A NOVEL MODULATION DIVERSITY ASSISTED ULTRA WIDEBAND COMMUNICATION SYSTEM

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ABSTRACT

In this paper, a novel modulation diversity assisted (MDA) ultra wideband (UWB) communication system is proposed. Pulse position modulation and pulse amplitude modulation are applied to successive pulses alternately to create modulation diversity and increase system capacity. The proposed system is similar to a transmitted-reference system in such that two pulses are always transmitted together in a doublet. One of the multipath distorted pulses can serve as a reference signal without explicit channel estimation. However, a MDA-UWB system possesses more advantages, such as smoother spectrum, higher bit rate. Coupled with an advanced low complexity receiver, detection performance is shown significantly better.

1. INTRODUCTION

Although ultra-wideband (UWB) techniques appeared more than four decades ago, there emerges a renewed interest recently in the industry and academia [1], [2], after the first regulation in UWB was issued in 2002. Conventional UWB systems employ RAKE receivers. However, there are two major problems therein. First, it is practically difficult to estimate the channel accurately because there are too many unknowns. Secondly, a low complexity receiver cannot afford too many fingers in dense multipath UWB channels. To deal with these challenges, a transmitted-reference (TR) UWB system is introduced in [3]. In such a system, a pulse without data modulation is transmitted before each data-modulated pulse. Because the two pulses are undergoing the same multipath channel, the first pulse in the doublet can be used as a reference to detect information carried on the second pulse. This simple TR transceiver avoids explicit estimation of a possibly long UWB channel while still capturing full multipath energy. However, a TR system is not bandwidth efficient and has big performance loss due to the noisy template. In [4], [5], [6], [7], different methods are discussed to solve these problems.

In this paper, we design a modulation diversity assisted (MDA) transmission scheme by using the diversity concept. Pulse position modulation (PPM) and pulse amplitude modulation (PAM) are employed on a pulse train in an alternating way. As a result, two neighboring pulses have different modulation formats. Because information is modulated differently on pulses, modulation diversity is achieved. At the receiver end, diversity can be exploited for better template estimation and symbol detection. Because PPM modulation is observed to have nonzero mean [8], a first-order template estimator can be easily constructed based on PPM pulses. Subsequently, amplitude modulated pulses are adaptively utilized to improve estimation of the reference signal. Low complexity correlation receivers are finally used to demodulate information symbols. We can show MDA-UWB systems overcome some drawbacks in TR-UWB systems while maintaining most of their merits. MDA-UWB systems improve bandwidth efficiency and spectral characteristics. Although an energy efficient TR system [4] can achieve the same information rate as our MDA system, it has worse power spectral density and poorer detection performance.

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2. MDA-UWB MODELLING

In a MDA-UWB system, any two neighboring pulses are modulated by different modulation methods, either PPM or PAM. For simplicity, consider only binary modulation and each information-carried pulse is only transmitted once. But discussions can be readily extended to repetitive transmissions (a multiple-frame scenario). The transmitted signal is given by

$$s(t) = \sum_{n=-\infty}^{\infty} [p(t-nT_f-\frac{1-b_n^{(0)}}{2}\sigma)+b_n^{(1)}p(t-nT_f-T_d)]. \quad (1)$$

Here, $p(t)$ is a monocycle. T_f is the frame duration. Each frame contains one doublet. $b_n^{(0)}, b_n^{(1)} \in \{\pm 1\}$ are the two information bits transmitted during the nth frame. The first bit modulates the first pulse using PPM and σ is the modulation delay. The second pulse delayed by T_d is modulated by PAM.

To better capture signal energy, we use a filter matched to the transmitted pulse. If we define a new waveform $w(t) = p(t) \star h(t) \star p(-t)$, with $\star$ denoting convolution and $h(t)$ capturing effects of transimitter, channel and receiver antenna, then we can obtain the following received signal model:

$$r(t) = \sum_{n=-\infty}^{\infty} [w(t-nT_f-\frac{1-b_n^{(0)}}{2}\sigma)+b_n^{(1)}w(t-nT_f-T_d)]+v(t) \quad (2)$$

where $v(t)$ is AWGN with double-sided power spectral density $N_0/2$. After sampling every T_s seconds, we obtain discrete time samples $r(i) = r(t)|_{t=iT_s}$ as follows

