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# REFERENCE RANGE CORRELATION (RRcR) RANGING AND PERFORMANCE BOUNDS FOR ON-BODY UWB-BASED BODY SENSOR NETWORKS

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**Abstract**—In this paper, we propose a reference range correlation-based (RRcR) ranging technique suitable for low-power on-body wireless body sensor networks (WBSNs) via ultra wideband (UWB) radios. The proposed technique is based on the presence of reference nodes, and is assumed to have line-of-sight (LOS) links. We show that the performance of the proposed technique outperforms matched-filtering-based time-of-arrival (MF-TOA) estimators with no *a priori* and with perfect channel knowledge. We further show that increasing the number of reference node up to twenty provides significant enhancement in the performance traded for higher overall power consumption. Then, we study the effect of timing-misalignment on the Ziv-Zakai lower bound (ZZLB), and provide numerical results. The presented results are based on simulations in the IEEE 802.15.6a on-body-to-on-body channel (CM3) in the UWB band as well as actual measurements.

## 1. INTRODUCTION

Impulse radio ultra wideband (IR-UWB) is a good candidate for low-power wireless body sensor network (BSN) applications. One of the challenging applications of BSNs is fine human movement tracking [1]. UWB systems have the potential for providing high ranging and positioning accuracies. However, designing a highly accurate ranging system with low-power consumption is a challenging task, and has many implications. Particularly, ranging is based on determining the

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time-of-arrival (TOA) of the first-path. UWB channels are dense multi-path channels, in which the first-path is not necessarily the strongest, or is not always sufficiently separated from later-arriving paths, which makes the TOA estimation a challenging task.

Essentially, TOA estimation is either performed by threshold-crossing (TC), also known as leading-edge (LE) detectors, or matched filtering-based (MF) estimators. In threshold-based approaches, determination of the optimum threshold is critical, as it highly affects the system performance. A small threshold increases the probability of false alarm (detecting noise as the TOA), and large thresholds increase the probability of missing the direct-path. Both cases provide erroneous TOA estimates [2]. Typically, threshold design is based on the channel statistics, and due to the large number of available multi-path components and channel variations, accurate and fast channel estimation becomes a challenging task [3].

On the other hand, MF estimators determine the maximum value of the cross-correlation of the received pulse and a pre-stored template pulse. In the absence of multi-path, a MF-based TOA estimator is the optimal estimator. In multi-path channels, the MF requires *a priori* knowledge of the received pulse. In that case, the maximum (MAX) selection criterion is applied to determine the maximum output within a selected window. Absence of *a priori* channel knowledge makes the performance of MF-estimators suboptimal. Another concern related to MF-estimators is that they require very high-sampling rates for resolving the large number of available multi-paths associated with UWB channels [3–5]. This requirement can be overcome by implementing the MF using a sliding-correlator, which reduces the sampling requirement to the pulse repetition frequency (PRF). Generally, ranging applications can have low PRFs compared to communication systems [6]. Transmitter receiver synchronization requirement of TOA-based ranging approaches adds another implication to the system design. Moreover, clock jitter is an important performance metric that needs to be considered while evaluating the accuracy of UWB ranging and positioning systems [2, 7]. However, for on-body WBSNs, this should not be a big issue since all nodes can ultimately be tied to the same on-body clock. From the achievable ranging accuracy point of view, energy detection (ED) estimators exhibit an error floor of $T_s/\sqrt{12}$ at high signal-to-noise ratio (SNR), where $T_s$ is the integration window. On the other hand, stored-reference estimators, based on the MF, have a performance that approaches the Cramer-Rao lower bound (CRLB) at high SNRs [3].

There have been recent research trials trying to overcome the above mentioned implications associated with the design of highly accurate, but less-complex, UWB ranging systems. For instance, some techniques proposed using a piece of the received signal as the correlation template [8]. However, there is still a crucial need for new approaches suitable for emerging UWB applications (such as accurate motion tracking), that are capable of providing high ranging accuracy at low-complexity and low power consumption [9].

