Performance of Ultralow-power IR-UWB Correlator Receivers for Highly Accurate Wearable Human Locomotion Tracking and Gait Analysis Systems

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Abstract—In this paper we study low-power impulse radio ultra-wideband (IR-UWB) correlation receivers with suboptimal templates, as a promising candidate for a highly accurate wearable human locomotion tracking system. Such a system is theoretically capable of providing a ranging accuracy of 1mm in practical multipath fading channels at a SNR of 18dB. This ranging accuracy is ten times better than the ranging accuracy provided by currently available systems. Furthermore, we study the theoretical BER and the improved Ziv-Zakai lower-bound on ranging accuracy in AWGN and dense multipath fading channels. We show that low-power is traded for a minimal performance loss for both BER and TOA accuracy.

Index Terms—Ultra-wideband (UWB), gait analysis, Body Area Networks (BANs), error analysis, low-power receivers, improved Ziv-Zakai lower bound (ZZLB), Pulse-Position Modulation (PPM), and multipath channel.

I. INTRODUCTION

Quantitative gait analysis refers to the measurement, description, and assessment of the quantities that characterize the human locomotion using measurement systems [1], [2]. The choice of a suitable measurement system is controlled by multiple factors, such as the accuracy and reliability, cost, and power consumption. Sophisticated measurement systems employ optical tracking systems to track the displacement of markers placed at particular anatomical sites on the limb segments [3], [4]. Standard gait analysis is based on either optical, magnetic, or ultrasound motion tracking systems. Even though optical tracking systems are the most accurate systems, it is worth saying that some of the gait parameters require a certain level of accuracy that is not provided by current measuring systems [5]. For instance, for the base-of-support (BOS), the reported measurement accuracy is not sufficient to be clinically accepted. A typical BOS is equal to 8.5cm for normal adults, while the reported error is 1.17cm, thus the relative error is \( \approx 14.6\% \) [5], [6].

Ultimately, the use of wearable healthcare systems is a promising solution not only for gait analysis, but also for general health monitoring and the early detection of abnormal conditions [7]. A promising technology for wireless body area networks (WBANs) that offers low-power consumption and robust performance in dense-multipath environments is the ultra wideband (UWB) technology [8]. According to Federal Communications Commission (FCC) regulations, UWB signals are defined to have a -10dB bandwidth that is greater than 500MHz, or a fractional bandwidth that is greater than 20% with a maximum emission power spectral density of -41.3dBm/MHz. UWB transceivers can be implemented using either digital or analog architectures. Impulse radio (IR) implementation of ultra-wideband (UWB) systems has great potential for low-complexity, low-power, high-precision, and low-cost implementation. However, the implementation of UWB systems has many challenges. One of these challenges is the design of a power-efficient UWB template pulse generator. Typically, the correlation operation and template generation must be performed at very high speed, which implies a tradeoff between power consumption and template generation accuracy [9], [10].

The optimum receiver requires that the template waveform be matched to the received pulse. Nevertheless, the generation of a Gaussian pulse (the most common pulse shape suggested for IR-UWB) template is difficult and power-consuming [11]. Windowed sinusoidal waveforms have been proposed in the literature as a power efficient-solution, since generating a sinusoidal wave is straightforward [12], and when windowed it can resemble the main pulse [11], [13]. According to [14], an IR-UWB analog correlation receiver using a complex-sinusoidal template requires 40mW for a signal bandwidth of 500MHz and a bit rate of 2Mbps, which is less than the power consumed by a transmitted reference receiver using the same design parameters. The power consumption of the corresponding digital receiver architecture requires 119mW [14]. Moreover, an average data-rate of 500Kbps is realized by the transmission of a 1% duty cycle of the 50Mbps maximum allowable data-rate, which can reduce the power consumption by a factor of 100 compared to 100% duty cycle transmission [15].

When different transceivers are compared based on the

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1Markers are arranged based on well defined marker-sets. Markers should be placed at specific anatomical positions, where the objective of the data collection is to capture the movement of the underlying skeleton.

2The BOS is defined as the distance from heel-to-toe while walking. It is known to have clinical importance.
ranging accuracies that they can provide, at high SNR, energy detector (ED) estimators exhibit an error floor of $T_s/\sqrt{T_s}$, where $T_s$ is the integration window [16]. Typically, EDs require minimal integration windows $T_s$ equivalent to integer multiples $I$ of the pulse-width $T_p$. $T_s = IT_p$, as in practice multiple pulses are transmitted per bit.