$$r(i) = \sum_{n=-\infty}^{\infty} [w(i - nN_s - \frac{1-b_n^{(0)}}{2}L) + b_n^{(1)} w(i - nN_s - N_d)] + v(i) \quad (3)$$

where N_s, N_d, L are integers satisfying $T_f = N_s T_s, T_d = N_d T_s$ and $\sigma = LT_s$. $v(i)$ is the sampled noise. Suppose the duration of $w(t)$ is T_w and $q = \lceil \frac{T_w}{T_s} \rceil$ is the order of the discretized waveform $w(t)$. T_d is chosen to be greater than $T_w + \sigma$ to avoid interpulse interference as well as interframe interference. We collect first q samples within the first half frame into vector $\boldsymbol{r}_{n,1}$ and first q samples within the second half frame into vector $\boldsymbol{r}_{n,2}$:

$$\boldsymbol{r}_{n,1} = \sum_{m=0}^{1} a_{n,m} \boldsymbol{J}^m \boldsymbol{w} + \boldsymbol{v}_{n,1}, \;\; \boldsymbol{r}_{n,2} = b_n^{(1)} \boldsymbol{w} + \boldsymbol{v}_{n,2}, \quad (4)$$

where $a_{n,m} \triangleq \delta(b_n^{(0)} - (-1)^m)$, $\delta(\cdot)$ is the Kronecker delta function, $\boldsymbol{J}$ is a square matrix after shifting down all elements of an identity matrix $\boldsymbol{I}$ by L rows and $\boldsymbol{J}^0 = \boldsymbol{I}$. $\boldsymbol{w}, \boldsymbol{v}_{n,1}, \boldsymbol{v}_{n,2}$ are corresponding vectors with length q. In (4), the two separate signal vectors corresponding to two bits are modulated by different modulation schemes. Because they are transmitted through the same channel, they can be used as references for each other in order to detect information symbols. In addition, the inherent modulation diversity can be exploited to obtain accurate reference signal and thus improve detection performance. Although two modulation schemes are deployed in MDA-UWB systems, they can be easily implemented using the same circuit because PPM can be implemented as PAM with amplitude 0 or 1 according to (4).

Clearly, our proposed MDA approach is different from the TR approach [3]. But some connections can be built. First, both schemes transmit two pulses within one frame. Only the second pulse is modulated in TR while both pulses are modulated by data in a MDA-UWB system. Information rate of a MDA-UWB system is thus doubled and it is more energy efficient than a TR system. Second, explicit channel estimation may not be required for data detection in both systems. To achieve this, a TR system only uses the first pulse of each doublet as a reference while both pulses are used as a reference to each other in a MDA-UWB system. Finally, a MDA-UWB system has better power spectral density than a TR system. Compared with a closely related method [4], the proposed modulation and detection scheme also show better spectral characteristics and detection performance.

3. SPECTRAL CHARACTERISTICS

In this section, we evaluate the power spectrum density (PSD) of transmitted MDA-UWB signal and compare it with two other UWB modulation schemes, namely conventional TR [3] and TR pulse interval amplitude modulation (TR-PIAM) [4]. For all three systems, the transmitted signal $s(t)$ can be expressed as the convolution of monocycle pulse $p(t)$ and a series of Dirac delta funtions at different delays denoted by $u(t)$:

$$s(t) = u(t) \star p(t).$$

Then the PSD of $s(t)$ can be calculated as $S(f) = S_{uu}(f)|P(f)|^2$, where $S_{uu}(f)$ and $P(f)$ represent the PSD of $u(t)$ and the Fourier transform of $p(t)$ respectively. As $P(f)$ is common for different systems deploying the same pulse shape filter, we focus our attention only on $S_{uu}(f)$ for comparison purposes.

