AN ACCURATE ULTRA WIDEBAND (UWB) RANGING FOR PRECISION ASSET LOCATION

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Abstract—**This paper investigates a ranging method employing Ultra wideband (UWB) pulses under the existence of the line of sight (LOS) path in a multipath environment. Our method is based on the estimation of time of arrival of the first multipath. It averages the received pulses over multiple time frames, performs a correlation operation on the averaged signal, and detects the peak of the correlated signal. Our method reduces the ranging accuracy over conventional methods, and its accuracy is close to the Cramer-Rao lower bound (CRLB) on even for a low SNR.**

Index Terms— **UWB, ranging, asset location, CRLB, TOA**

I. INTRODUCTION

Ultra wideband (UWB) has been the focus of much research and development recently [1], [2]. A unique nature of UWB lies in its dual capabilities – communication and ranging. Ranging offers several applications such as see-through-the-wall, medical imaging, and collision avoidance. Previous ranging techniques include the exact time-difference-of-arrival estimation of narrowband signals either in the time-domain or in the spectral domain in [3],[4],[5]. Recently, impulse-based UWB ranging methods have been investigated in [6],[7],[8]. Since the FCC regulations limit power emission of UWB be at a low level, UWB ranging is mostly applied for short distance such as indoor and confined areas. Our method presented in this paper is intended for short distance ranging whose applications include asset location in a warehouse, position location for wireless sensor networks, and collision avoidance.

Cramer and Rao suggested a lower bound on estimation of the delay accuracy (which reduces to the ranging accuracy) based on the bandwidth and the signal-to-noise ratio (SNR) in E_b/N_0 of the received signal, often called CRLB [9]. This CRLB is valid under the additive white Gaussian noise (AWGN) channel, but it can also be used as a loose bound under a multipath environment [10].

This paper investigates a method for ranging using a train of UWB pulses in a multipath environment. Our method is based on the estimation of time-of-arrival (TOA) of the first multipath under the existence of the line of sight (LOS) path. It takes the average of the received pulses over multiple pulse repetition intervals (PRIs) and performs a correlation operation on the averaged signal with a template followed by detection of the peak of the correlated signal. The time of arrival is measured against the peak point of the correlated signal. The underlying rational for our method is that averaging operation reduces noise of the received signals corrupted by the statistically zero mean AWGN. The proposed method approaches the CRLB under even a low SNR.

II. PRELIMINARIES

Data communications requires harvest of maximal energy dispersed on multipaths using a rake receiver or similar. Ranging necessitates detection of the first multipath such as its time of arrival. Hence, the two systems, communication system and ranging system, often require different architectures and algorithms due to the difference in their objectives.

There are several components affect ranging accuracy based on the estimation of TOA, and they include multipaths, AWGN, interferences from other systems and imperfect synchronization. The multipaths result from non-LOS paths of a signal. Although the LOS path is not necessarily always the strongest path, the channel characteristics of spatially averaged power delay profile based on the measurements show that the first path is usually the strongest path [11]. *In this respect, the first multipath detection reduces to detection of the strongest path, which is employed in our method.* In other words, we estimate the TOA of the strongest path assuming it is the TOA of the first multipath. *Another assumption employed for our method is perfect synchronization between the transmitter and the receiver.* This assumption is necessary to separate the ranging error due to imperfect TOA estimation from imperfect synchronization.

Sources of interference from other systems may include GPS, microwave oven or hair dryer. Interferences from those sources are not considered in our simulation, since its impact is difficult to characterize.

A. UWB Pulses

Gaussian monopulses are widely used for UWB systems owing to the desirable shape of the spectrum and existence of simple closed form expression [12]. Figure 1 shows a train of Gaussian monopulses at the transmitter and the receiver sides. The PRI (pulse repetition interval) denotes the time duration

between pulses and TOA is the time-of-arrival. The received signal is modeled as the derivative of the transmitted signal, which is Gaussian doublet for this case.
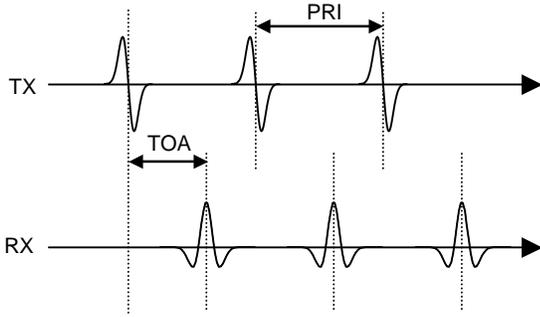
Figure 1: A Train of Gaussian Monopulses and Doublets

B. Multipaths and Inter-Symbol Interference

If PRI is not sufficiently long, multipaths can cause inter-symbol interference (ISI). RMS (Root Mean Square) delay spread is dispersion of multipaths over the time, and it is useful to find an adequate PRI value as investigated in [13]. We employed the channel model proposed by Cassioli et al [11].

