BER Performance Analysis of MRC Receive Diversity with Optimal and Rectangular Templates in UWB Off-Body Wireless Body Area Networks

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Categories and Subject Descriptors
H.4 [**Information Systems Applications**]: Miscellaneous

General Terms
Theory

ABSTRACT
Short range communications through wireless body area networks (WBANs) is evolving. In particular, in the on-body surface to off-body access node channel model (CM) namely, CM#4 of the IEEE 802.15.6a ultra wideband (UWB) WBAN, the characteristics of the channel are affected by the direction of body rotation. In this paper we investigate the bit-error-rate (BER) performance of correlator receivers with maximal-ratio-combining (MRC) receive diversity in WBAN CM#4 channel. We consider optimal and low-power rectangular template-based receiver alternatives assuming equally probable pulse position modulation (EC-PPM) scheme. We provide closed forms for the BER performance as well as numerical results based on Mote Carlo simulations.

Keywords
Performance analysis, maximal-ratio-combining (MRC), RAKE receivers, ultra-wideband (UWB), wireless body area networks (WBANs).

1. INTRODUCTION
Impulse-radio ultra wideband (IR-UWB) technology has the potential for low-cost and low-complexity transceiver design. Moreover, according to Federal Communication Commission, IR-UWB systems operate at very low-power levels, -41.3 dBm/MHz, due to their high fractional bandwidths. These advantages make it an attractive candidate for emerging high data-rate applications of wireless body area networks (WBANs). Nevertheless, due to the very short durations of IR-UWB pulses, they require high sensitivity against timing-errors [1], [2].

One major issue associated with the application of IR-UWB for WBANs is the power consumption of the receiver. Ultimately, non-coherent UWB receivers, such as Transmitted Reference (TR) and Energy Detection (ED) receivers are perfect candidates for low-power applications of UWB systems. However, low power consumption is traded for highly suboptimal performance as compared to coherent detectors. Low-power suboptimal template-based correlator receivers have recently been proposed as an alternative solution that provides an approaching performance to optimal detectors [2].

In this paper, we study the Bit-Error-Rate (BER) performance of optimal and suboptimal rectangular template-based correlator receivers with maximal-ratio-combining (MRC) for WBAN applications. In particular, we provide closed form equations for the BER performance, and provide numerical results based on Monte Carlo simulations. Specifically, we study the the BER performance of both receiver models assuming equally-correlated pulse position modulation (EC-PPM) scheme in additive white Gaussian noise (AWGN) and the CM#4 scenario of UWB WBAN channels.

The rest of the paper is organized as follows. Section 2 describes the channel model of IEEE 802.15.6a on-body-to-off-body channel model. Then, Section 3 introduces the template pulse, and provides closed forms for the BER performance of the receiver structures under investigation in the aforementioned channel model. Then, numerical results are given in Section 4. Finally, the conclusions are provided in Section 5.

2. CHANNEL MODEL
According to the IEEE 802.15 task group 6 (TG6) channel report, channel models (CMs) of WBAN are classified into CM#1 $\sim$ CM#4. This classification of channel models is categorized by location of the device. In CM#1 the device is inside of the body, whereas in CM#2 the transmit and receive devices are placed on the surface and inside of the body. On the other hand, in CM#3 the device is placed on the surface of the body, and finally in CM#4 the transmit device is on the surface of the body and receive device is placed off the body, as shown in Figure 1 [4]. Specifically, the

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BODYNETS 2013, September 30-October 02, Boston, United States

DOI 10.4108/icst.bodynets.2013.253606

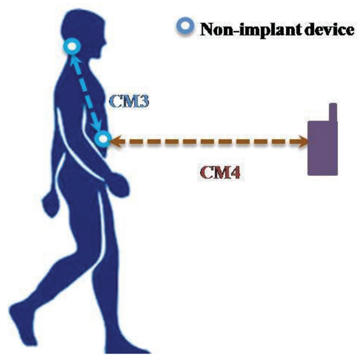

Figure 1: WBAN channel models.

Table 1: WBAN channel parameters for different body directions.

Body Angle	$k(\Delta k$[dB])
0°	5.111 (22.2)
90°	4.348 (18.8)
180°	3.638 (15.8)
270°	3.983 (17.3)

maximum distance of CM#4 channel model is 5 m.