This paper proposes a reference range correlation-based (RRcR) ranging approach suitable for on-body WBSNs. With this approach, our system is capable of providing a high ranging accuracy at low-power consumption ($\approx 1\,\text{mW}$) which is suitable for on-body communications. Furthermore, we study the effect of template timing-misalignment on the provided accuracy. This is done through the analysis of timing-misalignment on the improved Ziv-Zakai lower bound (ZZLB) in additive white Gaussian noise (AWGN) channel, and further by providing simulations in the IEEE 802.15.6a CM3 UWB body area network (BAN) channel model. Furthermore, we provide results based on actual measurements. Moreover, we study the power-consumption and ranging accuracy trade-offs based on the proposed ranging technique, and provide numerical results.

This paper is organized as follows. The proposed RRcR ranging algorithm is provided in Section 2 with results based on simulations and actual measurements. Moreover, the effect of timing-misalignment on the ZZLB is studied in Section 3, and numerical results are provided and compared to MF-based estimators. Section 4 studies the power-consumption, memory requirement, and battery lifetime of the proposed technique, and provides comparisons to conventional MF-TOA estimators. Finally, conclusions are given in Section 5.

## 2. PROPOSED RRcR RANGING TECHNIQUE

Assuming a zero-order Gaussian pulse defined in terms of pulse width $T_p$ and $\sigma^2 = \frac{T_p^2}{2\pi}$ as [10]:

$$p_0(t) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{\frac{-t^2}{2\sigma^2}} \tag{1}$$

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

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

Assuming a suboptimal template (windowed sinusoid) $v(t)$ in terms of the carrier frequency $\omega_c$ and window length $T$ is defined as $v(t) = \cos(\omega_c t)$, where $-T \leq t \leq T$ [11].

The assumed transmit signal $s(t)$ with $N_s$ time-hopping (TH) pulses $p(t) = p_n(t)$ is given by:

$$s(t) = \sum_{k=1}^{N_s} p\left(t - kT_f - c_k T_c\right) \quad (3)$$

where $T_f$ and $T_c$ are the frame and hop durations, respectively, and $c_k \in \{1, 2, 3, \ldots, N_s\}$ is the time-hopping code. The multi-path fading channel impulse response is represented as a series of impulses as:

$$h(t) = \sum_{l=1}^{L} \alpha_l \delta(t - \tau_l) \quad (4)$$

where, $L$ is the number of paths, $\alpha_l$ and $\tau_l$ are the gains and delays, respectively, and $\tau_1 < \tau_2 < \ldots < \tau_L$ and $\sum_{l=1}^{L} \alpha_l^2 = 1$. The received signal after the effect of multi-path is $r_{mp}(t) = s(t) \bigotimes h(t) = \sum_{l=1}^{L} \alpha_l p_l(t - \tau_l)$, where $p_l(t)$ is the normalized received pulse at the $l$-th tap, and $\bigotimes$ denotes convolution. Received signal $r(t)$ at a distance $d = c \cdot \tau_{toa}$, where $c$ is the speed of light $= 3 \cdot 10^8$ m/s [12], is:

$$r(t) = \sum_{k=1}^{N_s} r_{mp}\left(t - kT_f - kT_c - \tau_{toa}\right) + n(t) \quad (5)$$

where $n(t)$ is two-sided AWGN with variance $\sigma_n^2 = N_0/2$, and $N_0$ is noise power spectral density. The delay $\tau_{toa}$ is the TOA at the receive node. The correlator output in terms of the template signal $v(t)^\dagger$ with a sampling interval $t_s$ [3]:

$$z_s = \int_{(n-s)t_s}^{(n-1)t_s + N_s T_f} r(t) v(t - (n-1)t_s) dt \quad (6)$$

Obviously, the sampling interval affects the output of the correlator, and consequently the TOA estimate. Considering power consumption constraints, we assume the use of an analog sliding-correlator as proposed in [13]. The sampling interval in analog correlation is represented as time-shift. In our system, we assume a sampling interval (time-shift) = 10 ps, similar to [13]. Sliding-correlator determines the TOA of the signal of the strongest path [3]:

$$r_s(t) = \sum_{k=1}^{N_s} r_{mp}(t - kT_f - c_k T_c - \tau_{peak}) \quad (7)$$

† Optimally, the template pulse $v(t)$ should be a clean version of the transmitted pulse $p(t)$. Another low-power alternative, is to use suboptimal templates, sinusoidal templates, that resemble the original pulse [11].

