Throughput of Optimal and Suboptimal Low-power IR-UWB Coherent Receivers for Wireless Body-Area-Networks (WBANs)

Heba Shaban
Electronics and Comm. Eng. Dept.
Arab Academy for Science,
Technology & Maritime Transpot
(AASTMT).

M. Abou El-Nasr
Computer Engineering Dept.
Arab Academy for Science,
Technology & Maritime Transpot
(AASTMT).

R.M. Buehrer
Mobile and Portable Radio
Research Group (MPRG)
Virginia Tech.

Abstract

Impulse radio ultra wide band (IR-UWB) systems have the potential for low-power consumption as well as high data-rates over short distances. This makes them an attractive candidate for emerging wireless body-area-network (BAN) applications. In this paper, we investigate the performance of low-power suboptimal real sinusoidal-template based detectors for M-ary pulse-amplitude-modulation (PAM) and M-ary equally-correlated pulse-position-modulation M-ary (EC-PPM) modulation techniques in multipath channels. Furthermore, we provide numerical results in the UWB-based IEEE 802.15.6a channels, and evaluate the corresponding attainable throughput.

Index Terms

Ultra-wideband (UWB), Body Area Networks (BANs), low-power receivers, Pulse Amplitude Modulation (PAM), Pulse-Position Modulation (PPM), and multipath channel.

I. INTRODUCTION

Ultra wideband (UWB) technology is a promising solution for emerging low-power wireless sensor network applications, such as wireless body area networks (WBANs). In particular, impulse radio ultra wideband (IR-UWB) offers low-power consumption and robust performance in dense-multipath environments [1]. However, the implementation of UWB systems has many challenges, such as the design of a power-efficient UWB template pulse generator. Typically, the correlation operation represents the bottleneck of the design of a power efficient receiver. Generally, there is a common tradeoff between power consumption and template generation accuracy [2], [3].

Coherent detectors do not necessarily require more power consumption as compared to non-coherent detectors. Suboptimal-templates have been proposed as low power alternatives to optimal template-based coherent detectors. The main befit of this solution in addition to low-power consumption, the robust performance it can provide in dense multipath environments. According to [4], an IR-UWB analog correlation receiver using a complex suboptimal-sinusoidal template consumes 40 mW for a signal bandwidth of 500 MHz and bit rate of 2 Mbps, which is less than the power consumed by a transmitted reference receiver using the same design parameters. On the other hand, the power consumption of the corresponding digital receiver architecture requires 119 mW [4]. Moreover, emerging BAN applications require low data-rates, which reduces the power consumption requirement. In particular, an average data-rate of 500 kbps is realized by the transmission of a 1% duty cycle of the 50 Mbps maximum allowable data-rate, which can reduce the power consumption by a factor of 100 compared to 100% duty cycle transmission [5].

In this paper, we study the maximum allowable throughput of a receiver which uses suboptimal template pulses, and that is suitable for low-cost and low-power UWB systems. Essentially, the allowable throughput is dependent on the bit-error rate (BER) performance. So, we will investigate the BER performance and further use it to obtain the corresponding throughput assuming pulse amplitude modulation (PAM) and equally correlated pulse-position-modulation (EC-PPM) modulation schemes. Furthermore, we compare the performance of suboptimal coherent receivers to optimal detectors in the IEEE 802.15.6a channel model [6]. The organization of this paper is as follows. Section II provides the link budget, studies the BER performance, and provides results for the BER and data throughput in the UWB-based IEEE 802.15.6a channels. Then, the conclusions are provided in Section III.

II. LINK BUDGET AND PERFORMANCE EVALUATION

In our link budget calculations we will choose the maximum expected values, and sometimes even higher values in order to have an upper bound on the expected values rather than exact values. For instance, we will assume a path loss = 75.6 dB, where based on line-of-sight (LOS) links the path loss is expected to be ≈ 10 dB better than the selected value. Table

978-1-4244-6051-9/11/$26.00

TABLE I
LINK BUDGET FOR A PRACTICAL ON-BODY BAN SYSTEM [7].

