Monobit Digital Eigen-Based Receiver for Transmitted-Reference UWB Communications

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***Abstract*—Transmitted-reference impulse radio (TR-IR) is a low complexity UWB system which is suitable for highly dispersive multipath channel. However, TR-IR requires a wideband analog delay line which has high complexity and high energy consumption. In this letter, we propose a digital eigen-based (EB) receiver which first converts the analog signal to digital signal and then demodulates the received signal in digital domain. Computer simulation results show that the proposed receiver can outperform the conventional autocorrelation receiver. We also proposed a monobit digital EB (MEB) receiver as a low complexity alternative to the EB receiver. The bit-error-rate performance of MEB receiver have also been studied theoretically to show the quantization effect in this letter.**

***Index Terms*—Eigen-based (EB) receiver, autocorrelation receiver (AcR), impulse radio (IR), ultra-wideband (UWB).**

I. INTRODUCTION

TRANSMITTED-reference impulse radios (including differential transmitted-reference impulse radios) with autocorrelation receiver (TR-IR/AcR) have been proposed in [1]-[13]. The idea behind TR-IR/AcR is to exploit multipath diversity in slowly time-varying channels by coupling one or more data modulated pulses with one or more unmodulated reference (or pilot) pulses. The AcR delays the received pilot pulses to perfectly align with the data modulated pulses and their product is integrated for symbol detection.

The implementation of AcR generally requires wideband analog delay line (WADL) with length of several tens nanoseconds. However, to design WADL with such length in the low-power integrated circuit is daunting [14], [15]. To avoid the WADL, several alternative implementations of the TR idea have been proposed in [15]-[16]. In [15] and [16], the data modulated pulses and reference pulses are overlapped in time domain but they are separated through frequency shift and code-multiplexed schemes, respectively.

Recently, Zhang et al proposed an eigen-based coherent detector for UWB communications [17]-[18]. In a dense multipath environment, the transmitted signal is distorted by the superposition of randomly arrived multipath components. Therefore, employing the waveform received from the line-of-sight (LOS) component as template for signal detector is not optimal. Zhang et al treated the received signal as a random process with multiple dimensions and employed multiple templates with different base functions to detect the signal.

Inspired by [17]-[18], we propose a digital eigen-based (EB) receiver for TR-IR communications in this letter. Based on the received signal statistics, the received signal is decomposed into multiple dimensions. We collect the received signal energy by only exploiting the signal dimensions with larger eigenvalues. In doing so, the signal-to-noise ratio (SNR) at the receiver is improved since the channel noise is uniformly distributed over the multiple signal dimensions. We will show in Section IV that the proposed EB receiver outperforms the conventional AcR when the signal dimensions to be exploited are properly chosen. The proposed EB receiver converts the received analog signal to digital signal. The digital signal can be easily delayed for demodulation. Therefore, the WADL with high complexity and high energy consumption can be bypassed. It is noticed that TR-IR receiver based on analog to digital conversion in the frequency domain has been proposed in [19]. The proposed receiver in [19] does not consider the received signal statistics which is the major difference from our proposed EB receiver.

To further simplify the receiver structure, we also propose to study the monobit digital EB (MEB) receiver, which provides ideal tradeoff between system complexity and BER performance. The idea of applying monobit digital receiver with reduced complexity on UWB system was first introduced in [20]. It was shown that the proposed sigma-delta monobit modulation scheme with 5 times Nyquist rate oversampling can achieve the bit-error-rate (BER) performance of full-resolution digital receiver in addictive white Gaussian noise (AWGN) channel. Later on, digital receivers with finite resolution were also proposed [8], [9], and [21]. In this letter, it will be shown that the proposed MEB receiver with a sampling rate about 0.67 GHz has better system performance than the monobit AcR with a sampling rate about 5.99 GHz. Furthermore, we will derive the BER performance of MEB receiver theoretically to show the quantization effects.

The rest of the letter is organized as follows. Section II describes the system model, including the transmitter, the UWB channel, and the proposed receivers. In Section III, BER performances of the proposed receivers are derived. Theoretically predicted and computer simulated results are provided and discussed in Section IV. We conclude and summarize our letter in Section V.

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II. System Model

A. The Transmitter

For simplicity, we consider a peer-to-peer TR-IR system in quasi-static UWB environment in this letter. The proposed scheme can be applied to multiple access systems when the psuedo-random spreading codes as those proposed in [8] are included. To increase the transmission rate, the former transmitted data modulated pulses are used as pilot pulses for current symbol detection. Therefore, the system model is similar to that in [4], which is called differential TR-IR system.