In this paper, we study the performance of a receiver which uses suboptimal template pulses, and that is suitable for low-cost and low-power wearable gait analysis systems. We study the achievable ranging accuracy using the improved Ziv-Zakai lower bound (ZZLB) on the time-of-arrival (TOA) estimate. This bound transforms the performance evaluation of an estimation problem into a binary detection problem [23]. Thus, we investigate the BER performance and further use it to obtain the corresponding ZZLB. Moreover, we compare the performance of suboptimal coherent receivers to the optimal detectors in both AWGN and multipath channels.

II. TEMPLATE PULSES AND BER PERFORMANCE IN AWGN AND MULTIPATH CHANNELS

The $n$-th order Gaussian pulse $\omega_n(t)$ in terms of $\sigma^2 = T_p/2\pi$, and the pulse duration $T_p$, has the form [11]:

$$\omega_n(t) = \frac{d^n}{dt^n} \left( \frac{1}{\sqrt{2\pi}\sigma^2} e^{\frac{-t^2}{2\sigma^2}} \right)$$ (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 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 $\omega_c$, the oscillator frequency should be chosen to maximize the output SNR [11]:

$$SNR = \frac{E_s}{N_0} \frac{R_{pv}(\tau_c)}{R_{pp}(0)}$$ (2)

where, $E_s$ is the bit energy, $N_0$ is the noise PSD, $R_{pv}(\cdot)$ is the normalized cross-correlation of the received pulse and the template waveform, $\tau_c$ is the timing error, and $R_{pp}(\cdot)$ is the normalized auto-correlation of the received pulse.

A. Performance in AWGN Channel

Considering binary Pulse Position Modulation (BPPM), with a transmitted pulse $p(t)$, the optimal template is [9]:

$$v(t) = p(t) - p(t - \delta)$$ (3)

where, $\delta$ is the PPM modulation parameter. In the case of the optimum receiver, the BER can be minimized by choosing $\delta$ to minimize the autocorrelation [17]:

$$\delta_{opt} = \arg \min_{\delta} R_{pp}(\delta)$$ (4)

For equally correlated (EC) $M$-ary PPM, the transmitted signal is composed of $N_a$ time shifted pulses with $2 \leq M < N_a$, where each signal is identified by a sequence of cyclic shifts of an $m$-sequence of length $N_a$ [17]. The union bound on the bit error probability of EC $M$-ary PPM assuming an optimum receiver is [17]:

$$U_{BPB} = \frac{M}{2} Q \left( \frac{E_s}{2N_0} (1 - R_{pp\min}) \right)$$ (5)

$$R_{pp}(\tau) = \frac{1}{E_p} \int_{-\infty}^{\infty} p(t)p(t - \tau)dt$$ (6)

where, $Q(\cdot)$ is the Gaussian tail function [17], [18]. The alternate representation for the tail function is expressed as $Q(x) = \frac{1}{\sqrt{\pi}} \int_{0}^{\infty} e^{-\frac{x^2}{2w_0^2}} dt$ [18], $R_{pp\min} \triangleq R_{pp}(\delta_{opt})$, and $E_p$ is the pulse energy. The normalized cross-correlation function of the received pulse and windowed sinusoidal template (where $T$ is the window-length and $\omega_c$ is the carrier frequency) can be calculated as [11]:

$$R_{pv}(\tau) = \frac{1}{\sqrt{E_pE_v}} \int_{-T/2}^{T/2} p(t)\cos(\omega_c(t - \tau))dt$$ (7)

where $E_v$ is the template energy. Assuming that the received pulse is the Gaussian pulse $p(t) = \omega_0(t)$, this gives:

$$R_{pv}(\tau) = \frac{1}{4\sqrt{E_pE_v}} \left[ erf \left( \frac{1}{2\sqrt{2}\sigma} \Phi - \frac{1}{2\sqrt{2}\sigma} \Phi^* \right) \right] \left[ \exp \frac{-\omega_c}{2} + \exp \frac{-\omega_c}{2} \Phi^* \right]$$ (8)

where, $\Phi = T + 2i\omega_c\sigma^2$, $\Lambda = \sigma^2\omega_c + 2i\tau$, $i = \sqrt{-1}$, $\omega_c$ is the oscillator angular frequency in rad/sec, $T$ is the window duration, and $\tau$ is the time-shift. To minimize BER, we wish to choose the value of $\delta$ that minimizes the correlation $R_{pp\min}(\delta_{opt})$. Further, at the receiver we choose a sample time $\mu$ to maximize the correlation between the suboptimal template and the generated pulse:

$$\mu_{opt} = \arg \max_{\mu} R_{pv}(\mu)$$ (9)

