of the receiver. To increase the power efficiency, differential encoding is applied so the data-modulated waveform can also serve as a template [5]. These two characteristics are included in the generalized signal model described in Section II, and are detailed in Section III.

Repetition codes have been originally proposed in a binary UWB system [1] to achieve the adequate signal energy required for detection in the receiver, but might not be the best choice in the bit error probability (BEP) sense. Characteristics of some block codes can enhance the BEP performance. An M-ary UWB TR system employing block codes, which can also be described by the generalized TR signal model in Section II, are discussed in detail in Section IV. This system exploits the benefit of the minimum distance of block codes, and still maintains the modulation format so that the conventional correlation receiver which employs one delay and one correlator remains unchanged. Section V gives several numerical examples of both the binary and M-ary systems, and Section VI draws the conclusions.

II. A GENERALIZED MA TR SIGNAL MODEL

The transmitted signal of one user in this multiple access binary or M-ary TR modulation system can be generally expressed as

$$s_{\mathrm{tr}}(t) = \sum_{i=-\infty}^{\infty} d_{\lfloor i/N_{\mathrm{a}}\rfloor} q_{\lfloor i/N_{\mathrm{a}}\rfloor, \mathrm{mod}(i,N_{\mathrm{a}})} \times g_{\mathrm{tr}}\left(t - \left\lfloor \frac{i}{N_{\mathrm{a}}}\right\rfloor T_{\mathrm{f}} - \mathrm{mod}(i,N_{\mathrm{a}})T_{\mathrm{d}} - c_{\lfloor i/N_{\mathrm{a}}\rfloor}T_{\mathrm{c}}\right) \quad (1)$$

where N_{a} is the number of pulses in one frame which includes N_{d} data pulses and N_{r} reference pulses which are designed such that $a = N_{\mathrm{d}}/N_{\mathrm{r}}$ is an integer, $\lfloor x\rfloor$ is the integer part of x, $\mathrm{mod}(y,z)$ is y modulo z, T_{f} is the frame duration so the average repetition duration for each pulse is $T_{\mathrm{f}}/N_{\mathrm{a}}$, T_{d} is the time separation between two adjacent pulses in one frame, T_{c} is the time slot duration, $\{c_j\} \in \{0, 1, \ldots, N_{\mathrm{h}}-1\}$ and $\{d_j\} \in \{+1, -1\}$ are periodic pseudo-random hopping and spreading sequences which help avoiding catastrophic collisions and smooth spikes in the power spectral by increasing the period of the transmitted data, and $\{q_{j,l}\}$ are the code symbols of the l^{th} pulse in the j^{th} frame which depend on the data being transmitted. In (1), the user indicator is not shown because only single user performance is analyzed in this paper. For a multiple user system, $\{c_j\}$, $\{d_j\}$, T_d and $\{q_{j,l}\}$ are all user dependent.

Generally speaking, $\{q_{j,l}\}$ are not necessarily binary, and represent a pulse amplitude modulation (PAM). Even for $\{q_{j,l}\} \in \{+1,-1\}$, the system described in (1) can still be M-ary with $M \geq 2$, depending on how we correspond information bits to code symbols. In addition, the values of N_a, N_r, and N_d can be different for each user if the system is a variable transmission rate system. Pulses in the same frame have the same time shift and are multiplied by the same spreading code symbol. Thus the number of pulses in one frame affects the probability of collisions. An signal example is plotted in Figure 1.

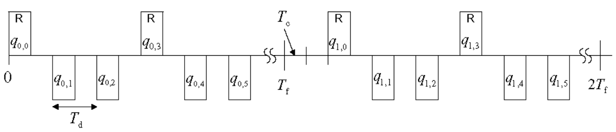

Fig. 1. An example of the novel TR method with $N_\mathrm{r} = 2$, $N_\mathrm{d} = 4$, $c_0 = 0$, $c_1 = 2$, $d_0 = 1$, and $d_1 = 1$. The letter R indicates a reference pulse.