Parameter	Value
$B.W._{\min}$ (bandwidth)	2 GHz
P_t (transmitted power in dB relative to a W)	-8.3 dBm
PL_0(path loss at reference distance (d_0))	44.6 dB
$PL(d)$(path loss at distance (d))	31 dB
PL_t(total path loss)	75.6 dB
G_t and G_r (Tx and Rx antenna gains)	0 dBi
Receiver Noise Figure (N_F)	10 dB
Pulse Rate (R_p)	50 Mp/s
Implementation Loss (L_a)	3 dB
Average received power at the receiver (P_R)	-83.9 dBm
Average noise power (P_N)	-114.9 dBm
Achieved E_b/N_0	31 dB
Required $E_b/N_0\|_{\text{req}}$ (dB)	21 dB
Link Margin (LM)	10 dB
Receiver Sensitivity (S_r)	-93.9 dBm

I summarizes the main link budget design parameters for an actual on-body wireless wearable healthcare system. Now, we will study the bit-error-rate (BER) of the system under investigation in multi-path channels assuming *M*-ary PAM and *M*-ary EC-PPM modulation schemes. We assume the transmitted pulse is the Gaussian pulse (the most commonly used pulse for UWB systems). The *n*-th order Gaussian pulse $\omega_0(t)$ in terms of $\sigma^2 = T_p/2\pi$, and the pulse duration T_p, has the form [8]:

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

Assuming a correlation receiver, the optimal template $v(t)$ should 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. When using a suboptimal windowed sinusoidal template, $v(t) = \cos(\omega_c(t))$ for a window-length T and carrier frequency ω_c, the oscillator frequency should be chosen to maximize the output SNR $= \frac{E_s}{N_0}\frac{\rho_{pv}^2(\tau_e)}{\rho_{vv}(0)}$, where, E_s is the bit energy, N_0 is the noise PSD, $\rho_{pv}(.)$ is the normalized cross-correlation of the received pulse and the template waveform, τ_e is the timing error, and $\rho_{vv}(.)$ is the normalized auto-correlation of the template pulse [8], [9]. Considering binary PPM (BPPM), with a transmitted pulse $p(t)$, the optimal template is [2]:

$$v(t) = p(t) - p(t-\delta) \tag{2}$$

where, δ is the PPM modulation parameter. In the case of the optimum receiver, the BER can be minimized by choosing δ.

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 [10]. The union bound on the bit error probability of EC *M*-ary PPM is [10], [9], [11], [7]:

Assuming suboptimal template-based receiver, the BER is calculated as:

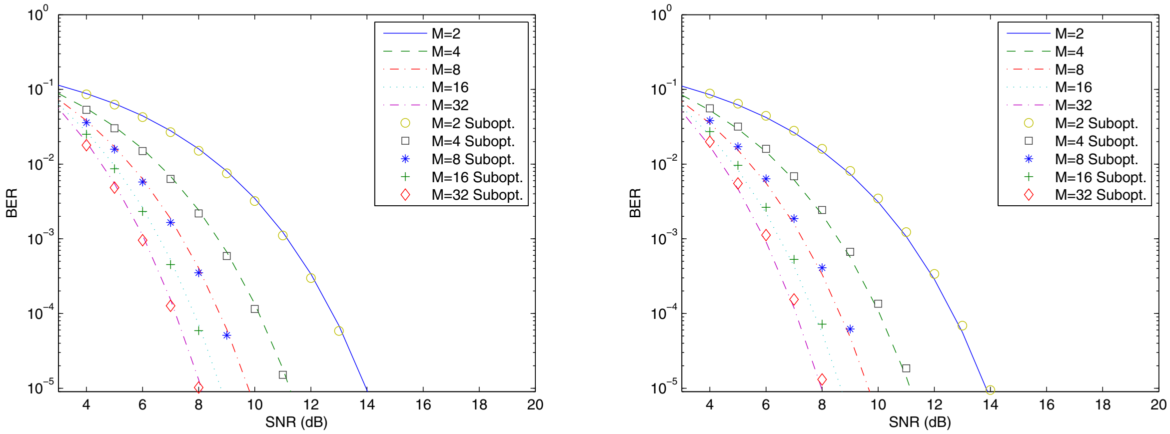
$$P_{\min}(z) \cong \frac{1}{N_{ch}}\sum_{k=1}^{N_{ch}} Q\left(\sqrt{\frac{SNR}{2}d_{k,i^{(*)}}^2(z)}\right) \tag{3}$$