For MDA-UWB signal (1), $u(t)$ is given by

$$u^{MDA}(t) = \sum_{n=-\infty}^{\infty} [\delta(t - nT_f - \frac{1-b_n^{(0)}}{2}\sigma) + b_n^{(1)} \delta(t - nT_f - T_d)]. \quad (5)$$

Because $u^{MDA}(t)$ is a cyclostationary process, its autocorrelation function (ACF) $\varphi_{uu}^{MDA}(t+\tau, t) = E\{u(t+\tau)u(t)\}$ is periodic in variable t with period T_f. The time-averaged ACF over one period can be derived as:

$$\varphi_{uu}^{MDA}(\tau) = \frac{2}{T_f}\delta(\tau) + \frac{1}{4T_f} \sum_{n \neq 0} [2\delta(\tau - nT_f) + \delta(\tau - nT_f - \sigma) + \delta(\tau - nT_f + \sigma)]. \quad (6)$$

The PSD $S_{uu}^{MDA}(f)$ is the Fourier transform of $\varphi_{uu}^{MDA}(\tau)$:

$$S_{uu}^{MDA}(f) = \frac{3}{2T_f} - \frac{1}{2T_f}\cos(2\pi f \sigma) + \frac{1}{2T_f^2} \sum_n \delta(f - \frac{n}{T_f})[1 + \cos(2\pi f \sigma)]. \quad (7)$$

The first two terms represent the continuous part of the signal spectrum whereas the last term represents the spectral lines.

Similarly, we can find $S_{uu}^{TR}(f)$ and $S_{uu}^{PIAM}(f)$, PSD for other two systems:

$$S_{uu}^{TR}(f) = S_{uu}^{PIAM}(f) = \frac{1}{T_f} + \frac{1}{T_f^2} \sum_n \delta(f - \frac{n}{T_f}). \quad (8)$$

Now let us examine the signal power $\mathcal{P}_c$ included in the continuous spectrum within the frequency band from $-F$ to F.

$$\mathcal{P}_c^{MDA} = \frac{F}{T_f}(3 - \frac{\sin(2\pi F \sigma)}{2\pi F \sigma}), \quad (9)$$

$$\mathcal{P}_c^{TR} = \mathcal{P}_c^{PIAM} = \frac{2F}{T_f}. \quad (10)$$

As $x > \sin(x)$ for $x > 0$, it can be easily shown the continuous spectrum $\mathcal{P}_c^{MDA}$ is larger than $\mathcal{P}_c^{TR}$ for any F. Because total power of the three signals is the same, we can conclude the spectrum of MDA-UWB signal is smoother than that of the TR signal or PIAM signal.

4. MDA-UWB RECEIVER STRUCTURE

4.1. Conceptual Receiver

We will introduce a simple receiver first. The reason to call it a conceptual receiver is that we would like to highlight how diversity can assist symbol detection without explicit channel estimation.

To detect those PAM modulated bits, referred as least significant bits (LSB), we use the PPM modulated pulse as a reference. To align the reference signal with signal $\boldsymbol{r}_{n,2}$, it is desirable to choose $\boldsymbol{r}_{n,1}$ as a reference if $b_n^{(0)} = 1$ and $\boldsymbol{J}'\boldsymbol{r}_{n,1}$ if $b_n^{(0)} = -1$. Here $'$ is a transpose operation. However, it is not known *a priori* whether $b_n^{(0)} = 1$ or $b_n^{(0)} = -1$. Noticing the autocorrelation function of $\boldsymbol{w}$ at zero offset is significantly larger in magnitude than any other at a nonzero offset, we construct a correlation template as $\boldsymbol{r}_{n,1} + \boldsymbol{J}'\boldsymbol{r}_{n,1}$ to ensure that one desired reference signal and one offset reference signal are always included for each of two possible cases. The resulting superimposed reference signal provides a large enough positive correlation with $\boldsymbol{w}$ which may correctly reflect the polarity of $b_n^{(1)}$. Consequently, the decision rule can be expressed by

$$\widehat{b}_n^{(1)} = \text{sgn}((\boldsymbol{r}_{n,1} + \boldsymbol{J}'\boldsymbol{r}_{n,1})'\boldsymbol{r}_{n,2}), \tag{11}$$

where $\text{sgn}(x) = 1$ if $x \geq 0$ and -1 otherwise.

Then we use the PAM modulated pulse as a reference to demodulate the PPM bit, referred as most significant bit (MSB), with the help of demodulated $b_n^{(1)}$:

$$\widehat{b}_n^{(0)} = \text{sgn}(\widehat{b}_n^{(1)}(\boldsymbol{r}_{n,2} - \boldsymbol{J}\boldsymbol{r}_{n,2})'\boldsymbol{r}_{n,1}). \tag{12}$$

Here, $\widehat{b}_n^{(1)}\boldsymbol{r}_{n,2}$ recovers received signal waveform by removing random polarity and therefore $\widehat{b}_n^{(1)}(\boldsymbol{r}_{n,2} - \boldsymbol{J}\boldsymbol{r}_{n,2})$ is a similar template as in a conventional PPM-UWB correlation receiver [2].