After going through a multipath channel, the received signal from one user with perfect synchronization is

$$r(t) = \sum_{i=-\infty}^{\infty} d_{\lfloor i/N_\mathrm{a}\rfloor} q_{\lfloor i/N_\mathrm{a}\rfloor,\mathrm{mod}(i,N_\mathrm{a})} g\left(t - \left\lfloor \frac{i}{N_\mathrm{a}} \right\rfloor T_\mathrm{f} - \mathrm{mod}(i, N_\mathrm{a}) T_\mathrm{d} - c_{\lfloor i/N_\mathrm{a}\rfloor} T_\mathrm{c}\right) + n(u,t) \qquad (2)$$

where $g(t)$, a single received waveform, is the convolution of the transmitted pulse $g_\mathrm{tr}(t)$ and the channel impulse response which includes the antenna and band-limited filter effects, $n(u,t)$ is the band-limited white Gaussian noise with one-sided power spectral density N_0 and bandwidth B_w.

III. Binary TR Systems

A. System Structure

In this binary system using the differential encoder, each bit along with the current state decide the corresponding coded symbols $q_{l,k}$. The repetition time of each bit is an integer multiple (M_b) of N_r in order to simplify the receiver structure. And either a is assumed an integer multiple of M_b or M_b is an integer multiple of a in this section. This is not a necessary condition in the implementation, and only sustains to make the BEP analysis easily illustrated but without loss of generality. If a and M_b are two arbitrary numbers, the error probability of each bits could be different. For $M_\mathrm{b} \geq a$, each bit is conveyed in M_b/a frames, otherwise, each frame contains a/M_b bits.

The definition of code symbols $q_{l,k}$ in this binary system is

$$q_{l,k} = \begin{cases} 1 & \mathrm{mod}(k, a+1) = 0 \\ q_{l,k-1} \times b_{\left\lfloor \frac{la}{M_\mathrm{b}} \right\rfloor + \zeta} & \text{otherwise,} \end{cases}$$

where

$$\zeta = \begin{cases} 0 & M_\mathrm{b} \geq a \\ \left\lfloor \frac{\mathrm{mod}(k,a+1)-1}{M_\mathrm{b}} \right\rfloor & M_\mathrm{b} < a. \end{cases}$$

Without the spreading sequence, the amplitude of the pulse whose position is an integer multiple of $a+1$ in each frame is always equal to one, and this pulse serves as a reference. The spreading sequence converts the polarities of pulses in one frame together, so the correlation receiver still apply here. Note that the minimum value of a is one, namely the maximum number of reference pulses in one frame (or bit) is equal to the number of data-modulated pulses, and half of the energy is spent on transmitting reference pulses. When $N_\mathrm{r} = N_\mathrm{d} = 1$, it represents conventional TR systems. By using Figure 1 and $M_\mathrm{b} = 1$ as an example, $(q_{0,0}, q_{0,1}, q_{0,2}, q_{0,3}, q_{0,4}, q_{0,5}) = (1, b_0, b_1, 1, b_0, b_1)$ and $(q_{1,0}, q_{1,1}, q_{1,2}, q_{1,3}, q_{1,4}, q_{1,5}) = (1, b_2, b_3, 1, b_2, b_3)$.

B. Detection and Performance Evaluation

Because the time separation between any two adjacent reference pulses is fixed to $(a+1)T_\mathrm{d}$ and N_r reference pulses exist in one frame, we need $N_\mathrm{r}-1$ fixed delays $(a+1)T_\mathrm{d}, 2(a+1)T_\mathrm{d}, \ldots, (N_\mathrm{r}-1)(a+1)T_\mathrm{d}$ in the receiver to average all the references in one frame. The correlator template is now the average of N_r references, and is cleaner than one reference pulse if $N_\mathrm{r} > 1$. The larger the N_r is, the cleaner the template is. The receiver complexity is also higher but feasible. In the one-shot detection of the 0^{th} bit, decision statistics are