In this paper, we study the BER performance of MRC receive diversity in CM#4 scenario, in which communication is between the body surface and a wireless access point using UWB frequency band (3.1 - 10.6 GHz). In the scenario under investigation, we can determine the propagation characteristics at the antennas of the human body and the off-body access node from the measured values. Both line of-sight (LOS) and non-line-of-sight (non-LOS) situations are considered in the CM#4 scenario. More specifically, the channel model is assumed to be a single cluster model with K-factor, and the model parameters are extracted using statistical analysis [1]. The one cluster with a direct path component as a generic WBAN channel model for LOS and NLOS communications is expressed as [1]:

$$h(t) = \sum_{m=0}^{\infty} \alpha_m \delta\left(t - \tau_m\right) \tag{1}$$

where τ_m is the sampling rate, α_m is the ray amplitude, and m is the number of rays. The phase of rays is uniformly distributed between 0 and 2π. Channel model parameters are summarized in Table 1, where Δk is the difference between the first and average impulse responses and k is defined as [1]:

$$k = \Delta k \left(\frac{\ln 10}{10}\right) \tag{2}$$

3. TEMPLATE PULSES AND BER PERFORMANCE IN AWGN AND OFF-BODY WBAN CHANNELS

The most commonly used pulse shape with UWB communications, the *n*-th order Gaussian pulse $\omega_0(t)$ in terms of $\sigma^2 = T_p/2\pi$ and pulse duration T_p, has the form [2]:

$$\omega_n(t) = \frac{d^{(n)}}{dt^n}\left(\frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-t^2}{2\sigma^2}}\right) \tag{3}$$

Considering a correlation receiver, the optimal template $v(t)$ should ultimately be matched to the received pulse $p(t) = \omega_n(t)$, where the pulse parameters are chosen to meet a specified Federal Communication Commission (FCC) system's allowable emission limits.

3.1 Performance in AWGN Channel

For binary pulse position modulation (BPPM) with a transmitted pulse $p(t)$, the optimal template is as [3]:

$$v(t) = p(t) - p(t - \delta) \tag{4}$$

where, δ is the BPPM modulation parameter. Assuming optimum detection, the BER can be minimized by choosing δ to minimize the autocorrelation [3]:

$$\delta_{opt} = \arg\left\{\min_{\delta} R_{pp}(\delta)\right\} \tag{5}$$

For *M*-ary EC-PPM, the transmitted signal is composed of N_s time shifted pulses with $2 \leq M < N_s$, where each signal is identified by a sequence of cyclic shifts of an *m*-sequence of length N_s [3]. The union bound on the BER probability of *M*-ary EC-PPM assuming an optimum correlation receiver is [3]:

$$U_{BPb} = \frac{M}{2} Q\left(\sqrt{\frac{E_s}{2N_0}(1 - R_{pp\,\min})}\right) \tag{6}$$

$$R_{pp}(\tau) = \frac{1}{E_p}\int_{-\infty}^{\infty} p(t)p(t-\tau)dt \tag{7}$$

where, $Q(.)$ is the Gaussian tail function [3], [4], $R_{pp\,\min} \triangleq R_{pp}(\delta_{opt})$, and E_p is the pulse energy. The normalized cross-correlation function of the received pulse and rectangular template (where T_r is the window length) can be calculated as [2], [5]:

$$R_{pv}(\tau) = \frac{A}{\sqrt{E_p}\sqrt{E_v}}\int_{-T/2}^{T/2} p(t)\mathrm{rect}(\frac{\mathrm{t}-\tau}{\mathrm{T_r}}))\mathrm{dt} \tag{8}$$

where, E_v is the template pulse energy and E_p is the received pulse energy. Without loss of generality, we assume that the received pulse is the Gaussian pulse $p(t) = \omega_0(t)$, and that the rectangular pulse width is equal to $T_r = T_p = 2\tau_p$, this gives [2]:

$$R_{pv}(\tau) = \frac{A\tau_p}{2\sqrt{2E_pE_v}}\left[\mathrm{erf}\left(\frac{\sqrt{2\pi}}{\tau_\mathrm{p}}(\tau + 2\tau_\mathrm{p})\right)\right] - \frac{A\tau_p}{2\sqrt{2E_pE_v}}\left[\mathrm{erf}\left(\frac{\sqrt{2\pi}}{\tau_\mathrm{p}}(\tau - 2\tau_\mathrm{p})\right)\right] \tag{9}$$

where, $\mathrm{erf}(.)$ is the error function defined as $\mathrm{erf(x)} = \frac{2}{\sqrt{\pi}}\int_0^{\mathrm{x}} \mathrm{e}^{-\mathrm{t}^2}\mathrm{dt}$ and τ is the time-shift. To minimize BER, we wish to choose the value of δ that minimizes the correlation $R_{pv\,\min}(\delta_{opt})$. Further, at the receiver we choose a sample time μ to maximize the correlation between the suboptimal template and the generated pulse:

$$\mu_{opt} = \arg\left\{\max_{\mu} R_{pv}(\mu)\right\} \tag{10}$$

with $R_{pv\max} = R_{pv}(\mu_{opt})$, the union bound on the bit error probability for equally correlated signals is defined as:

$$U_{BPb} = \frac{M}{2} Q\left(\sqrt{\frac{E_s}{2N_0}(R_{pv\max} - R_{pv\min})}\right) \quad (11)$$