where, $Q(.)$ is the Gaussian tail function, N_{ch} is the number of channel realizations, SNR is the signal-to-noise-ratio, $d_{\min}(z) = \min\limits_k d_{k,i^{(*)}}(z)$ is the minimum normalized distance, $i^{(*)} = \arg\min\limits_i d_{k,i}^2(z)$, and k is the argument of the minimization [12], [9]. Assuming the suboptimal sinusoidal template, the corresponding BER is:

$$P_{\min}(z) \cong Q\left(\sqrt{\frac{\text{SNR}}{2}\left(\rho_{pv\max} - \rho_{pv\min}\right)}\right) \tag{4}$$

where, ρ_{pv} is the normalized cross-correlation function of the received pulse and windowed sinusoidal template and $\rho_{pv\min} \triangleq \rho_{pv}(\tau_{opt})$. The template pulse parameters, T is the window-length and ω_c is the carrier frequency. ρ_{pv} can be calculated as [8]:

$$\rho_{pv}(\tau) = \frac{1}{\sqrt{E_p}\sqrt{E_v}}\int\limits_{-T/2}^{T/2} p(t)\cos(\omega_c(t-\tau))dt \tag{5}$$



(a)

(b)

Fig. 1. a) BER performance comparison of *M*-ary EC-PPM modulation in IEEE 802.15.6a CM♯3 channel for the fifth order Gaussian pulse with optimal and suboptimal templates. and b) BER performance comparison of *M*-ary EC-PPM modulation in IEEE 802.15.6a CM♯4 channel for the seventh order Gaussian pulse with optimal and suboptimal templates.

where, E_p is the pulse energy and E_v is the template energy.

For *M*-ary PAM modulation with suboptimal sinusoidal template the corresponding BER is:

$$P_{\min}(z) \cong \frac{1}{N_{ch}} \sum_{k=1}^{N_{ch}} Q\left(\sqrt{\frac{3n\mathrm{SNR}\rho_{\mathrm{pv\,max\,k,i}(*)}(\mathrm{z})}{M^2-1}}\right) \tag{6}$$

where, n is the number of bits. Now, we will use the analysis provided above to compare the performance of IR-UWB correlation receivers with optimal and suboptimal templates in the UWB IEEE 802.15.6a on-body-to-on-body CM♯3 and on-body-to-off-body CM♯4 channel models. Then, we will use the obtained results to obtain the attainable data throughput for the range 1 - 4 m as defined by the IEEE 802.15 task group 6 (TG6) committee for BAN applications.

As was mentioned before, the optimal template $v(t)$ should be matched to the received pulse $p(t) = \omega_n(t)$, where the pulse parameters should be chosen to meet a specified FCC system's allowable emission limits. Since BANs should work in indoor and outdoor environments, we select the fifth and seventh derivative gaussian pulses for indoor and outdoor environments, respectively [7], [11]. For *M*-ary PPM modulation, the performance loss caused by sinusoidal templates with appropriately chosen parameters is < 0.2 dB, as depicted in the semi-analytic simulation results in Figure 1. Figures 1(a) and (b) show the BER performance of ARake receivers for various modulation orders in the IEEE 802.15.6a channel assuming the fifth order Gaussian pulse in CM♯3 model, and seventh order Gaussian pulse in CM♯4 model, respectively.

The corresponding throughput for *M*-ary PAM is depicted in Figures 2(a) and (b) for the IEEE 802.15.6a CM♯3 and CM♯4 channel models, respectively assuming the fifth order Gaussian pulse. Similarly, throughput for *M*-ary PAM is depicted in Figures 2(c) and (d) for the IEEE 802.15.6a CM♯3 and CM♯4 channel models, respectively assuming the seventh order Gaussian pulse and *M*-ary EC-PPM modulation. As can be seen, suboptimal templates are traded for a ≈ 2 Mbps throughput degradation. Moreover, as expected, the throughput degrades when the effect of surrounding environment is included, as in the case of CM♯4 model.