Figure 2 displays the average power delay profile of Cassioli's model. Time is measured relative to the first arriving multipath, and the amplitude of each vertical line represents the energy gain of each 2 ns delay bin. Note that a multipath "dies out" if its power is less than 6 dB above the noise floor in Cassioli's model, and all channel profiles "die out" within 300 ns. On average, over 92% of total energy arrives within 100 ns. This means that a PRI greater than 100 ns would experience very little ISI. Also, on average, over 95% of pulses dissipate their energy after about 120 ns and over 99% of pulses after about 160 ns. Since PRI's impact on the overall measurement time in negligible for our method, we set PRI to 200 ns for our methods to avoid ISI.
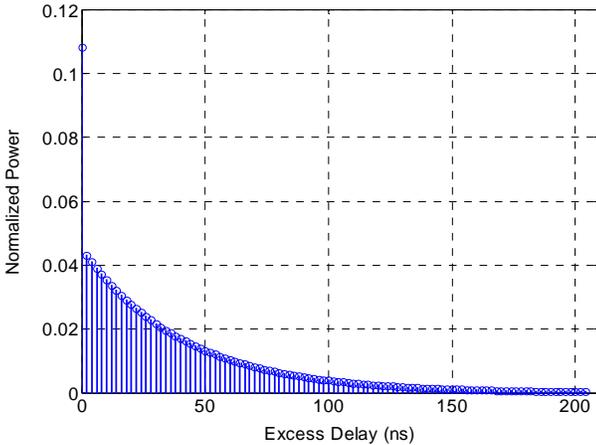
Figure 2: Average Power Delay Profile of the Cassioli Channel

C. Noise

As noted earlier, we do not consider interference from other systems. So the remaining major source which impacts the ranging accuracy is AWGN. AWGN has statistically zero mean, and its variance is the noise power. So time average of a sufficient number of received signals over multiple PRIs eliminates AWGN, which is the key idea of the proposed method.

D. Cramer-Rao Lower Bound

The Cramer-Rao lower bound (CRLB) indicates the low bound on the unbiased delay estimate as shown in (1) [9].

$$\sigma_{\hat{\tau}}^2 \geq \frac{1}{8\pi^2\beta_f^2 SNR} \tag{1}$$

where $\sigma_{\hat{\tau}}^2$ is the variance (equivalently error) of the TOA estimates, β_f is the bandwidth of the received signal, and the SNR is in E_b/N_0. The CRLB for the ranging distance can be obtained as the product $c \cdot \sigma_{\hat{\tau}}$, where c is the speed of light ($=3\times10^8$ m/sec). The equation indicates that the impact of the SNR to CRLB is linear, while the impact of the bandwidth is quadratic. In this respect, UWB is a good candidate for accurate ranging.

Figure 3 shows CRLBs on the ranging error in terms of SNR for the four different bandwidths, 0.5 GHz, 0.75 GHz, 1 GHz, and 3.3 GHz. The figure indicates that theoretical low bounds are less than 5 cm for the entire range of the SNR experimented under the bandwidth of 3.3 GHz.
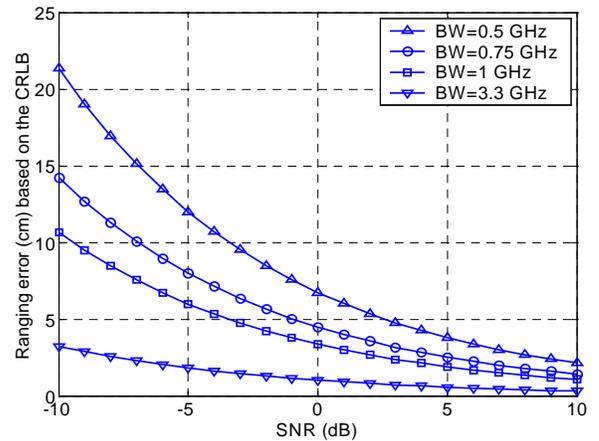
Figure 3: Low Bound of Ranging Errors

III. PROPOSED RANGING METHOD

A TOA estimation for a received signal may be performed by detecting the peak of (i) the original received signal or (ii) the signal correlated with a template. Either case, the estimation based on a single pulse is subject to AWGN. Our proposed approach is to estimate the TOA based on a train of pulses instead of a single pulse. The time average of the received pulses reduces AWGN to enhance the accuracy. Like a single

pulse case, the TOA can be estimated by detecting the peak of the signal correlated with the average value and a template (which is a Gaussian doublet for our system). The use of multiple pulses increase the processing time, but the overall processing time is a fraction of second. So use of a large number of pulses does not pose any problem in practice. The process is explained more formally in the following.