4.2. Advanced Receiver

In practice, due to noisy reference signals, detection performance degrades a lot with the above simple conceptual receiver. This motivates us to seek an advanced receiver for performance improvement. We will show this goal can be accomplished by fully utilizing the diversity embedded in PPM and PAM modulated pulses.

In model (4), the information about the pulse shape and multipath channel response is included in vector $\boldsymbol{w}$. We want to use it as a reference waveform to detect information symbols. It has been observed PPM signals have nonzero mean [8]. Thus, we can construct a first-order blind estimator to obtain an estimate of the reference signal $\boldsymbol{w}$. With (4), the mean of vector $\boldsymbol{r}_{n,1}$ is

$$\bar{\boldsymbol{r}}_1 = E\{\boldsymbol{r}_{n,1}\} = \frac{1}{2}(\boldsymbol{I} + \boldsymbol{J})\boldsymbol{w}. \tag{13}$$

We can use N data vectors $\boldsymbol{r}_{n,1}$ to estimate the mean by sample average $\widehat{\bar{\boldsymbol{r}}}_1 = \frac{1}{N}\sum_{n=1}^{N}\boldsymbol{r}_{n,1}$ and minimize the estimation error $\|\widehat{\bar{\boldsymbol{r}}}_1 - \bar{\boldsymbol{r}}_1\|^2$. This yields our initial estimator:

$$\widehat{\boldsymbol{w}}_0 = 2\boldsymbol{T}^{-1}\widehat{\bar{\boldsymbol{r}}}_1, \;\; \boldsymbol{T} = \boldsymbol{I} + \boldsymbol{J}. \tag{14}$$

Although this estimator has a simple structure, it may have poor performance as analyzed later. Fortunately, we can improve it greatly as a result of the diversity design in MDA-UWB systems. With the initial template, correlation-based detector is used to demodulate the rest N PAM bits during the same interval as previous N PPM bits

$$\widehat{b}_{n,int}^{(1)} = \text{sgn}(\widehat{\boldsymbol{w}}_0'\boldsymbol{r}_{n,2}), \;\; n = 1, \cdots, N. \tag{15}$$

The subscript int stands for an intermediate estimate. Then a cleaner reference signal is obtained through simple average operation:

$$\widehat{\boldsymbol{w}}_1 = \frac{1}{N}\sum_{n=1}^{N}\widehat{b}_{n,int}^{(1)}\boldsymbol{r}_{n,2}. \tag{16}$$

It is used to construct correlation templates for symbol detection. The detection process can be described as following

$$\widehat{b}_n^{(0)} = \text{sgn}\left((\widehat{\boldsymbol{w}}_1 - \boldsymbol{J}\widehat{\boldsymbol{w}}_1)'\boldsymbol{r}_{n,1}\right), \;\; \widehat{b}_n^{(1)} = \text{sgn}(\widehat{\boldsymbol{w}}_1'\boldsymbol{r}_{n,2}). \tag{17}$$

Here, the template $\widehat{\boldsymbol{w}}_1 - \boldsymbol{J}\widehat{\boldsymbol{w}}_1$ for PPM detection resembles the template in conventional PPM-UWB systems [2]. In order to improve system performance, we continue to update the estimate of $\boldsymbol{w}$ in an adaptive way in the detection stage after $n = N$

$$\widehat{\boldsymbol{w}}_{n-N+1} = \frac{1}{n}[(n-1)\widehat{\boldsymbol{w}}_{n-N} + \widehat{b}_n^{(1)}\boldsymbol{r}_{n,2}]. \tag{18}$$

We would like to mention although we discuss a discrete-time model and digital receivers for MDA-UWB systems here, the same idea can be implemented in analog circuits because of the unique structure of $\boldsymbol{T}$ in (14) and consequently $\boldsymbol{T}^{-1}$. Continuous time operation is highly desirable for any UWB detection algorithm because extremely high sampling rate is prohibitive in low complexity UWB systems. Due to limited space, we leave discussion about this issue elsewhere.