$$\begin{aligned} z(l,j) &= \int_{I_\mathrm{L}}^{I_\mathrm{L}+T_\mathrm{corr}} \left[\sum_{n=0}^{N_\mathrm{r}-1} r(t - n(a+1)T_\mathrm{d})\right] \\ &\times \left[\sum_{m=0}^{N_\mathrm{r}-1} r(t - m(a+1)T_\mathrm{d} - T_\mathrm{d})\right] dt \\ &= b_0 N_\mathrm{r}^2 \eta E_\mathrm{p} + n_\mathrm{d}(l,j) + n_\mathrm{r}(l,j) + n_\mathrm{n}(l,j) \end{aligned}$$

where $0 \leq l \leq \lceil \frac{M_\mathrm{b}}{a} \rceil - 1$, $0 \leq j \leq \min(M_\mathrm{b}, a) - 1$, $I_\mathrm{L} = lT_\mathrm{f} + c_l T_\mathrm{c} + (N_\mathrm{a} - a + j)T_\mathrm{d}$, $E_\mathrm{p} = \int_0^\infty g^2(t)dt$, $\eta = \int_0^{T_\mathrm{corr}} g^2(t)dt/E_\mathrm{p}$ is the efficiency factor, T_corr is the correlator's integration time, and

$$n_\mathrm{d}(l,j) = q_{l,N_\mathrm{a}+j-a} N_\mathrm{r} \sum_{m=0}^{N_\mathrm{r}-1} \int_0^{T_\mathrm{corr}} g(t) \times n(u, t - m(a+1)T_\mathrm{d} - T_\mathrm{d} + I_\mathrm{L}) dt, \qquad (3)$$

$$n_\mathrm{r}(l,j) = q_{l,N_\mathrm{a}+j-a-1} N_\mathrm{r} \sum_{m=0}^{N_\mathrm{r}-1} \int_0^{T_\mathrm{corr}} g(t) \times n(u, t - m(a+1)T_\mathrm{d} + I_\mathrm{L}) dt, \qquad (4)$$

$$n_\mathrm{n}(l,j) = \sum_{m'=0}^{N_\mathrm{r}-1} \sum_{m=0}^{N_\mathrm{r}-1} \int_0^{T_\mathrm{corr}} n(u, t - m(a+1)T_\mathrm{d} + I_\mathrm{L}) \times n(u, t - m'(a+1)T_\mathrm{d} - T_\mathrm{d} + I_\mathrm{L}) dt. \qquad (5)$$

The decision rule is

$$z = \sum_{l=0}^{\lceil M_\mathrm{b}/a \rceil - 1} \sum_{j=0}^{\min(M_\mathrm{b},a)-1} z(l,j) \underset{-1}{\overset{1}{\gtrless}} 0, \qquad (6)$$

and the demodulation block diagram is plotted in Figure 2.

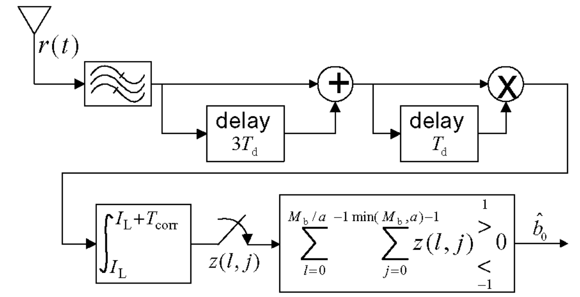

Fig. 2. Demodulation block diagram of the signal plotted in Figure 1.

Generally speaking, $z = \sum_l \sum_j z(l,j)$ does not have Gaussian distribution because of the noise $\times$ noise term $n_{\mathrm{n}}(l,j)$, and the probability density function of z is difficult to calculate. But under some circumstances, the BEP using (6) can be evaluated theoretically by using the quadratic Gaussian form (see Appendix B, [6]). Unfortunately, this binary system with $N_{\mathrm{d}} = N_{\mathrm{r}} = 1$ only, which indicates the conventional TR system, can fit those conditions, and its exact BEP with an idea front-end bandpass filter was evaluated [7]. For a UWB system, due to its large noise time$\times$bandwidth, the central limit theorem is applied, and the noise $\times$ noise can be modelled Gaussianly. The BEP is therefore a function of the mean and variance of z in (6). The means of $n_{\mathrm{r}}(l,j)$ and $n_{\mathrm{d}}(l,j)$ are zero because of the white noise process $n(u,t)$, and the mean of $n_{\mathrm{n}}(l,j)$ is also zero because T_{d} is much greater than the noise correlation time. Therefore,

$$\mathbb{E}\{z(l,j)\} = b_0 N_{\mathrm{r}}^2 \eta E_{\mathrm{p}}, \quad \text{for all } l, j. \tag{7}$$