III. CONCLUSIONS

WBAN applications require low-power consumption and high BER performance for the transmission of critical medical data. This paper showed that IR-UWB correlation receivers with suboptimal templates are good candidates for low-power accurate WBAN systems. We investigated the BER of *M*-ary PAM and *M*-ary EC-PPM in multipath channels using suboptimal templates, and provided results based on semi-analytic simulations in the IEEE 802.15.6a channel. We further estimated the corresponding data throughput, and showed that suboptimal templates are traded for ≈ 2 Mbps throughput degradation.

REFERENCES

[1] M. Di Renzo, R. Buehrer, and J. Torres, "Pulse shape distortion and ranging accuracy in UWB-based body area networks for full-body motion capture and gait analysis," *IEEE Global Telecommunications Conference, 2007. GLOBECOM '07.*, pp. 3775–3780, 26-30 Nov. 2007.
[2] B. Hu, N. C. Bueaulieu, "Pulse shapes for ultrawideband communication systems," *IEEE Trans. On Wireless Comm*, vol. 4, no. 4, pp. 1789–1797, Jul. 2005.

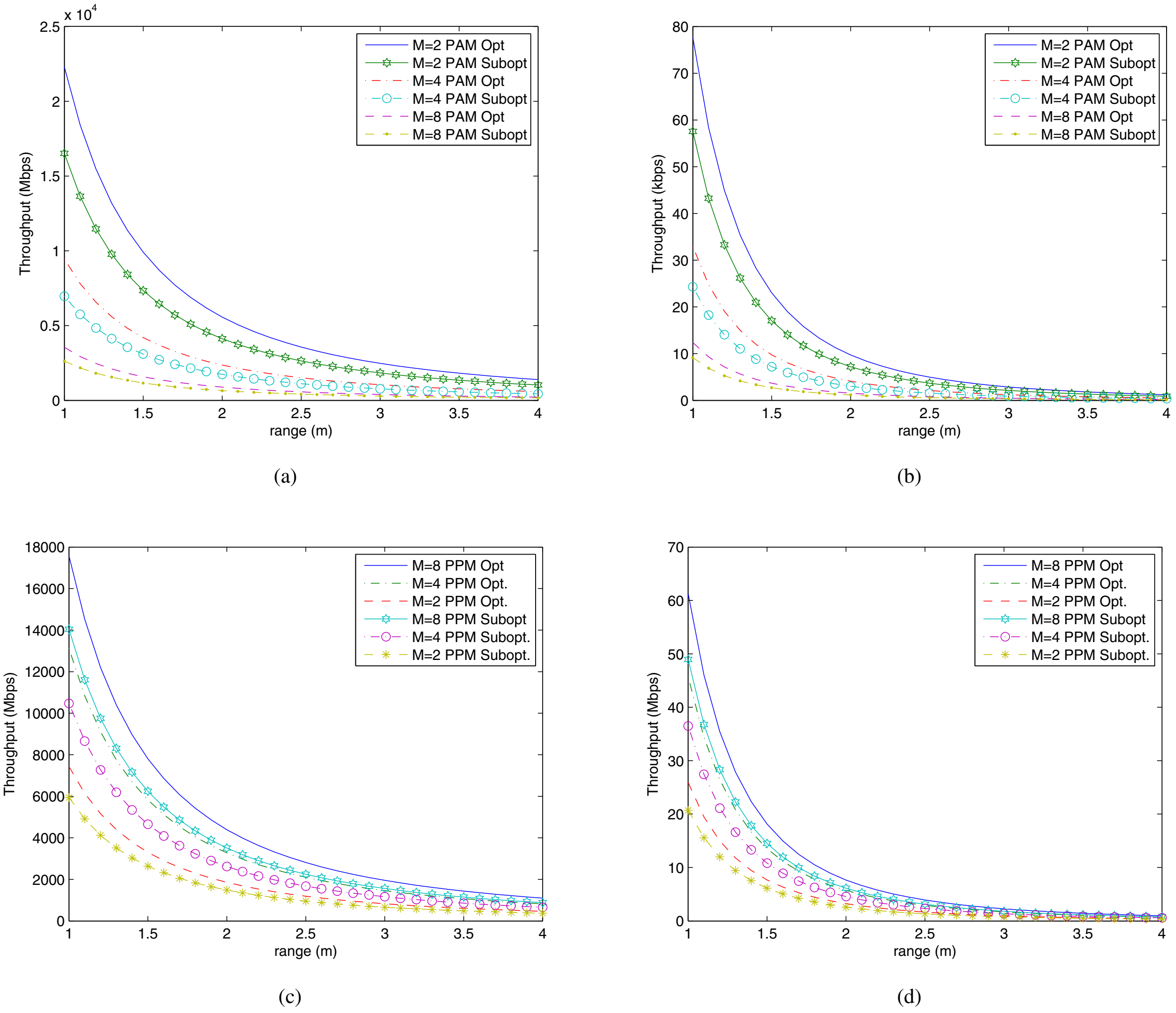


Fig. 2. a) Throughput for M-ary PAM in the IEEE 802.15.6a CM♯3 assuming the fifth order Gaussian pulse for optimal and suboptimal templates. b) Throughput for M-ary PAM in the IEEE 802.15.6a CM♯4 assuming the fifth order Gaussian pulse for optimal and suboptimal templates. c) Throughput for M-ary EC-PPM in the IEEE 802.15.6a CM♯3 assuming the seventh order Gaussian pulse for optimal and suboptimal templates. and d) Throughput for M-ary EC-PPM in the IEEE 802.15.6a CM♯4 assuming the seventh order Gaussian pulse for optimal and suboptimal templates.

[3] J. Zahng, T. D. Abhayapala, and R. A. Kennedy, "Role of pulses in ultra wideband systems," in *Proc of 2005 IEEE International Conference on Ultra-Wideband, 2005. ICU 2005*, 2005, pp. 565– 570.