The sequence of independent and identically distributed data symbols $\cdots b_{-1}b_0b_1b_2\cdots$, where $b_i \in \{-1,1\}$, is differentially encoded into another symbol sequence $\cdots d_{-1}d_0d_1d_2\cdots$, where $d_i = (b_i d_{i-1}) \in \{-1,1\}$. Each symbol interval of duration T is divided into N_s frames, each with a duration of T_f. The transmitted signal is described by

$$s(t) = \sum_i \sum_{j=0}^{N_s-1} d_i \omega(t - iT - jT_f) \tag{1}$$

where $\omega(t)$ is a causal pulse of duration T_ω.

B. The Channel Model

The transmitted signal propagates through a quasi-static dense multipath fading UWB channel. The random channels are generated according to [22], where the clusters and the rays in each cluster form Poisson arrival processes with different, but fixed rates. The amplitude of each ray is modeled as a lognormal distributed random variable. The channel impulse response model can be written, in general, as

$$g(t) = \sum_l \alpha_l \delta(t - \tau_l) \tag{2}$$

where α_l and τ_l denote, respectively, the amplitude and the delay associated with the l^{th} path. We assume that the signal arriving at the receiver is perfectly time-synchronized and the path delays are normalized with $\tau_1 = 0$. Furthermore, to preclude intersymbol interference and intrasymbol interference, we set $T_f \geq T_\omega + T_d$, where T_d is the maximum excess delay of the UWB channel.

At the receiver, the received signal is expressed as follows

$$r(t) = \sum_i \sum_{j=0}^{N_s-1} d_i h(t - iT - jT_f) + n(t) \tag{3}$$

where

$$h(t) = \omega(t) \otimes g(t) \tag{4}$$

in which $\otimes$ denotes convolution. In (3), $n(t)$ is lowpass filtered (LPF) additive white Gaussian noise (AWGN) with two-sided power spectral density $N_o/2$. The autocorrelation function of $n(t)$ is

$$R_n(\tau) = \mathrm{E}[n(t+\tau)n(t)] = N_o W \mathrm{sinc}(W\tau) \tag{5}$$

where W $(W \gg 1/T)$ is the bandwidth of the lowpass filter. The ratio, E_b/N_o, of the system is defined as $\frac{2N_s}{N_o}\int_0^{T_\omega} \omega^2(t)dt$.

C. The Digital Eigen-Based (EB) Receiver

In [17]-[18], the received UWB signal is treated as random process since it contains randomly arrived multipath components and severe inter pulse interference exists. In this letter, we treat $r(t)$ as a multi-dimensional random process and employ the EB receiver to detect $r(t)$ as in [17]-[18]. Because $r(t)$ is the linear combination of $h(t)$ and the channel noise, it is important to study the covariance structure of $h(t)$, which is as follows

$$R_h(\tau) = \mathrm{E}[h(t + \tau + (k-1)T_c)h(t + (k-1)T_c)]. \tag{6}$$

In (6), T_c is the support length of eigenfunctions. For convenience, T_c is designed to be $T_c = T_f/L$, where L is a positive integer. Let $\phi_p(t)$ denote the eigenfunction of the covariance function $R_h(\tau)$ such that

$$\int_0^{T_c} R_h(t-\tau)\phi_j(t)dt = \lambda_p \phi_p(t),\ 0 \leq t < T_c \tag{7}$$

with $\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq ...$ denoting the eigenvalues. Therefore, the k^{th} chip of the received signal can be expanded as

$$r(t) = \sum_{p=0}^{\infty} r_{kp}\phi_p(t-(k-1)T_c), (k-1)T_c \leq t < kT_c \tag{8}$$

where the projection coefficients r_{kp} are the correlation output given by

$$r_{kp} = \int_{(k-1)T_c}^{kT_c} r(t)\phi_p(t-(k-1)T_c)dt. \tag{9}$$

Because $\{r_{kp}\}$ contain all the information about $r(t)$, we can detect the received signal by using $\{r_{kp}\}$. The detector implements

$$D_i : \begin{cases} > 0; \text{ decide } b_i = +1 \\ \leq 0; \text{ decide } b_i = -1 \end{cases} \tag{10}$$

where D_i is the decision statistics expressed as follows

$$D_i = \sum_{p=1}^{P} \lambda_p \sum_{k=1}^{\lceil T_{int}/T_c \rceil} \sum_{j=0}^{N_s-1} r_{(iN_sL+jL+k)p} r_{(iN_sL-N_sL+jL+k)p}. \tag{11}$$

In (11), $\lceil \bullet \rceil$ denotes integer ceiling, P is the number of signal dimensions to be exploited for symbol detection, and T_{int} is the integration interval in conventional AcR which is $T_\omega \leq T_{int} \leq T_d$.