3.2 Performance in Dense Multipath Channel

The conditional BER of the n-th user at the output of the MRC is expressed as [4], [6], [7]:

$$P_b(E\{\alpha_{k,l}\}_{l=1}^{L}) = Q\left(\sqrt{\bar{\eta}}\right) \quad (12)$$

Obviously, the BER is calculated in terms of the Gaussian Q-function represented by $Q(x) = \int\limits_{x}^{\infty} \frac{1}{\sqrt{2\pi}} e^{-\left(\frac{y^2}{2}\right)} dy$ for $x \geq 0$ [4].

For multi-path fading channels, we consider the alternative representation of the Q-function [4], [8].

$$Q(x) = \frac{1}{\pi} \int\limits_{0}^{\pi/2} \exp\left(-\frac{x^2}{2\sin^2\theta}\right) d\theta, \quad (13)$$

The BER calculation involves the integral [4], [6]:

$$I = \int_0^\infty Q\left(\sqrt{\bar{\eta}}\right) p_{\bar{\eta}}(\bar{\eta}) d\bar{\eta} \quad (14)$$

where $p_{\bar{\eta}}(\bar{\eta})$ is the probability distribution function (PDF) of the signal-to-noise-ratio (SNR). The moment generating function (MGF) $M_{\eta_l}(s)$ is defined as [4], [9]:

$$M_{\eta_l}(s) \triangleq \int\limits_{0}^{\infty} p_{\eta_l}(\eta_l) e^{s\eta_l} d\eta_l \quad (15)$$

For Ricean fading, the MGF is as [4], [10], [11]:

$$M_{\bar{\eta}(s)} = \frac{1+K}{(1+K) - s\bar{\eta}} \exp\left(\frac{Ks\bar{\eta}}{(1+K) - s\bar{\eta}}\right) \quad (16)$$

where K is the Ricean factor. The conditional BER in the product form is [4], [8]:

$$P_b(E/\{\bar{\eta}_l\}_{l=1}^{L}) = \frac{1}{\pi} \int\limits_{0}^{\pi/2} \prod_{l=1}^{L} \exp\left(-\frac{\bar{\eta}_l}{2\sin^2\theta}\right) d\theta \quad (17)$$

The average BER for independent identically distributed (*i.i.d*) paths [4], [12]:

$$P_b(E) = \int\limits_{0}^{\infty}\int\limits_{0}^{\infty} ... \int\limits_{0}^{\infty} P_b(\{\bar{\eta}_l\}_{l=1}^{L}) \prod_{l=1}^{L} p_{\bar{\eta}_l}(\bar{\eta}_l) d\bar{\eta}_1 d\bar{\eta}_2 ... d\bar{\eta}_L \quad (18)$$

$$P_b(E) = \int\limits_{0}^{\infty}\int\limits_{0}^{\infty} ... \int\limits_{0}^{\infty} \frac{1}{\pi} \int\limits_{0}^{\pi/2} \prod_{l=1}^{L} \exp\left(-\frac{\bar{\eta}_l}{2\sin^2\theta}\right) . p_{\bar{\eta}_l}(\bar{\eta}_l)\, d\theta d\bar{\eta}_1 d\bar{\eta}_2 ... d\bar{\eta}_L \quad (19)$$

The BER in terms of the moment generating function (MGF) is [4], [6], [7]:

$$P_b(E) = \frac{1}{\pi} \int\limits_{0}^{\pi/2} \prod_{l=1}^{L} \mathrm{M}_{\bar{\eta}_l}\left(-\frac{(1 - R_{pp\min})}{4\sin^2\theta}\right) d\theta \quad (20)$$

$$P_b(E) = \frac{1}{\pi} \int\limits_{0}^{\pi/2} \left(\mathrm{M}_{\bar{\eta}_l}\left(-\frac{(1 - R_{pp\min})}{4\sin^2\theta}\right)\right)^L d\theta \quad (21)$$

where, L is the number of MRC fingers. Because of the independence, the average MGF can by written as [6], [13]:

$$P_b(E) = \frac{1}{\pi} \int\limits_{0}^{\pi/2} \left(\mathrm{M}_{\bar{\eta}_l}\left(-\frac{R_{pv\max} - R_{pv\min}}{4\sin^2\theta}\right)\right)^L d\theta \quad (22)$$

where,

$$M_{\bar{\eta}}(s) = \prod_{l=1}^{L} M_{\bar{\eta}_l}(s) \quad (23)$$

Thus, the average probability of error can be obtained by substituting (16) into (21) for MRC with optimal template and in (22) for suboptimal template. Substituting with the MGF gives (23) and (24) for optimal and suboptimal templates, respectively.