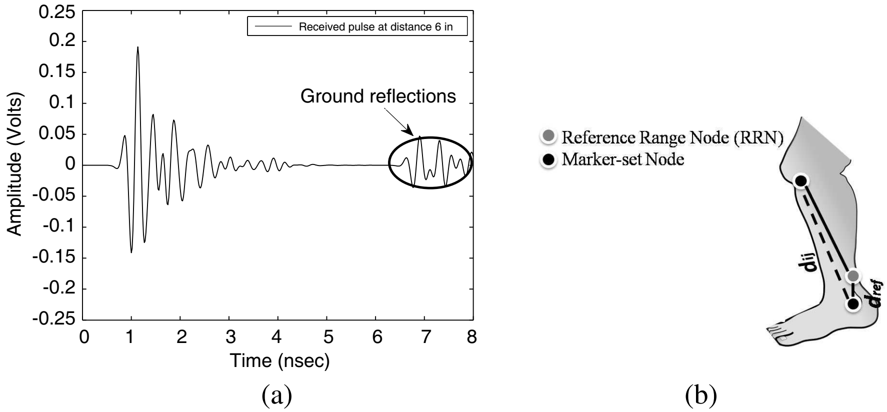



**Figure 1.** (a) Received on-body pulse at 6 in tx.-rx. antenna separation distance indicating ground reflections based on replicated measurement data, and (b) simplified schematic diagram of RRcR measurement setup.

where, $\tau_{peak}$ is the TOA of the strongest path. It is worth noting that the strongest path does not necessarily represent the direct-path.

The UWB-BAN channel is characterized by two clusters, with the first cluster due to the diffraction of propagating waves, and the second due to reflections from the ground [14]. These clusters are statistically independent, and typically the second cluster occurs between 7 and 10 ns after the first cluster [15]. Figure 1(a) shows a received on-body pulses at 6 in spacing from the transmit antenna placed on the same side of the body. When transmit and receive antennas are placed on different sides of the body, ground reflections tend to be dominant [14, 15]. Intuitively, this is because of the presence of body parts that obstruct the line-of-sight (LOS) link between the transmit and receive antennas. According to [9], when a body limb obstructs the direct LOS link, an attenuation of up 20 dB occurs depending on the amount of first Fresnel zone obstruction. This obstruction causes the propagation wave to diffract around the obstructing body limb causing a pulse shape distortion. When the link is LOS, with no Fresnel zone obstruction, there is no pulse shape distortion [9]. In order to guarantee accurate TOA estimates, target nodes, among which the distances are measured, need to have LOS links [16].

Inspired by the above mentioned properties of UWB-BAN channel, we propose a reference range correlation-based (RRcR) ranging algorithm, as depicted in Figure 1(b). Our proposed technique is suitable for on-body WBSN applications that require high ranging and localization accuracies. Basically, nodes measure the distances between the different points on the body during movement. Ranging data is acquired between different nodes while the subject is walking throughout the estimation of the TOA of the first path (which could be measured based on the fact that on-body nodes are synchronized), which is then converted to a distance estimates. The measurements include the intersegmental distances that have line-of-sight (LOS) links, which are guaranteed through the predetermination of the node sub-groups that have LOS links, as depicted in Figure 2. For each group, we assume the presence of three nodes per segment in addition to one extra node from a neighboring segment. The latter node is chosen such that its segment has a LOS with the other three nodes segment while walking. The proposed algorithm further assumes the presence of a minimum number of three nodes, namely the transmit, receive and one or more reference-range nodes (RRNs). The RRNs have predetermined and fixed ranges. These nodes are used as a reference for the measured node. Assuming that both RRNs and the node with unknown range exhibit the same channel (at least when considering paths arriving within the first $2T_p$ seconds), the RRNs can be used for correcting the difference between the determined $\tau_{peak}$ and