In [17], Zhang et al estimate the eigenvalues, $\{\lambda_p\}$, and eigenfunctions, $\{\phi_p\}$, from real UWB data. In this letter, we estimate the eigenvalues and eigenfunctions by using the UWB channel models [22]. Take UWB channel model CM 1 [22] as an example. The random channels generated according to CM 1 are convoluted with the pulse, $\omega(t)$, to obtain the channel responses, $\{h(t)\}$. The support length of eigenfunctions, T_c, is chosen to be 1.50 ns. We estimate the covariance structure of channel response, $R_h(\tau)$, and thus its eigenvalues and eigenfunctions by taking ensemble averaging of $[h(t+\tau+(k-1)T_c)h(t+(k-1)T_c)]$ instead of expectation as that in (6). The above mentioned eigenvalues and eigenfunctions are applicable to any random channel generated by UWB channel model CM 1.

D. Monobit Digital Eigen-Based (MEB) Receiver

From the description above, we know that the proposed EB receiver does not require the WADL which is prerequisite for the conventional AcR. However, if the number of signal dimensions to be exploited, P, is large, the receiver complexity is still high. We want to further reduce the receiver complexity. In this letter, we study the MEB receiver whose decision statistics is

$$D_i = \sum_{p=1}^{P} \lambda_p \sum_{k=1}^{\lceil T_{int}/T_c \rceil} \sum_{j=0}^{N_s-1} \Big\{ \text{sign}\left[r_{(iN_sL+jL+k)p}\right] \cdot \text{sign}\left[r_{(iN_sL-N_sL+jL+k)p}\right] \Big\} \quad (12)$$

where sign $[\bullet]$ denotes the sign of $[\bullet]$.

III. Performance Analysis

In this section, mathematical formulas for predicting the BER performances of TR-IR systems with the EB and MEB receivers are derived.

A. Performance of Digital EB Receiver

Without loss of generality, we assume that $b_i = 1$ is transmitted. At the receiver, the projection coefficients, r_{kp}, of the received signal can be expressed as follows

$$r_{kp} = h_{kp} + n_{kp} \quad (13)$$

where

$$h_{kp} = \int_{(k-1)T_c}^{kT_c} h(t)\phi_p(t-(k-1)T_c)dt \quad (14)$$

and

$$n_{kp} = \int_{(k-1)T_c}^{kT_c} n(t)\phi_p(t-(k-1)T_c)dt. \quad (15)$$

In (15), n_{kp} is a Gaussian random variable with zero mean and variance $N_o/2$ because $\int_0^{T_c} \phi_p^2(t)dt = 1$. From Section II, the decision variable D_i for EB receiver in (11) can be expressed as

$$D_i = \sum_{p=1}^{P} \lambda_p \sum_{k=1}^{\lceil T_{int}/T_c \rceil} \sum_{j=0}^{N_s-1} \left(h_{kp} + n_{(iN_sL-N_sL+jL+k)p}\right) \left(h_{kp} + n_{(iN_sL+jL+k)p}\right). \quad (16)$$

Rewrite (16) as follows

$$D_i = S + N_i. \quad (17)$$

In (17), S is the desired signal component,

$$S = N_s \sum_{p=1}^{P} \lambda_p \mathcal{E}_p \quad (18)$$

where

$$\mathcal{E}_p = \sum_{k=1}^{\lceil T_{int}/T_c \rceil} h_{kp}^2 \quad (19)$$

and N_i is the noise component

$$\begin{aligned} N_i = & \sum_{p=1}^{P} \lambda_p \sum_{k=1}^{\lceil T_{int}/T_c \rceil} h_{kp} \sum_{j=iN_s}^{iN_s-1} \big(d_i n_{(iN_sL-N_sL+jL+k)p} + d_{i-1} n_{(iN_sL+jL+k)p}\big) \\ & + \sum_{p=1}^{P} \lambda_p \sum_{k=1}^{\lceil T_{int}/T_c \rceil} \sum_{j=iN_s}^{iN_s-1} n_{(iN_sL-N_sL+jL+k)p} \, n_{(iN_sL+jL+k)p}. \end{aligned} \quad (20)$$