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

$$U_{BPB} = \frac{M}{2} Q \left( \frac{E_s}{2N_0} (R_{pv\max} - R_{pp\min}) \right)$$ (10)

B. Performance in Dense Multipath Channel

The BER of low complexity PRake receivers [19], assuming PPM modulation and optimal templates in terms of the moment generating function (MGf), $M_{ij}$, over a Nakagami-$m$ channel with uniform power delay profile (PDP), and $L_p$ independent identically distributed (i.i.d.) paths is [19]:

$$P_{b,PRake} = \frac{1}{\pi} \int_{0}^{\pi/2} \left( M_{ij} \left( 1 - \frac{R_{pp\min}}{4m\sin^2 \theta} \right) \right) L_p d\theta$$ (11)
where, $\bar{\eta} = E_s/LN_0$. Ideal Rake (ARake) receivers capture all the energy in all $L$ paths, i.e., $L_p = L$ [19]. Substituting with the MGF $M_\eta(s) = (1 - \frac{\bar{\eta}^2}{m})^{-m}$ gives:

$$P_b,_{\text{ARake}} = \frac{1}{\pi} \int_0^{\pi/2} \left( \frac{4m \sin^2 \theta}{4m \sin^2 \theta + \bar{\eta}(1 - R_{pp_{\min}})} \right)^{mL_p} d\theta$$

The probability of bit error of PRake receivers for PPM modulation with a suboptimal template is:

$$P_b,_{\text{PRake}} = \frac{1}{\pi} \int_0^{\pi/2} \left( \frac{4m \sin^2 \theta}{4m \sin^2 \theta + \bar{\eta}(R_{pp_{\max}} - R_{pp_{\min}})} \right)^{mL_p} d\theta$$

The MGF for correlated Nakagami-$m$ fading is:

$$M_\eta(s) = \prod_{l=1}^{L} \left( \frac{1 - \frac{s \bar{\eta}_l}{mL}}{mL} \right)^{-m} [\det[c_{u_j}]]^{-m}$$

where,

$$c_{u_j} = \begin{cases} 1 & u = j \\ \sqrt{\rho_{u_j}} \left( 1 - \frac{mL}{s \bar{\eta}_j} \right)^{-1} & o.w. \end{cases}$$

where $\rho_{u_j}$ is the fading power correlation between sub-bands $u$ and $j$ [18]. The corresponding error probability is:

$$P_b,_{\text{PRake}} = \frac{1}{\pi} \int_0^{\pi/2} \left( \frac{4m \sin^2 \theta + \bar{\eta}(R_{pp_{\max}} - R_{pp_{\min}})}{4m^2L_p \sin^2 \theta} \right)^{mL_p} \cdot [\det[c_{u_j}]]^{-m} d\theta$$

and,

$$c_{u_j} = \begin{cases} 1 & u = j \\ \sqrt{\rho_{u_j}} \left( 1 + \frac{4m^2L_p \sin^2 \theta}{R_{pp_{\max}} - R_{pp_{\min}} \bar{\eta}_j} \right)^{-1} & o.w. \end{cases}$$

III. TEMPLATE DESIGN AND NUMERICAL RESULTS

In this section, we use the analysis provided above to compare the performance of IR-UWB correlation receivers with optimal and suboptimal templates in AWGN and dense multipath channels.

Using windowed sinusoids was proposed in the literature as an alternative solution for low-power template generation in the analog domain, since windowed sinusoids can approximate the optimal templates and are easily generated in the analog domain [11]. However, this solution suffers from the sensitivity of the correlator output SNR to timing errors. Receiver structures with suboptimal sinusoidal templates are more sensitive to timing errors as compared to optimal receivers [11]. Complex sinusoids were proposed to compensate for the SNR degradation in the presence of timing errors, but this structure requires nearly double the power required for the corresponding structure with real sinusoids [20], [14].