The transmitted pulse train can be expressed as follows:

$$p_{TX}(t) = \sum_{j=0}^{N-1} p(t - j \cdot T_f) \tag{4}$$

In (4), $p(t)$ is a Gaussian monopulse, T_f is PRI, and N is the number of pulses in a train. The received pulse train propagated through the multipath channel is shown in (5).

$$p_{RX}(t) = h(t) * p_{TX}(t) + n(t) \tag{5}$$

where the $h(t)$ is the channel impulse response and $n(t)$ is the zero-mean AWGN process. Since the E[$n(t)$] is zero, if we take the time-average of both sides of (5), the noise term is eliminated as shown in (6).

$$p_{RX\_AVG}(t) = \sum_{j=0}^{N-1} \left[p(t) * h_j(t + j \cdot T_f) \right] \tag{6}$$

(6) indicates that the averaging operation accumulates received signals over the symbol duration (i.e., PRI), while the noise is eliminated. Finally, a correlation between the averaged signal and template is performed as shown in (7).

$$p_{AVG\_CR}(t) = \int_0^{T_f} p_{RX\_AVG}(\tau) \cdot p(t - \tau) d\tau \tag{7}$$

It should be noted that the correlation on the averaged signal (which is considered in our paper) and the average of correlated individual signals are the same process since the correlation is a linear process. That is, the order of processing does not important for this impact on the ranging accuracy. The waveforms involved in the process are shown in Figure 4.

IV. UWB RANGING SYSTEM MODEL

A UWB ranging system can be modeled in three parts: a transmitter, a channel, and a receiver. Figure 5 shows a block diagram of our system model. The transmitter transmits a bit stream into a train of output pulses. To simulate the output of the transmitter, we considered Gaussian monopulses with the center frequency of 1.7 GHz and the bandwidth of 3.3 GHz. Spectral energy outside the 3.1 GHz to 10.6 GHz range is attenuated with a bandpass filter and recovered with an equalizer at the receiver. The two antennas were modeled as a differentiation operation, which results in Gaussian doublets for the Gaussian monopulses transmitted.

The channel model considers the effects of multipath fading and AWGN. We use the Cassioli et al.'s indoor UWB channel model based on the transversal filter model [11]. The model

considers both large-scale and small-scale effects. Since UWB channel models vary depending on the antenna type, we note that this channel model uses omni-directional antennas.
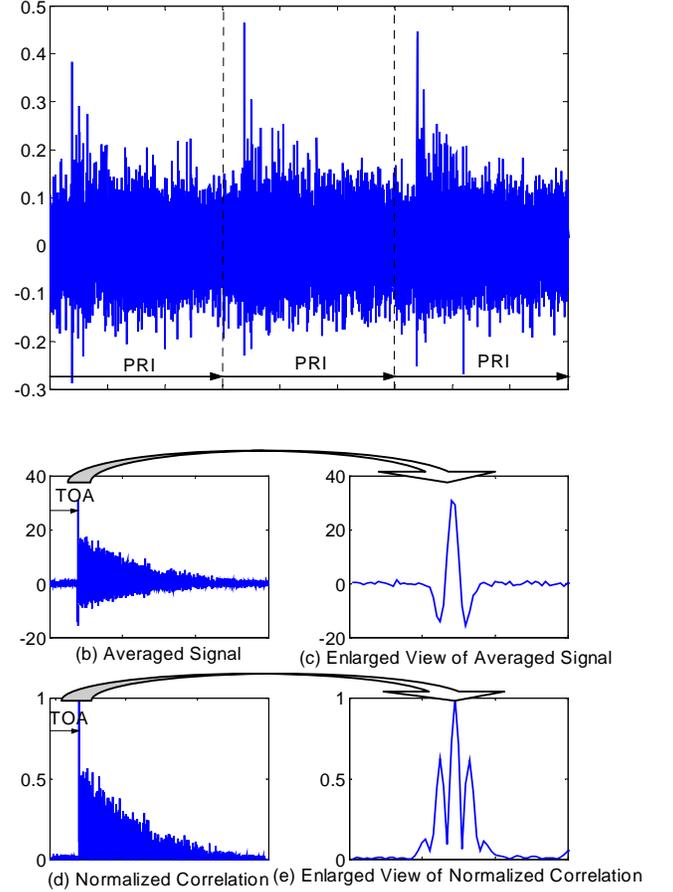
Figure 4: Waveforms of Averaged and Correlated Signals
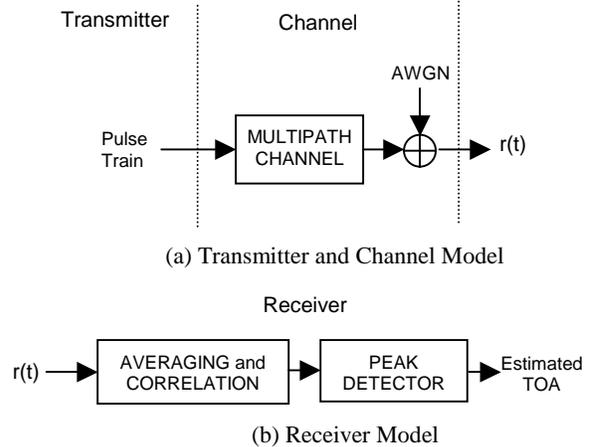
Figure 5: Block Diagram of the Proposed UWB Ranging System