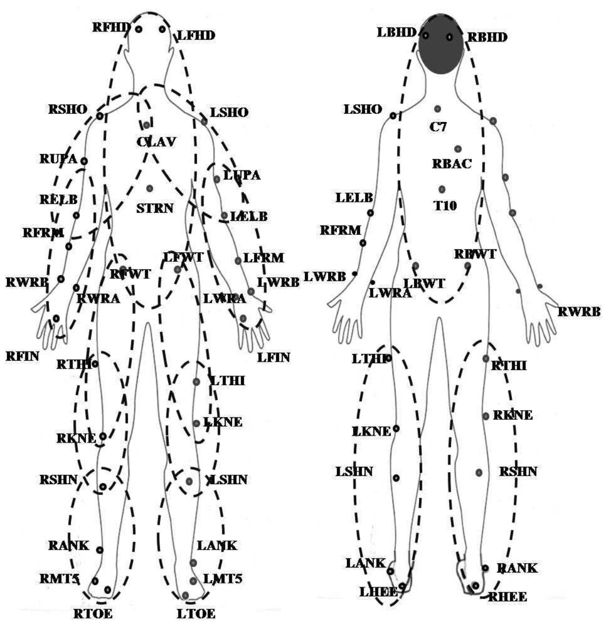



**Figure 2.** Grouping of nodes into LOS regions.

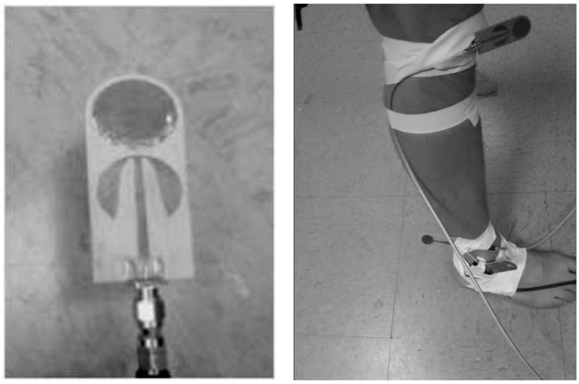
the actual $\tau_{toa}$ of the direct-path. Thus, typically the reference nodes are used to eliminate the ambiguity in the TOA determination cased by the effect of multi-path propagation. Unlike time-difference-of-arrival (TDOA) ranging techniques, the proposed RRcR technique assumes that all nodes are synchronized.

The detailed TOA estimation procedure of the proposed RRcR assuming the presence of $N_R$ reference nodes is as follows:

(i) Calculate the matched-filter (MF) output at the RRN.
(ii) Estimate the corresponding $\tau_{peak_{ref}}$.
(iii) From the known $d_{ref}$, calculate the corresponding $\tau_{toa_{ref}}$.
(iv) Calculate $\tau_{\delta_i} = \tau_{peak_{ref_i}} - \tau_{toa_{ref_i}}$ for each reference node.
(v) Calculate $\tau_\delta = \frac{1}{N_R}\sum_{i=1}^{N_R}\tau_{\delta_i}$.
(vi) At the unknown range node, also calculate the MF output.
(vii) Determine the corresponding $\tau_{peak_{ij}}$.
(viii) Use the calculated $\tau_\delta$ from the RRN to estimate the actual $\tau_{toa_{ij}}$ for this node.
(ix) Calculate $\tau_{toa_{ij}} = \tau_{peak_{ij}} - \tau_\delta$.

### 2.1. RRcR Actual Measurement Procedure

In order to evaluate the system performance based on real-data, on-body UWB measurements were taken at the MPRG[‡] labs. The following equipments were used: HP33120A function generator, Tektronix CSA8000B Digital Sampling Oscilloscope, Geozondas pulser (GZ1106DL1, GZ1117DN25), and antennas manufactured by the Time Domain corporation [17], as depicted in Figure 3(a). The test subject was allowed to walk, and the received pulses were recorded and stored. The length of the pulses was 4000 samples. In this measurement set, we measured the knee-to-heel distance assuming the presence of three nodes, namely the knee, heel, and reference nodes. The actual measurement setup is depicted in Figure 3(b). Figure 4 shows the output of an analog sliding-correlator. It also shows $\tau_{peak}$ and $\tau_\delta$ determination at the RRN node. Further results based on the actual measurement set will be provided in the following section.



(a) (b)

**Figure 3.** (a) UWB antenna from time domain corporation, and (b) MF output depicting TOA estimation at RRN based on actual measurements.