Suboptimal template design requires the appropriate choice of the sinusoidal wave frequency, and the integration window-length [11]. Figure 1a shows the optimal and suboptimal templates assuming the seventh order Gaussian pulse, and Figure 1b shows the corresponding autocorrelation and cross-correlation functions. Figure 2 shows the cross-correlation function of the Gaussian pulse and the sinusoidal template versus the frequency of the sinusoidal template at different time samples, and correlation window-lengths using (8). As shown, the cross-correlation function is highly sensitive to both the sinusoidal template frequency, and the integration window. The normalized cross-correlation coefficient can be $> 0.9$ for appropriate choice of sinusoidal templates. For $M$-ary PPM modulation, the performance loss caused by sinusoidal templates with appropriately chosen parameters is < 0.2dB, as depicted in the simulation results in Figure 3. Furthermore, the simulated BER performance of ARake receivers is shown in Figure 4 for BPPM and 4-PPM schemes in IEEE 802.15.4a outdoor NLOS channel, for the seventh order Gaussian pulse, and sinusoidal templates.

IV. TOA THEORETICAL LOWER BOUNDS

The primary motivation for using UWB technology (besides the wide spectrum available) is the ability of UWB pulses to provide very accurate distance estimates using Time-of-Arrival (TOA) measurements [8], [21]. In general, the accuracy can be improved by increasing either the SNR at the receiver or the effective signal bandwidth of the transmitted signal [22]. Error bounds are essential for providing a performance limit of any estimator in terms of the mean square error (MSE) [8]. From estimation theory, the mean square error (MSE) $\sigma^2_{\hat{\tau}}$ of any unbiased estimate $\hat{\tau}$ of the time-of-arrival $\tau$ is under-bounded by the Cramer-Rao Lower Bound (CRLB) [23]:

$$\sigma^2_{\hat{\tau}} = E \left\{ (\hat{\tau} - \tau)^2 \right\} \geq \text{CRLB}$$

where the measurement error is $\varepsilon_{\hat{\tau}} = \hat{\tau} - \tau$ and $E \{ . \}$ denotes the statistical expectation [23].

A. TOA lower-bounds

The CRLB for the ranging error estimate can be calculated from the relation:

$$\sigma^2_{\hat{d}} = c \sigma_{\hat{\tau}}$$

where, $c = 3 \times 10^6$ m/sec is the speed of light [24]. When no-multipath is present [23]:

$$\text{CRLB} = \frac{N_0/2}{E_p \beta^2} = \frac{1}{2 \beta^2 SNR}$$

where, pulse-energy-to-noise ratio is represented by $E_p/N_0$, and $\beta^2$ is the second moment of the spectrum $P(f)$ of the pulse shape used $p(t)$ defined by [23]:

$$\beta^2 = \frac{\int_{-\infty}^{\infty} f^2 |P(f)|^2 df}{E_p}$$

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Another representation for the Gaussian pulse defined in terms of pulse-width $T_p$ and $\tau_p = 0.5 * T_p$, as [23] is:

$$\omega_0(t) = \exp\left(-2\pi \left(\frac{t^2}{\tau_p^2}\right)\right)$$

(22)

The $n$-th order Gaussian pulse has the form [11]:

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

(23)

The mean square estimation error is then [23]:

$$E \{\epsilon_{\tau}^2\} = \frac{1}{2} \int_0^\infty z P \left\{ |\epsilon_{\tau}| \geq \frac{z}{2} \right\} dz$$

(24)

where the expectation is with respect to $\tau$ and $r(t)$, $P(\tau)$ is the probability density function (pdf) of the TOA in the absence of any information. It is assumed to be uniformly distributed in the interval $[0, T_a]$. $P \left\{ |\epsilon_{\tau}| \geq \frac{z}{2} \right\}$ is equivalent
to the probability of a binary detection scheme with equally-probable hypothesis, where $T_a$ is the observation window [23].

The TOA ranging approach is based on the estimation of the arrival time of the first detected path. Typically, optimum detection involves the correlation of the received waveform with a locally generated template waveform, which adds to the receiver complexity [22]. However, this requirement is precluded for non-coherent receivers, where the detection process depends solely on the received pulses [22], [25]. One promising low-power non-coherent receiver is the energy detection (ED) correlation receiver, where the correlation is replaced by a squaring device. Generally speaking, EDs consume smaller amounts of power as compared to coherent stored-reference receivers since they do not require template generation. However, this simplification is traded for a degradation in the estimation performance. Assuming the ED detector, and a corresponding pulse-width 0.8ns, the corresponding B.W. is 2GHz for the seventh-order Gaussian pulse\(^3\) [26], the maximum achievable ranging accuracy is 6.9cm for an integration window that is equal to the pulse-width. This precludes the choice of ED detectors. Obviously, for such a high target ranging accuracy, the MF seems an appropriate choice, where its performance approaches the CRLB at high SNRs.