Apparently, $n_{\mathrm{d}}(l,j+1) = q_{l,N_{\mathrm{a}}+j-a+1} q_{l,N_{\mathrm{a}}+j-a-1} n_{\mathrm{r}}(l,j)$ due to the differential encoder in transmitters, otherwise the noises in (3), (4) and (5) are uncorrelated. The covariances of $z(l,j)z(l',j')$ can be computed as in [5], and

$$\begin{aligned}
&\mathbb{C}\mathrm{ov}\{z(l,j)z(l',j')\} \qquad\qquad (8)\\
&= \begin{cases} N_{\mathrm{r}}^3 N_0 \eta E_{\mathrm{p}} + \frac{1}{2} N_{\mathrm{r}}^2 B_{\mathrm{w}} T_{\mathrm{corr}} N_0^2 & l = l', j = j' \\ \frac{1}{2} q_{l,N_{\mathrm{a}}+j+1-a} q_{l,N_{\mathrm{a}}+j-1-a} N_{\mathrm{r}}^3 N_0 \eta E_{\mathrm{p}} & l = l', j - j' = 1 \\ \frac{1}{2} q_{l,N_{\mathrm{a}}+j+2-a} q_{l,N_{\mathrm{a}}+j-a} N_{\mathrm{r}}^3 N_0 \eta E_{\mathrm{p}} & l = l', j' - j = 1 \\ 0 & \text{otherwise.} \end{cases}
\end{aligned}$$

By using (7), (8), the mean and variance of z are

$$\begin{aligned}
\mathbb{E}\{z\} &= b_0 N_{\mathrm{r}}^2 \eta E_{\mathrm{p}} \left\lceil \frac{M_{\mathrm{b}}}{a} \right\rceil \min(M_{\mathrm{b}}, a) = b_0 N_{\mathrm{r}}^2 \eta E_{\mathrm{p}} M_{\mathrm{b}}, \\
\mathbb{V}\mathrm{ar}\{z\} &= M_{\mathrm{b}} N_{\mathrm{r}}^3 N_0 \eta E_{\mathrm{p}} \left(2 - \frac{1}{\min(M_{\mathrm{b}}, a)} \right) \\
&+ \frac{1}{2} M_{\mathrm{b}} N_{\mathrm{r}}^2 B_{\mathrm{w}} T_{\mathrm{corr}} N_0^2.
\end{aligned}$$

Due to the symmetry of the receiver noise and transmitted data bits, the single user multipath BEP performance conditioned on one channel realization using Gaussian assumption is

$$\begin{aligned}
P_{\mathrm{b}} &= Q\left(\left[\left(1 + \frac{1}{a}\right) \left(2 - \frac{1}{\min(M_{\mathrm{b}}, a)}\right) \left(\frac{N_0}{\eta E_{\mathrm{b}}}\right) \right.\right. \\
&\left.\left. + \frac{B_{\mathrm{w}} T_{\mathrm{corr}} M_{\mathrm{b}}}{2} \left(1 + \frac{1}{a}\right)^2 \left(\frac{N_0}{\eta E_{\mathrm{b}}}\right)^2 \right]^{-\frac{1}{2}} \right)
\end{aligned} \tag{9}$$

where $Q(\cdot)$ is the Gaussian Q-function, and the bit energy $E_{\mathrm{b}} = M_{\mathrm{b}} N_{\mathrm{r}} (1 + \frac{1}{a}) E_{\mathrm{p}}$ because one bit uses $\frac{N_{\mathrm{r}} M_{\mathrm{b}}}{a}$ reference pulses in average. It is worth noting that the multiple access capability, which is not shown here, is expected to become worse with increasing N_{a} while M_{b} is fixed because the probability of collision increases.