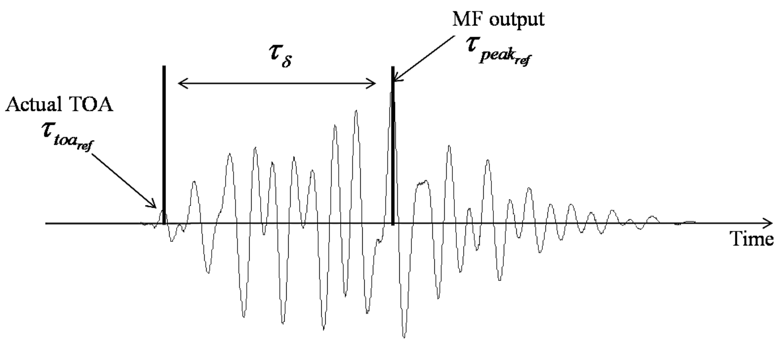



**Figure 4.** MF output depicting TOA estimation at RRN based on actual measurements.

## 2.2. Numerical Results

In this section, we provide numerical results based on actual measurements as well as simulations in the IEEE 802.15.6a CM3 UWB-BAN channel model. The performance of the proposed RRcR is compared to MF-TOA estimators for optimal and suboptimal templates based on actual measurement data in Figure 5 for distance

‡ Mobile and Portable Radio Research Group, a part of the Wireless @ Virginia Tech research group.

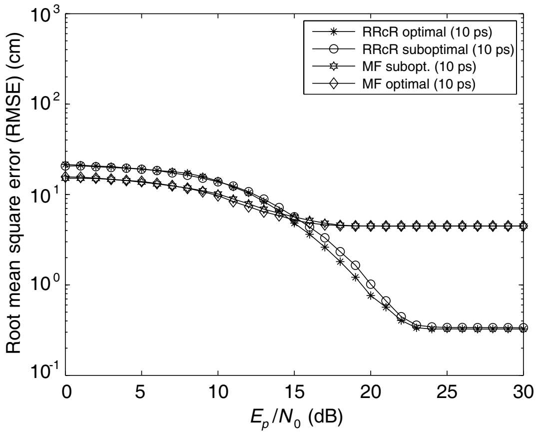



**Figure 5.** Comparison between measured knee-to-ankle distance using RRcR and MF with optimal and suboptimal template-based estimators based on actual measurements for the TOA distance estimate.

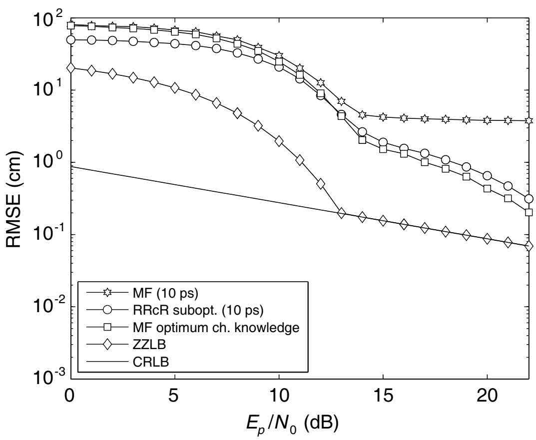



**Figure 6.** Performance of proposed RRcR compared to MF without and with perfect channel knowledge, ZZLB, and CRLB (cm) in the IEEE 802.15.6a CM3 UWB channel assuming suboptimal template pulse.

estimate assuming a 10 ps sampling time for practical implementation issues. As can be seen, the performance of RRcR provides substantial improvement over MF-TOA estimators with optimal and suboptimal templates. From figure, the maximum achievable accuracy using MF-TOA estimator is 4.47 cm. This value is compared to 0.33 cm using the proposed RRcR with one RRN. Moreover, the performance of RRcR with suboptimal template approaches the performance of RRcR with optimal template. The same holds for MF-TOA estimators with optimal and suboptimal templates. Figure 6 shows the performance of RRcR also with one RRN compared to MF-estimator for both no-*a priori* channel information and perfect channel knowledge cases along with the corresponding ZZLB and CRLB for the case of suboptimal template in the IEEE 802.15.6a CM3 UWB channel model. As can be seen, RRcR shows substantial improvement over MF estimator with no-*a priori* channel knowledge, and approaches the performance of MF with perfect channel knowledge at high SNR. RRcR with one RRN

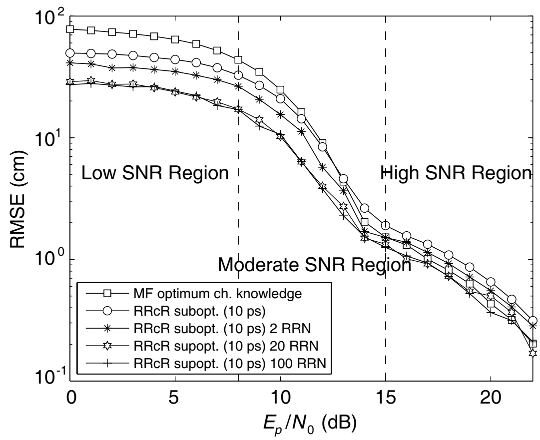



**Figure 7.** Performance of proposed RRcR (cm) for various number of RRNs in the IEEE 802.15.6a CM3 UWB channel assuming suboptimal template pulse.