We know that the first term in (20) is Gaussian. The second term is the sum of products of two uncorrelated Gaussian processes, which can be seen as approximately Gaussian from the central limit theorem. Therefore, using the same approach as in [5], we can obtain the conditional variance of N_i as

$$\text{Var}\left[N_i | h(t)\right] = \sum_{p=1}^{P} \lambda_p^2 \left[N_o N_s \mathcal{E}_p + \frac{1}{4}\lceil T_{int}/T_c \rceil N_o^2 N_s\right]. \quad (21)$$

Therefore, the conditional BER performance for TR-IR system with the EB receiver is

$$P_{EB}(e|h(t)) = Q\left(\frac{S}{\sqrt{\text{Var}\left[N_i|h(t)\right]}}\right) \quad (22)$$

where $Q(z) = \left(1/\sqrt{2\pi}\right)\int_z^\infty \exp(-y^2/2)dy$.

B. Performance of MEB Receiver

The BER performance derivation of the MEB receiver is different from conventional methods as in [3] and [5]. At first, we rewrite the expression (12) as follows

$$D_i = \sum_{p=1}^{P} \lambda_p \sum_{k=1}^{\lceil T_{int}/T_c \rceil} Z_{ikp} \quad (23)$$

where

$$\begin{aligned} Z_{ikp} &= \sum_{j=0}^{N_s-1} \Big\{ \text{sign}\left[r_{(iN_sL+jL+k)p}\right] \cdot \text{sign}\left[r_{(iN_sL-N_sL+jL+k)p}\right] \Big\} \\ &= \sum_{j=0}^{N_s-1} \text{sign}\left[r_{(iN_sL+jL+k)p} r_{(iN_sL-N_sL+jL+k)p}\right]. \end{aligned} \quad (24)$$

The probability density function of D_i is difficult to obtain. Therefore, we start from the study of the probability density function of $r_{(iN_sL+jL+k)p} r_{(iN_sL-N_sL+jL+k)p}$, denoted as $f(r)$. From (13)-(15), $r_{(iN_sL+jL+k)p}$ and $r_{(iN_sL-N_sL+jL+k)p}$ are independent Gaussian random variables with the same nonzero mean h_{kp} and variance $N_o/2$. From [23], it is known that $f(r)$ is in the form of a doubly infinite series in Whittaker functions, which is very complex. However, its characteristic function is simple, which is shown as follows

$$\Psi(\mu) = \left(1 + \frac{N_o^2}{4}\mu^2\right)^{-\frac{1}{2}} \exp\left(-\frac{\frac{N_o}{2}\mu^2 h_{kp}^2 - \sqrt{-1}\mu h_{kp}^2}{1 + \frac{N_o^2}{4}\mu^2}\right). \quad (25)$$

We can utilize the characteristic function $\Psi(\mu)$ to obtain the probability that sign $\left[r_{(iN_sL+jL+k)p} r_{(iN_sL-N_sL+jL+k)p}\right]$

is equal to 1, denoted as P_{jk}^{1}, and the probability that sign $\left[r_{(iN_sL+jL+k)p}r_{(iN_sL-N_sL+jL+k)p}\right]$ is equal to -1, denoted as P_{jk}^{-1}. It is known that

$$P_{jk}^{1}+P_{jk}^{-1}=1 \tag{26}$$

and

$$P_{jk}^{1}-P_{jk}^{-1}=\int_{-\infty}^{\infty}f(r)\mathrm{SGN}(r)dr \tag{27}$$

where

$$\mathrm{SGN}(r)=\begin{cases}-1 & r<0\\ 0 & r=0\\ 1 & r>0\end{cases}. \tag{28}$$

With the help of Fourier transform pair

$$\int_{-\infty}^{\infty}f(r)\mathrm{SGN}(r)dr\longleftrightarrow\frac{1}{2\pi}\ \Psi(\mu)\otimes\frac{2}{\sqrt{-1}\mu}\bigg|_{\mu=0}, \tag{29}$$

we can obtain P_{jk}^{1} and P_{jk}^{-1}. In (24), Z_{ikp} is the sum of N_s Binomial random variables with identical probability distribution. Since $N_s\gg 1$, by evoking central limit theorem, Z_{ikp} is approximately Gaussian with mean

$$\mathrm{E}\left[Z_{ikp}\right]=N_s\left(P_{kp}^{1}-P_{kp}^{-1}\right) \tag{30}$$