IV. M-ary TR Systems

A. System Structure

The TR signal model in (1) can also be applied to an M-ary modulated system by utilizing block codes. The transmitted codeword $\mathbf{v}_j \triangleq [v_{j,0}, v_{j,1}, \ldots, v_{j,N_{\mathrm{s}}-1}]^{\mathrm{t}}$ are selected by $m = \log_2 M$ bits $\mathbf{b}_j \triangleq [b_{jm}, b_{jm+1}, \ldots, b_{(j+1)m-1}]^{\mathrm{t}}$ from the code book $\{\mathbf{u}_0, \mathbf{u}_1, \ldots, \mathbf{u}_{M-1}\}$. The code length N_{s} is assumed an integer multiple of N_{d}, which is not a necessary but a convenient assumption. In this system each codeword can be transmitted in one or more than one frame, depending on the ratio of N_{s} and N_{d}. The selected codeword is mapped to the modulated code symbols as follows

$$q_{l,k} = \begin{cases} 1 & \mathrm{mod}(k, a+1) = 0 \\ \xi \times v_{\left\lfloor \frac{l}{N_{\mathrm{s}}/N_{\mathrm{d}}} \right\rfloor, \zeta} & \text{otherwise,} \end{cases} \tag{10}$$

where $\zeta = \mathrm{mod}\left(l, \frac{N_{\mathrm{s}}}{N_{\mathrm{d}}}\right) N_{\mathrm{d}} + \left\lfloor \frac{k}{a+1} \right\rfloor a + \mathrm{mod}(k, a+1) - 1$, and

$$\xi = \begin{cases} 1 & N_{\mathrm{r}} > 1 \\ q_{l,k-1} & N_{\mathrm{r}} = 1. \end{cases} \tag{11}$$

Transmitting each code symbol in the selected codeword more than one time is not considered here, therefore transmitting more than one reference pulses and implementing the average process in each frame can complicate the receiver more compared to the system described in the previous section. For $N_{\mathrm{r}} > 1$, each set, which is defined as one reference pulse and its a following data pulses, is different from other sets in the same frame. Thus extra delays are required to retrieve each code symbols in different sets separately. When $N_{\mathrm{r}} = 1$ and $a = N_{\mathrm{d}}$, with a differential encoder in the transmitter, the receiver can retrieve all the code symbols by using the conventional correlation receiver with only one delay T_{d}. The performance improvement compared to the traditional TR system is gained by increasing the power efficiency and selecting a good block code. The performance of this $N_{\mathrm{r}} = 1$ case is discussed in the following.

B. Detection and Performance Evaluation

In the detection of the transmitted codeword $\mathbf{v}_0$, the decision statistics by using a correlation receiver are $\mathbf{y}_0 = [y_{0,0}, y_{0,1}, \ldots, y_{0,N_{\mathrm{s}}-1}]^{\mathrm{t}}$ where $y_{0,m} = z\left(\left\lfloor \frac{m}{N_{\mathrm{d}}} \right\rfloor, \mathrm{mod}(m, N_{\mathrm{d}}) + 1\right)$, and

$$z(l,j) = \int_{lT_{\mathrm{f}}+c_l T_{\mathrm{c}}+jT_{\mathrm{d}}}^{lT_{\mathrm{f}}+c_l T_{\mathrm{c}}+jT_{\mathrm{d}}+T_{\mathrm{corr}}} r(u,t) r(u, t - T_{\mathrm{d}}) dt \tag{12}$$

$$= v_{0,lN_{\mathrm{d}}+j-1} \eta E_{\mathrm{p}} + n_{\mathrm{d}}(l,j) + n_{\mathrm{r}}(l,j) + n_{\mathrm{n}}(l,j) \tag{13}$$

for $0 \le l \le \frac{N_s}{N_d} - 1$, $1 \le j \le N_d + 1$, and

$$n_d(l,j) = q_{l,j}\int_0^{T_{\rm corr}} g(t)n(u, t + lT_f + c_lT_c + (j-1)T_d)dt,$$

$$n_r(l,j) = q_{l,j-1}\int_0^{T_{\rm corr}} g(t)n(u, t + lT_f + c_lT_c + jT_d)dt,$$

$$n_n(l,j) = \int_0^{T_{\rm corr}} n(t + lT_f + c_lT_c + jT_d) \times n(u, t + lT_f + c_lT_c + (j-1)T_d)dt.$$