**Table 1.** Performance improvement of RRcR over MF-TOA with perfect channel knowledge for different number of RRNs in the IEEE 802.15.6a CM3 UWB channel model.

| ♯ of RRNs | Low SNR (4 dB) | Moderate SNR (10 dB) | High SNR (18 dB) |
|---|---|---|---|
| 1 | 22.48 cm | 3.93 cm | 0.16 cm |
| 2 | 31.80 cm | 9.3 cm | 0.27 cm |
| 20 | 42.39 cm | 14.57 cm | 0.36 cm |
| 100 | 41.8 cm | 14.17 cm | 0.36 cm |

outperforms the MF with perfect channel knowledge at the low signal to noise ratio region (0–8 dB). At the moderate and high SNR regions (above 8 dB), the performance of the proposed RRcR with one RRN approaches the performance of MF with perfect channel knowledge. Moreover, Figure 7 shows the performance of the proposed RRcR technique in the IEEE 802.15.6a CM3 UWB channel model with one, two, twenty and one-hundred RRNs. Obviously, in the low SNR region, the proposed RRcR provides a substantial improvement over the MF-TOA estimator. At the low SNR, the improvement is in the order of few tens of centimeters, and at the moderate SNR it is on the order of few centimeters. Whereas, at the high SNR, this improvement is on the order of few millimeters. Intuitively, this is because of the fact that at high SNRs MF-TOA estimators in general provide a high ranging accuracy that theoretically approaches the CRLB depending on the fading statistics of the first path [3]. Thus, the improvement at this region is expected to be lesser than the other regions. On the other hand, at the low SNR region, MF-TOA estimators provide a low ranging accuracy, and thus the proposed RRcR provides a substantial improvement at this region. Table 1 summarizes the performance comparison results of the proposed RRcR over the MF-TOA with perfect channel knowledge at the low, moderate, and high SNR regions for one, two, twenty, and one-hundred RRNs. Typically, as the number of RRNs is increased, the RRcR provides an increased accuracy. However, increasing the number of RRNs above twenty does not lead to significant improvement in the performance. Obviously, this is because of increasing the number of nodes above that number does not provide any further information about the ambiguity in the TOA estimate cased by the multi-path channel. Nevertheless, it is worth noting that the improvement in performance is traded for a bigger amount of overall system power-consumption, as will be discussed in detail in Section 4.

## 3. TOA LOWER-BOUNDS

In this section, we derive the ZZLB on the TOA estimate in the presence of tamplate-pulse timing misalignment with the received pulse assuming optimal and suboptimal templates. The mean square estimation error of TOA is [10]:

$$E\left\{\varepsilon_{\hat{\tau}}^{2}\right\}=\frac{1}{2}\int_{0}^{\infty} zP\left\{|\varepsilon_{\hat{\tau}}|\geq\frac{z}{2}\right\}dz \tag{8}$$

where the expectation is with respect to $\tau$ and $p(t)$, and $P_\tau(\tau)$ is the probability density function (pdf) of the TOA in the absence of any information. It is assumed to be uniformly distributed in the observation interval $[0, T_a]$. $P\{|\varepsilon_{\hat{\tau}}| \geq \frac{z}{2}\}$ is equivalent to the probability of a binary detection scheme with equally-probable hypotheses, where $T_a$ is the observation window [10].

Generally, the CRLB provides a loose lower bound on the TOA estimate which is not realizable in multi-path environments [10]. Another bound that provides more accurate results suitable for multi-path environments is the ZZLB. The ZZLB for the coherent detection of binary signaling is as given by [10]:

$$\mathrm{ZZLB} = \frac{1}{T_a} \int_0^{T_a} z(T_a - z) P_{\min}(z) dz \tag{9}$$

where, $P_{\min(z)}$ is the minimum attainable probability of error. This bound transforms the estimation problem into a binary detection problem, which simplifies the bound estimation in multi-path environments. The derivation of $P_{\min}(z)$ depends on the receiver's *a priori* knowledge about the multi-path phenomena [10].