5. PERFORMANCE ANALYSIS

For our proposed receivers, the detection performance will be determined by the accuracy of our estimation of $\boldsymbol{w}$. Thus, we evaluate mean-square-error (MSE) of the two estimators $\widehat{\boldsymbol{w}}_0$ and $\widehat{\boldsymbol{w}}_1$.

MSE of $\widehat{\boldsymbol{w}}_0$ can be calculated as the trace of the covariance matrix of $\delta\boldsymbol{w}_0 = \widehat{\boldsymbol{w}}_0 - \boldsymbol{w}$, which is given below without detailed derivations due to limited space:

$$\text{COV}(\delta\boldsymbol{w}_0) = \frac{1}{N}\boldsymbol{T}^{-1}\boldsymbol{\Psi}\boldsymbol{w}\boldsymbol{w}'\boldsymbol{\Psi}'\boldsymbol{T}'^{-1} + \frac{4\sigma_v^2}{N}\boldsymbol{T}^{-1}\boldsymbol{T}'^{-1}, \tag{19}$$

where $\boldsymbol{\Psi} = \boldsymbol{I} - \boldsymbol{J}$.

For (16), we will find accurate analysis is complicated because it is dependent on both $\widehat{\boldsymbol{w}}_0$ and detection of $b_n^{(1)}$. Moreover, the nonlinear sign function is involved in (15). To simplify our analysis, we assume perfect detection of $b_n^{(1)}$ has been achieved. From simulations, we will see this is a good assumption because the resulted analysis predicts experimental results with high accuracy. If $b_n^{(1)}$ has been decoded perfectly, the covariance matrix of $\delta\boldsymbol{w}_1$ is

$$\text{COV}(\delta\boldsymbol{w}_1) = \frac{\sigma_v^2}{N}\boldsymbol{I}. \tag{20}$$

Comparing the last term in (19) with (20), we can easily find trace of the former is always greater than that of the latter because

$$\text{tr}\left(\boldsymbol{T}^{-1}\boldsymbol{T}'^{-1}\right) = q + (q-L) + \cdots + (q-dL) > q, \tag{21}$$

where $d = \lfloor \frac{q}{L} \rfloor$. Therefore, we conclude $\widehat{\boldsymbol{w}}_1$ has a much smaller MSE than $\widehat{\boldsymbol{w}}_0$. Better detection performance can be gained if $\widehat{\boldsymbol{w}}_1$ is used as a correlation template.

Detection performance of both PPM bits and PAM bits using a correlation receiver conditioned on estimated $\boldsymbol{w}$ can be found [9]

$$P_e^{PPM} = Q\left(\frac{\boldsymbol{w}'\boldsymbol{\Psi}\widehat{\boldsymbol{w}}}{\sqrt{\frac{N_0}{2}\|\boldsymbol{\Psi}\widehat{\boldsymbol{w}}\|^2}}\right), \;\; P_e^{PAM} = Q\left(\frac{\boldsymbol{w}'\widehat{\boldsymbol{w}}}{\sqrt{\frac{N_0}{2}\|\widehat{\boldsymbol{w}}\|^2}}\right), \tag{22}$$

where $Q(x) \triangleq \int_x^\infty \frac{1}{\sqrt{2\pi}}e^{-\frac{x^2}{2}}dx$. Then bit error rate (BER) can be calculated by taking expectation of (22) with respect to $\widehat{\boldsymbol{w}}$, whose closed forms will be pursued in the future.

6. SIMULATIONS

In our simulations, we chose normalized second derivative of Gaussian pulse with duration of 0.7ns as the transmitted monocycle. The discrete-time IEEE UWB CM1 channel model [10] with sampling period of 0.1ns is adopted. Maximum delay spread is 40ns by truncating its tail. We assume the channel is static and the receiver is synchronized with the transmitter. Other system parameters are chosen as $T_d = 42$ns, $T_f = 84$ns and $\sigma = 0.8$ns.

With (7) and (8), we plotted the continuous spectrum of three UWB signals in Fig. 1: MDA, TR and PIAM. They are normalized by the peak of MDA-UWB signal spectrum corresponding to $\sigma = 0.2ns$. The shape of MDA-UWB signal spectrum varies with σ while that of TR or PIAM signal is independent of σ. Nonetheless, the continuous spectrum of MDA-UWB signal is always higher than that of the TR or PIAM signal. This implies MDA-UWB signal has lower spectral lines and smoother spectrum. It will cause less interference to coexisting radio systems. From our simulation, $\sigma = 0.2$ns is suggested in order to maximally smooth the MDA-UWB signal spectrum.