The mean of $z(l,j)$ conditioned on the transmitted codeword is

$$\mathbb{E}\{z(l,j)|\mathbf{v}_0\} = \overline{z(l,j)} = v_{0,lN_d+j-1}\eta E_p. \qquad (14)$$

It is clear that $q_{l,j}q_{l,j-2}n_d(l,j) = n_r(l,j-1)$, otherwise the noise terms above are uncorrelated. So the covariance of any two statistics conditioned on the transmitted codeword is

$$\mathbb{C}\mathrm{ov}\{z(l,j)z(l',j')|\mathbf{v}_0\} \qquad (15)$$
$$= \begin{cases} N_0\eta E_p + \frac{1}{2}B_w T_{\rm corr} N_0^2 & l=l', j=j' \\ \frac{1}{2}q_{l,j+1}q_{l,j-1}N_0\eta E_p & l=l', j=j'-1 \\ \frac{1}{2}q_{l,j}q_{l,j-2}N_0\eta E_p & l=l', j=j'+1 \\ 0 & \text{otherwise}, \end{cases}$$

where $q_{l,j+1}q_{l,j-1}$ and $q_{l,j}q_{l,j-2}$ can be related to the transmitted codeword $\mathbf{v}_0$ by using (10) and (11).

Both (14) and (15) show the mean and covariance matrix of $\mathbf{y}_0$ depend on the transmitted codeword $\mathbf{v}_0$. By defining $\bar{\mathbf{y}}_0 \triangleq \mathbb{E}\{[y_{0,0}, y_{0,1}, \ldots, y_{0,N_s-1}]^t\}$, the covariance matrix of $\mathbf{y}_0$ conditioned on the transmitted codeword $\mathbf{v}_0 = \mathbf{u}_j$ is

$$M_{\mathbf{u}_j} = \mathbb{E}\{[\mathbf{y}_0 - \bar{\mathbf{y}}_0][\mathbf{y}_0 - \bar{\mathbf{y}}_0]^t|\mathbf{u}_j\} \qquad (16)$$

which can be acquired by applying (15). Maximum likelihood detection, minimum distance detection, or hard detection can be exploited in the digital signal processing to detect the transmitted codeword and the corresponding information bits. By assuming the noise $\times$ noise Gaussian distributed, the likelihood function is

$$L(\mathbf{y}_0|\mathbf{u}_j) = \frac{1}{\sqrt{2\pi\det(M_{\mathbf{u}_j})}} \times \exp\left\{-\frac{1}{2}[\mathbf{y}_0 - \bar{\mathbf{y}}_0]^t M_{\mathbf{u}_j}^{-1}[\mathbf{y}_0 - \bar{\mathbf{y}}_0]\right\}.$$

Maximum likelihood detection chooses the codeword which maximizes the likelihood function

$$\hat{\mathbf{v}}_0 = \max_j L(\mathbf{y}_0|\mathbf{u}_j).$$

Minimum distance detection selects the codeword whose distance to $\mathbf{y}_0$ is the shortest

$$\begin{aligned}\hat{\mathbf{v}}_0 &= \min_j \|\mathbf{y}_0 - \mathbf{u}_j\| \\ &= \min_j \|\mathbf{y}_0 - \mathbf{u}_j\|^2 \\ &= \min_j \|\mathbf{u}_j\|^2 - 2\mathbf{y}_0^t\mathbf{u}_j \end{aligned} \qquad (17)$$

where $\|\cdot\|$ denotes the norm of a vector. If codewords in the code book have the same norm, (17) can be reduced further to