[4] J. Ryckaert, M. Verhelst, M. Badaroglu, S. DAmico, V. De Heyn, C. Desset, P. Nuzzo, B. Van Poucke, P. Wambacq, A. Baschirotto, W. Dehaene, and G. Van der Plas",, "A CMOS ultra-wideband receiver for low data-rate communication," *IEEE J. Solid-State Circuits*, vol. 42, no. 1, pp. 2515–2525, Nov. 2007.

[5] F. Troesch, C. Steiner, T. Zasowski, T. Burger, and A. Wittneben, "Hardware aware optimization of an ultra low power UWB communication system," *IEEE International Conference on Ultra-Wideband, 2007. ICUWB 2007.*, pp. 174–179, Sept. 2007.

[6] K. Y. Yazdandoost, "Channel model for body area network (BAN)," Tech. Rep., 2008, doc: IEEE P802.15-08-0780-04-0006.

[7] H. Shaban, "A novel highly accurate wireless wearable human locomotion tracking and gait analysis system via UWB radios," Ph.D. Dissertation, Virginia Tech, 2010.

[8] L. Sangyoub, "Design and analysis of ultra-wide bandwidth impulse radio receiver," Ph.D. dissertation, Southern California University, 2002.

[9] H. Shaban, M. Abou El-Nasr, and R. Buehrer, "Performance of ultralow-power IR-UWB correlator receivers for highly accurate wearable human locomotion tracking and gait analysis systems,"*IEEE Global Telecommunications Conference, 2009. GLOBECOM'09.*, 30 Nov. - 4 Dec. 2009, pp. 1–6.

[10] F. Remirez-Mireles, "On the performance of ultra wide-band signals in gaussian noise and dense multipath," *IEEE Trans. On Veh. Tech.*, vol. 5, no. 50, pp. 244–249, Jan. 2001.

[11] H. Shaban, M. Abou El-Nasr, and R. Buehrer, "Toward a highly accurate ambulatory system for clinical gait analysis via UWB radios," *Information Technology in Biomedicine, IEEE Transactions on*, vol. 14, no. 2, pp. 284 –291, March 2010.

[12] D. Dardari, C.-C. Chong, and M. Z. Win, "Improved lower bounds on time-of-arrival estimation error in realistic uwb channels," *Ultra-Wideband, The 2006 IEEE 2006 International Conference on*, pp. 531–537, Sept. 2006.