Averaged MSEs with respect to N for the two reference estimators are plotted in Fig. 2 with cross representing $\widehat{\boldsymbol{w}}_0$ and circle $\widehat{\boldsymbol{w}}_1$. The results are obtained over 20 randomly generated CM1 channels with $E_b/N_0 = 15$dB. MSEs decrease inversely proportionally with N for both estimators. As we have analyzed in the previous section, estimator $\widehat{\boldsymbol{w}}_1$ has significant smaller MSEs than $\widehat{\boldsymbol{w}}_0$. The improvement is more than one order. Despite the assumption made on the perfect detection of $b_n^{(1)}$, analytical results for both estimators match with the experimental results very well.

Finally, we examine the BER of MDA-UWB systems and compare it with conventional TR systems [3] and PIAM systems [4] in Fig. 3. A conceptual MDA receiver has comparable performance as a PIAM receiver and both of them outperform a conventional TR receiver at high signal to noise ratios. But an advanced MDA receiver can improve detection performance substantially. From Fig. 3b, such an improvement is more than 8dB at BER of 10^{-2}.

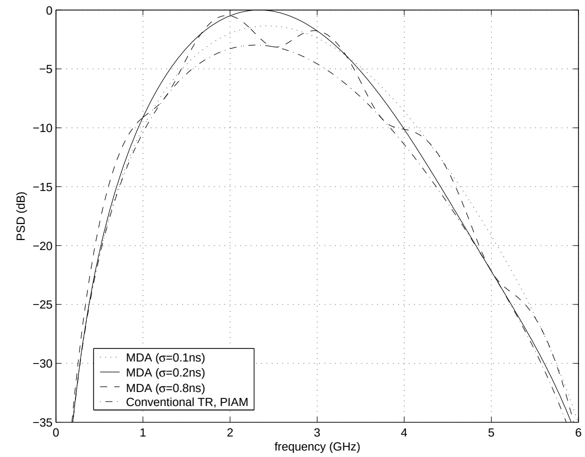

Fig. 1. Continuous spectrum of transmitted signals.

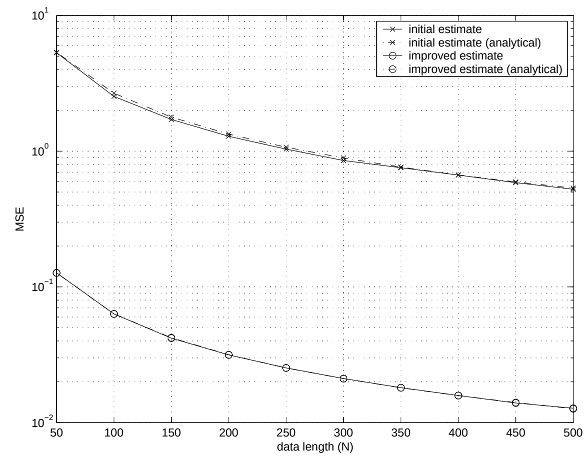

Fig. 2. MSEs of two reference signal estimators under E_b/N_0=15dB.

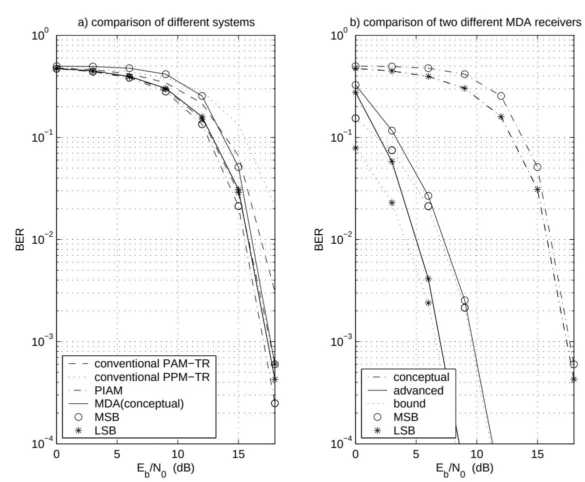

Fig. 3. Detection performance comparison of different systems.

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