For suboptimal templates, the minimum attainable probability of error is [18]:

$$P_{\min}(z) = Q\left(\sqrt{\frac{E_p}{N_0}(\rho_{pvI}(0) - \rho_{pvI}(z))}\right) \tag{10}$$

The normalized cross-correlation function of the received pulse $p(t)$ and real windowed sinusoidal template is [11]:

$$\rho_{pvI}(\tau) = \frac{1}{\sqrt{E_p}\sqrt{E_v}} \int_{-T/2}^{T/2} p(t) \cos(\omega_c(t - \tau)) dt \tag{11}$$

where $E_v$ is the template energy. Without loss of generality, we assume that the received pulse is the Gaussian pulse $p(t) = p_0(t)$ from which all derivatives could be obtained. Assuming the zero-order Gaussian pulse, the corresponding closed-form cross-correlation function is:

$$\rho_{pvI}(\tau) = \frac{\sqrt{2\pi}\sigma}{2\sqrt{E_p}\sqrt{E_v}} \left[erf\left(\frac{1}{2\sqrt{2}\sigma}\Phi\right) + erf\left(\frac{1}{2\sqrt{2}\sigma}\Phi^*\right)\right] \cos\left(\frac{\omega_c}{2}\Theta\right) \tag{12}$$

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/s, $T$ is the window duration, and $\tau$ is the time-shift, $\Theta = -i\Lambda$, and $\cos(\frac{\omega_c}{2}\Theta) = 0.5(\exp(i\frac{\omega_c}{2}\Theta) + \exp(-i\frac{\omega_c}{2}\Theta))$. The corresponding ZZLB is:

$$\mathrm{ZZLB} = \frac{1}{T_a}\int_0^{T_a} z\,(T_a - z)\,Q\left(\sqrt{\frac{E_p}{N_0}(\rho_{pvI}(0) - \rho_{pvI}(z))}\right)dz \qquad (13)$$

The template $v(t)$ should be matched to the received pulse $p(t) = p_n(t)$, where the pulse parameters are chosen to meet a specified Federal Communications Commission (FCC) system's allowable emission limits. When using a suboptimal windowed sinusoidal template, the oscillator frequency should be chosen to maximize the output SNR [11].

The evaluation of the estimator in complex channel models is not analytically tractable [10]. Thus, in multi-path channels ZZLB is commonly evaluated using measured channel impulse responses or Monte Carlo simulations [10].

### *3.0.1. Effect of Timing Misalignment*

For the suboptimal template, the effect of timing-misalignment $\tau_e$ on the BER performance of PPM scheme is:

$$P_{\min}(z) = Q\left(\sqrt{\frac{E_p}{N_0}\frac{[\rho_{pvI}(\tau_e) - \rho_{pvI}(z-\tau_e)]^2}{\rho_{pvI}(0) - \rho_{pvI}(z)}}\right) \qquad (14)$$

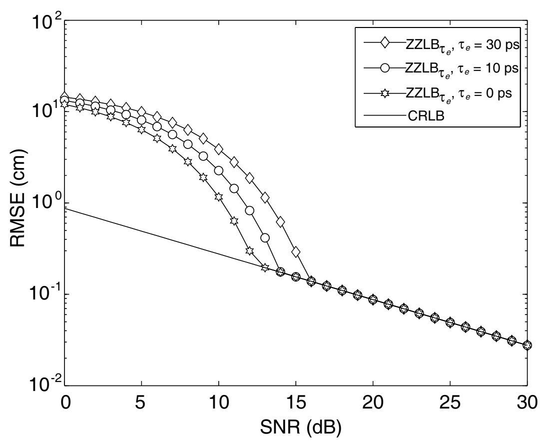



**Figure 8.** ZZLB$_{\tau_e}$ (cm) for various values of timing mismatch $\tau_e$ in the IEEE 802.15.6a CM3 UWB channel model, assuming suboptimal template and seventh-order Gaussian pulse.