$$\hat{\mathbf{v}}_0 = \max_j \mathbf{y}_0^t\mathbf{u}_j,$$

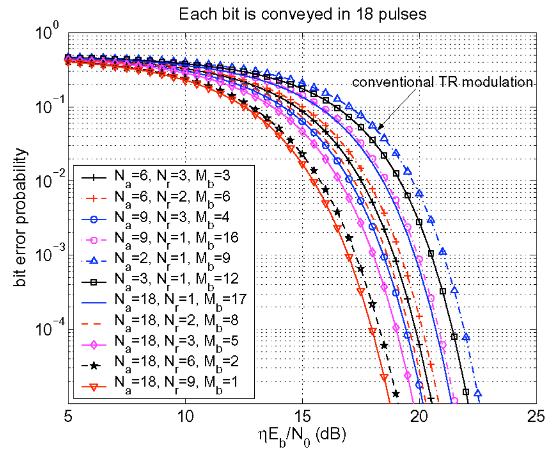

Fig. 3. BEPs of the binary TR system with $B_w = 4$GHz, $T_{\rm corr} = 20$ ns, and different values of N_a, N_r, and M_b. In this figure, each bit is conveyed in 18 pulses.

which is equal to the maximum correlation detection. Hard detection quantizes $\{y_{0,m}\}_{m=0}^{N_s-1}$ to +1 or -1 using a one bit ADC, then correlates the quantized $\mathbf{y}_0$ with eligible codewords in the code book to find the one producing the maximum correlation,

$$\hat{\mathbf{v}}_0 = \max_j \mathrm{sgn}(\mathbf{y}_0^t)\mathbf{u}_j,$$

where

$$\mathrm{sgn}(x) = \begin{cases} +1 & x \ge 0 \\ -1 & x < 0, \end{cases}$$

and $\mathrm{sgn}(\mathbf{y}_0^t) = [\mathrm{sgn}(y_{0,0}), \mathrm{sgn}(y_{0,1}), \ldots, \mathrm{sgn}(y_{0,N_s-1})]^t$.

V. Numerical Examples

Equation (9) with different values of N_r, N_d, and M_b is plotted in Figure 3 with $B_w = 4$GHz and $T_{\rm corr} = 20$ ns. For all the curves, each bit is transmitted through 18 pulses which include reference and data pulses. For a specific N_r which determines the noise variance in the correlator template, the larger the N_a (or N_d) is, the better the BEP performance is because of higher power efficiency. For a specific N_a, a larger N_r means less bit energy is spent on data pulses, but more reference pulses can be averaged as a correlator template. A better performance under this situation indicates that the noisy template is a more serious problem than the low power efficiency in a TR system. For this 18 pulses per bit case, Figure 3 shows that the difference between the best and worst performance at BEP=1e-4 is 4.4dB.

The BEP performance of the UWB system with M-ary TR modulation in a single user multipath environment with $T_{\rm corr} = 20$ ns and $B_w = 4$GHz is simulated using repetition codes, orthogonal Walsh-Hadamard codes [8], as well as biorthogonal Walsh-Hadamard codes which include Wash-Hadamard codes and their negatives, and results are plotted in Figure 4 and 5. Figure 4 shows the minimum distance detection, with a simpler digital signal processing structure, performs almost the same as the maximum likelihood detection. The minimum distance detection does not consider the covariance of any two correlator outputs in (15) which, seen from the structure of the covariance, does not affect the performance much. The hard detection, which uses only one bit to represent the correlator output, has the simplest receiver structure among these three detection methods with a 1.5dB penalty. This figure also exhibits that codes with longer length in the same category perform better because of the larger distance of two codewords.