4. NUMERICAL RESULTS

This section gives numerical results based on the derived expressions in Section 3, as well as simulation results. The simulation model was carried out based on the parameters described in Section 2. Figure 2 shows a BER performance comparisons of optimal and suboptimal template-based receivers with MRC diversity assuming 0^0 body rotation. As can be seen, suboptimal template-based receivers with MRC diversity is traded for minimal BER degradation. Also, Monte Carlo simulations assuming optimal template-based receivers with MRC receive diversity were carried out and compared to the derived theoretical formulas. Figure 3 shows a BER performance comparison of the formulas obtained in the previous section with simulation results for 180^0 body rotation. As can be noticed from the figure, simulated results are in good agreement with the derived formulas.

5. CONCLUSIONS

This paper investigated the BER performance of optimal and rectangular template based receivers with MRC receive diversity in CM#4 scenario of the IEEE 802.15.6a UWB WBAN channel. Closed form formulas were derived and presented for the BER performance as well as numerical results based on Monte Carlo simulations. Also, the effect of body rotation on the BER performance was evaluated. Numerical results showed that suboptimal templates were traded for minimal BER performance degradation.

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$$P_b(E) = \frac{1}{\pi} \int_0^{\pi/2} \left(\frac{4\sin^2\theta(1+K)}{4\sin^2\theta(1+K) + \bar{\eta}\,(1 - R_{pp\,\min})} \exp\left(\frac{-K\bar{\eta}\,(1 - R_{pp\,\min})}{4\sin^2\theta(1+K) + \bar{\eta}\,(1 - R_{pp\,\min})} \right) \right)^L d\theta \quad (23)$$

$$P_b(E) = \frac{1}{\pi} \int_0^{\pi/2} \left(\frac{4\sin^2\theta(1+K)}{4\sin^2\theta(1+K) + \bar{\eta}\,(R_{pv\,\max} - R_{pv\,\min})} \exp\left(\frac{-K\bar{\eta}\,(R_{pv\,\max} - R_{pv\,\min})}{4\sin^2\theta(1+K) + \bar{\eta}\,(R_{pv\,\max} - R_{pv\,\min})} \right) \right)^L d\theta \quad (24)$$

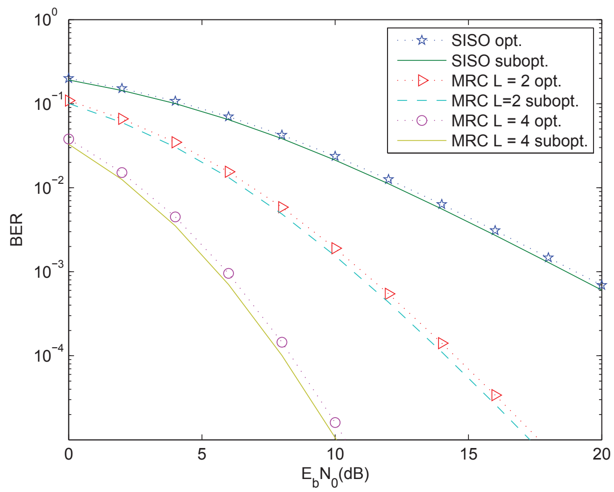

Figure 2: BER performance comparison of optimal and sub-optimal template-based receivers with MRC receive diversity assuming 0^0 rotation angle for different number of receive diversity.

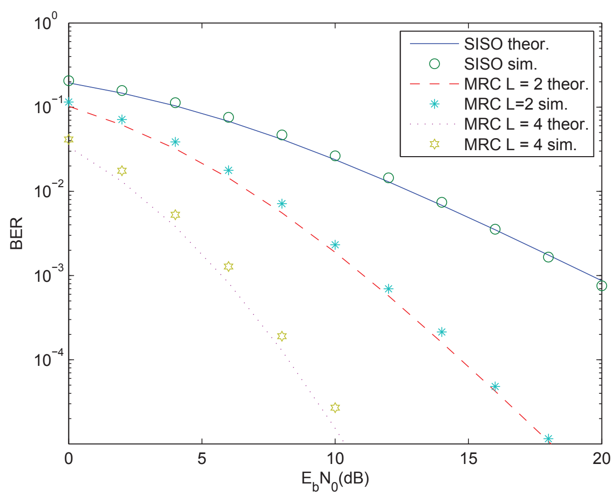

Figure 3: Comparison between theoretical and simulated BER performance of optimal template-based receivers with MRC receive diversity assuming 180^0 rotation angle for different number of receive diversity.

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