**Table 2.** Overall Power consumption and memory requirement for the proposed RRcR with different number of RRNs.

| ♯ of RRNs | Overall memory | Overall power | Battery lifetime |
|---|---|---|---|
| 1 | 8.09 Gigabytes/day | 10 mW | 4.6 days |
| 2 | 9.56 Gigabytes/day | 11.8 mW | 3.9 days |
| 20 | 35.61 Gigabytes/day | 44.2 mW | 1.1 days |
| 100 | 151.49 Gigabytes/day | 188.2 mW | 0.25 days |

where $\rho_{pvI}(\cdot)$ is the normalized cross-correlation of the received pulse and the template waveform, and $\tau_e$ is the timing error.

The ZZLB with the effect of timing misalignment for suboptimal template is given in Equation (15).

$$\mathrm{ZZLB}_{\tau_e} = \frac{1}{T_a} \int_0^{T_a} z\,(T_a - z)\, Q\left(\sqrt{\frac{E_p}{N_0} \frac{\left[\rho_{pvI}(\tau_e) - \rho_{pvI}(z - \tau_e)\right]^2}{\rho_{pvI}(0) - \rho_{pvI}(z)}}\right) dz \quad (15)$$

In order to obtain results for the TOA bounds using realistic BAN channels, the ZZLB was simulated using a semi-analytic simulation approach with the IEEE 802.15.6a CM3 UWB BAN channel model. The resulting ZZLB for suboptimal template is shown in Figure 8 for $\tau_e = 10$ and 30 ps. Since the target SNR is within the high SNR region (at which performance approaches the CRLB), the effect of the allowable timing misalignment (10 ps) has no effect on the target SNR.

## 4. POWER CONSUMPTION AND BATTERY LIFETIME OF PROPOSED SYSTEM

This section studies the memory and battery lifetime requirements based on practical design parameters. We start by estimating the memory requirement assuming no RRN (typically for the MF-TOA estimator) as follows. Assuming 16 bits per range estimate, this gives 2 bytes per frame per node. For a 41 node BAN, the overall data per frame = 82 bytes/frame. Memory requirements for all UWB nodes per day = 24 ∗ 60 ∗ 60/1 ms ∗ 100 bytes = 3.54e9 bytes/day. The overall power consumption and battery lifetime are estimated as follows. for a 1 kHz sampling rate, the duty-cycle per node = 2 μs/1 ms = 2e-3. A typical coherent UWB sliding-correlator requires a ≈ 100 mW [13]. Hence, the average power consumption for a 0.2% duty-cycle = 100 mW ∗ 2e-3 = 0.2 mW. If the system is considered to have one battery, thus considering all 41 nodes, the average power consumption

$= 8.2\,\mathrm{mW}$[§]. Considering a common 1.5 V voltage source, this gives 5.47 mA. For a common battery (AAA battery) source (750 mAh), the average battery-life is 750 mAh/5.47 mA = 137.19 hrs/24 = 5.7 days. Table 2 extends the above results for the proposed RRcR with one, two, twenty, and one-hundred RRNs, assuming 0.2 mW power consumption per node.

## 5. CONCLUSIONS

Motivated by the properties of IR-UWB as a good candidate for highly accurate ranging and positioning on-body UWB-based WBSNs, we proposed the RRcR ranging technique. The proposed technique is suitable for providing high accuracy, real-time on-body ranging measurements. We showed that the proposed technique with one RRN provides substantial improvement over MF-TOA estimators without *a priori* channel knowledge, and approaches the performance of MF estimators with perfect channel knowledge. We also showed that increasing the number of RRNs enhances the system performance, such that the proposed RRcR outperforms the corresponding MF-TOA estimators with perfect channel knowledge. Explicitly we showed that in general, the performance improvement over the MF-TOA estimators with perfect channel knowledge is on the order of few tens of centimeters at the low SNR region, on the order of few centimeters at the moderate SNR region, and on the order of few millimeters at the high SNR region. We further showed that increasing the number of RRNs above twenty does not provide significant enhancement in the provided ranging accuracy. Furthermore, we studied the effect of timing-misalignment on the ZZLB for optimal and suboptimal templates, and provided closed-forms in AWGN channel, and semi-analytic simulations in the IEEE 802.15.6a CM3 UWB channel. Moreover, we studied the tradeoffs between the number of RRNs and power-consumption.

## ACKNOWLEDGMENT

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[§] The overall power consumption is calculated assuming a common battery. This value does not deviate from the FCC regulations, which requires an average power consumption of 0.1–1 mW per node [19].

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