For codewords with the same norm which is the case for repetition, Walsh-Hadamard, and biorthogonal Walsh-Hadamard codes, the BEP depends on the distributions of the cross-correlations of any two codewords, $\mathbf{u}_i^t\mathbf{u}_j$, in the code book. The smaller the cross-correlations are, the more unlike the codewords are, and the better the performance is. When E_b/N_0 increases, the largest cross-correlation dominates the BEP. Figure 5 compares repetition codes to orthogonal Walsh-Hadamard codes with the same code length (M) by using the minimum distance detection. When $M = 4$, the cross-correlation of any two repetition codewords is either 0 or -4, and that of any two Wash-Hadamard codewords is always 0. Therefore, repetition codes perform better than Wash-Hadamard codes. But for $M \geq 8$, the largest cross-correlation of repetition codes is always greater than that of Wash-Hadamard codes. Thus Wash-Hadamard codes outperform repetition codes with increasing E_b/N_0.

Figure 4 also compares repetition codes to biorthogonal Walsh-Hadamard codes with the same code length ($M/2$) using minimum distance detection. For $M = 4$, biorthoghnal codewords are the same with the repetition codewords, thus their performance is the same. When $M \geq 8$, one of the cross-correlations of any two biorthogonal codewords is equal to $-M/2$, and others are equal to 0. But we can always find two repetition codewords with cross-correlation greater than zero. Therefore, biorthogonal codes outperform repetition codes.

For the same value of M and E_b/N_0, the codewords in Figure 4 with the code length $M/2$ perform better than the codewords with the code length M in Figure 5. This again illustrates that the noise $\times$ noise degrades BEP performance more when the pulse energy to the noise power ratio of the correlator input is smaller. However in a realistic system, how large the pulse energy can be depends on the hardware issues as well as the FCC regulation.

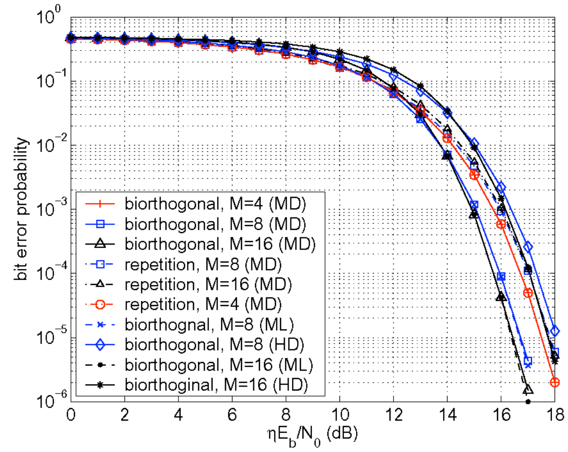

Fig. 4. BEPs of biorthogonal Walsh-Hadamard codes and repetition codes. ML, MD, and HD denote maximum likelihood detection, minimum distance detection, and hard detection, respectively.

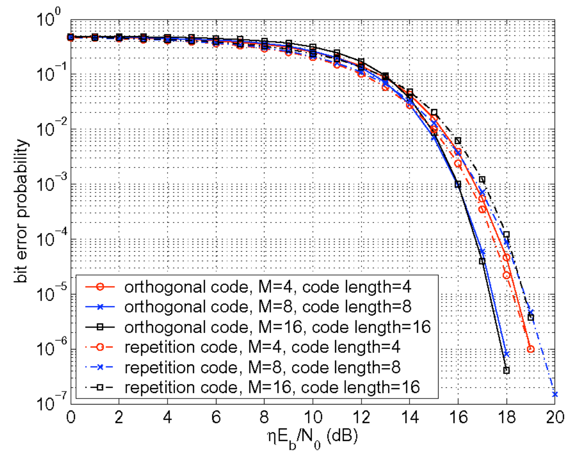

Fig. 5. BEP comparisons between orthogonal Walsh-Hadamard codes and repetition codes by using the minimum distance detection.

VI. Conclusions

This paper proposes a generalized TR signal model for a multiple access UWB system which can be applied to both binary and M-ary modulation. For the binary system, the BEP performance and receiver complexity can be traded by choosing different system parameters. For the M-ary system, block codes other than repetition codes are exploited. Results show both orthogonal and biorthogonal codes outperform repetition codes when $M \geq 8$, and larger the code book size is, better the performance is. The performance figures in this paper again illustrate that the noise $\times$ noise degrades BEP performance seriously when the pulse energy to the noise power ratio is small.

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