and variance

$$\mathrm{Var}\left[Z_{ikp}\right]=4N_sP_{kp}^{1}P_{kp}^{-1}. \tag{31}$$

Therefore, D_i in (23) is the summation of $P\lceil T_{int}/T_c\rceil$ Gaussian random variables. D_i is also Gaussian with conditional mean

$$\mathrm{E}\left[D_i|h(t)\right]=\sum_{p=1}^{P}\lambda_p\sum_{k=1}^{\lceil T_{int}/T_c\rceil}\mathrm{E}\left[Z_{ikp}\right] \tag{32}$$

and conditional variance

$$\mathrm{Var}\left[D_i|h(t)\right]=\sum_{p=1}^{P}\lambda_p^2\sum_{k=1}^{\lceil T_{int}/T_c\rceil}\mathrm{Var}\left[Z_{ikp}\right]. \tag{33}$$

Therefore, the conditional BER for TR-IR system with MEB receiver is

$$P_{MEB}(e|h(t))=Q\left(\frac{\mathrm{E}\left[D_i|h(t)\right]}{\mathrm{Var}\left[D_i|h(t)\right]}\right). \tag{34}$$

By taking the expectation of (22) or (34) with respect to $h(t)$, we obtain the system BER performance with EB or MEB receiver, respectively, as follows

$$P(e)=\mathrm{E}\left[P_{EB,\,MEB}(e|h(t))\right]. \tag{35}$$

IV. Simulations and Numerical Results

In this section, we present computer simulated and numerically evaluated results to validate our designs. In all cases, the random channels are generated according to [22]. The sampling interval is 0.167 ns. The bandwidth of the lowpass filter is 2.994 GHz. As in [24], we select the shape of the monocycle $\omega(t)$ to be the second derivative of a Gaussian pulse, namely, $\left[1-4\pi(t/\tau_m)^2\right]\exp[-2\pi(t/\tau_m)^2]$, where $\tau_m=0.2877$ ns. In the legends of all our plots, "Simu" represents the BER performance obtained by computer simulation of the overall transmission chain while "Theo" denotes numerical results obtained by using (35).

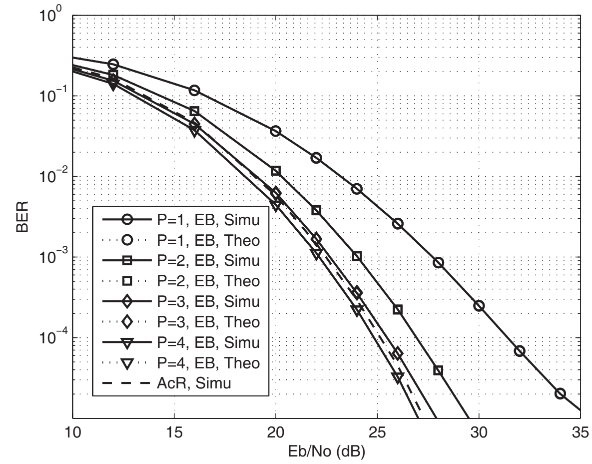

Fig. 1. BER comparison of the digital EB receiver and AcR for various number of signal dimensions to be exploited, P, in UWB channel model CM 1.

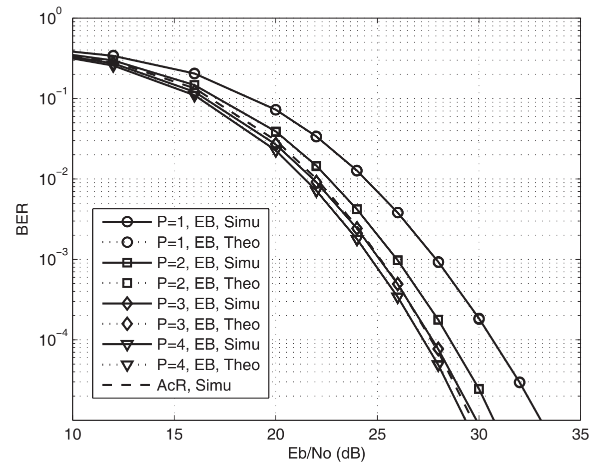

Fig. 2. BER comparison of the digital EB receiver and AcR for various number of signal dimensions to be exploited, P, in UWB channel model CM 4.