Generally, the CRLB provides a loose bound on the TOA estimate which is not realizable in multipath environments [23]. Another bound that provides more accurate results suitable for multipath environments is the Ziv-Zakai lower bound (ZZLB). The improved ZZLB for the coherent detection of binary signaling is as given by [23]:

$$\text{ZZLB} = \frac{1}{T_a} \int_0^{T_a} z(T_a - z) P_{\text{min}}(z) dz$$ (25)

where, $P_{\text{min}}(z)$ is the minimum attainable probability of error expressed as [23]:

$$P_{\text{min}}(z) = Q \left( \sqrt{\frac{E_p}{N_0}}(1 - R_{pp}(z)) \right)$$ (26)

where $E_p$ is the pulse energy and $R_{pp}(z)$ is the pulse autocorrelation. For the suboptimal template, the corresponding minimum attainable probability of error is:

$$P_{\text{min}}(z) = Q \left( \sqrt{\frac{E_p}{N_0}(R_{pv}(0) - R_{pv}(z))} \right)$$ (27)

This bound transforms the estimation problem into a binary detection problem, which simplifies the bound estimation in multipath environments. The derivation of $P_{\text{min}}(z)$ requires the a priori knowledge of the multipath phenomena [23].

The evaluation of the estimator in complex channel models is not analytically tractable [23]. As a result, the ZZLB is typically evaluated using experimentally measured channel impulse responses or Monte-carlo simulations [23].

$$P_{\text{min}}(z) \approx \frac{1}{N_{\text{ch}}} \sum_{k=1}^{N_{\text{ch}}} Q \left( \sqrt{\frac{\text{SNR}}{2} d_{k,i(*)}^2(z)} \right)$$ (28)

$$P_{\text{min}}(z) \approx Q \left( \sqrt{\frac{\text{SNR}}{2} d_{\text{min}}^2(z)} \right)$$ (29)

where $d_{\text{min}}(z) = \min_k d_{k,i(*)}(z)$ is the minimum normalized distance and $k$ is the argument of the minimization [23].

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 should be chosen to meet a specified FCC system’s allowable emission limits. Since the human locomotion tracking system under investigation should work in indoor and outdoor environments, we chose the seventh derivative gaussian pulse, to satisfy the FCC masks for both environments. The corresponding ZZLB for the optimal and suboptimal templates are shown in Figure 5. In order to obtain results for the TOA bounds using realistic BAN channels, the ZZLB was simulated using a semi-analytic simulation approach in the BAN channel model described in [27]. The ZZLB was calculated for the simulated channels and the average is depicted in Figure 6 for the distance bound, assuming the back, side, and front channel models. As seen from the results, an accuracy of 0.11cm is achievable at an $E_p/N_0 = 18$dB, which defines the target $E_p/N_0$. Different link budget calculations for low-power and low-cost detectors for BAN applications showed that the achievable $E_p/N_0$ is $> 18$dB with appropriate link margins [28], [29].

V. CONCLUSION

Gait analysis is one of the WBANS applications that requires low-power consumption and high ranging accuracy. This paper showed that IR-UWB correlation receivers with suboptimal templates are good candidates for low-power accurate wearable human locomotion tracking systems suitable for gait analysis. Low-power consumption is traded for a minimal performance degradation. The BER performance and improved ZZLB of an IR-UWB correlation receiver with a suboptimal template were analyzed and compared to the optimum receiver in AWGN and dense multipath channels. Results showed that the performance degradation is minimal compared to the optimal receiver. It was shown that these receivers are theoretically capable of providing a ranging accuracy equal to 1mm at a SNR of 18dB. This ranging accuracy is ten times better than the ranging accuracy reported in the literature for current measuring systems. The 18dB SNR requirement is achievable by low-power receiver architectures with suitable link margins. The power consumption for 100% duty cycle is on the order of few tens of milli-watts. Due to the low data-rate requirement of human locomotion tracking, the power consumption could further be decreased by approximately two orders of magnitude. Thus, the resulting power consumption is $\approx 1$mW.

\(^3\)Seventh-order Gaussian pulse was chosen to satisfy the FCC masks for both indoor and outdoor environments.
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