In Fig. 1 and Fig. 2, we compare the bit-error-rate (BER) performance of the proposed digital EB receiver with the conventional AcR in CM 1 and CM 4 UWB channels [22]. For both receivers, we choose the number of frames in a symbol duration, N_s, of 8 and the frame durations, T_f, of 50 ns in CM 1 UWB channels and 120 ns in CM 4 UWB channels, respectively. For the conventional AcR, the optimal integration intervals, $T_{int}=10.19$ ns in CM 1 UWB channels and $T_{int}=41.75$ ns in CM 4 UWB channels, computed using the method in [7] at the E_b/N_o of 20 dB, are employed. The simulation results show that by employing digital EB receiver, the system BER performance improves with the increase of signal dimensions to be exploited, P. When $P=4$, the proposed digital EB receiver outperforms the conventional AcR by about 0.3 dB in both CM 1 and CM 4 UWB channels at BER of 10^{-5}. This is because the channel noise is uniformly distributed over the multiple signal dimensions. By only exploiting the signal dimensions which have larger SNR, we actually improve the SNR at the EB receiver. It is also found that the theoretical results can predict the simulation results with very good accuracy.

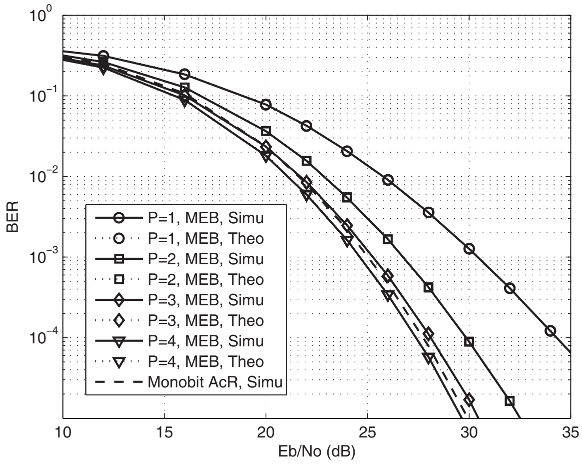

Fig. 3. BER comparison of the MEB receiver and monobit AcR for various number of signal dimensions to be exploited, P, in UWB channel model CM 1.

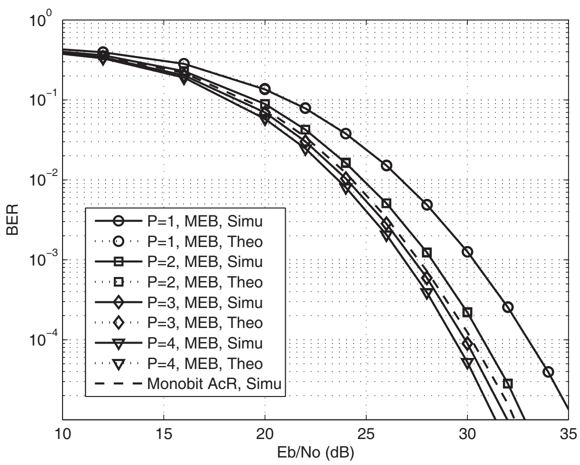

Fig. 4. BER comparison of the MEB receiver and monobit AcR for various number of signal dimensions to be exploited, P, in UWB channel model CM 4.

In Fig. 3 and Fig. 4, we compare the BER performance of the proposed MEB receiver with the monobit AcR in CM 1 and CM 4 UWB channels [22]. The system parameters are the same with those in Fig. 1 and Fig. 2. The monobit AcR employed is as in [20] with sampling interval of 0.167 ns. The simulation results show that at BER of 10^{-5}, the proposed MEB receiver with $P = 4$ is about 0.3 dB and 0.9 dB better than the conventional monobit AcR in CM 1 and CM 4 UWB channels, respectively. The reason that MEB receiver with $P = 4$ has a larger performance gain in CM 4 than in CM 1 may be that the received signal energy is more concentrated on several specific dimensions in CM 4 than in CM 1. In Fig. 3 and Fig. 4, the theoretical results computed using (34) match the simulation results.

V. CONCLUSIONS

In this letter, we have proposed a digital EB receiver for TR-IR systems. The simulation results have shown that when the number of signal dimensions to be exploited, P, is equal to 4, the proposed system outperforms the conventional AcR in CM 1 and CM 4 UWB channels. To further simplify the EB receiver, we also studied the MEB receiver. It was found that with much lower sampling rate, the MEB receiver may have better BER performance than the monobit AcR. We have also derived the theoretical BER performances of EB and MEB receivers which can accurately predict the simulation results.

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