The average power delay spread shown in Figure 2 illustrates the dispersion of the symbol energy over the delay time. The maximum delay of a multipath is set to within 300 ns in our channel model, while PRI itself is set to 200 ns. Since the channel model varies due to small-scale effects, we generated a new channel profile on every ten pulses. Lastly, the receiver

performs the average operation over 1000 pulses, which simulates 0.2 *ms* of the received signal.

V. SIMULATION RESULTS

The *default* simulation parameters are given as follows.

- T-R distance = 10 m
- SNR = -10 dB
- PRI = 200 ns
- Number of pulses in a train = 1000
- Number of experiments = 10 for each case

We considered a train of 1000 pulses for averaging in each experiment and repeated the same experiment for ten times. For the purpose of comparison, we also obtained the individual TOAs of the 1000 received pulses based on a threshold scheme. The threshold value for the scheme is set to 0.70 of the normalized value, and the TOA of a pulse is the shortest time to crossover the threshold value.

Figure 6 shows simulation results for the proposed method. The label "MEAN_TOA" denotes the mean value of the individual TOAs obtained from the 1000 received pulses, and "PROP" denotes the proposed method. Figure 6 (a) shows the ranging error as the SNR changes from -15 dB to 0 dB. As the SNR increases, both the mean TOA and proposed method approach to the low bound of Cramer and Rao, CRLB, but the error of the proposed method reduces much faster and is near zero above –5 dB.

Figure 6 (b) shows the impact of the number of pulses in a pulse train. As the number of pulses increases from 500 to 1500, the ranging accuracy of the MEAN_TOA stays the same, but the error increases for the proposed method. Note that the error is close to zero for 1500 pulses for our method. So it suggests that the ranging error for our method approaches to zero by processing a larger number of pulses. However, it is important to note that our method can eliminate the ranging error due to multipaths and AWGN, but there are still other factors such as imperfect synchronization and non existence of LOS can cause ranging error.

Figure 6 (c) shows the impact of PRI on the ranging accuracy. As expected, the ranging error increases sharply for both methods if the PRI becomes shorter than a certain value due to the increase of the inter-symbol interference. Note that when the PRI is greater than 200 ns, it has little impact on the performance.

Table I shows the mean and the standard deviation of the ranging errors for various SNR values, while all the other parameters are set to default values. The table indicates both the mean and the standard deviation of the ranging error for our method approaches to zero rapidly as the SNR increases and remains at zero for SNR ≥ - 5 dB. In contrast, the ranging error for MEAN_TOA decreases rather slowly and fails to reach zero even at SNR = 0 dB. (Further simulation shows that the ranging error closely approaches to the CRLB at the SNR = 15 dB.) This shows that MEAN_TOA cannot benefit from the increased number of pulses received. Since the TOA for each pulse is

determined for every symbol and thus the mean of the TOAs (the output of MEAN_TOA) is almost the same that of single pulse reception, there is no advantage for MEAN_TOA except for reducing the variances of experiments even though the number of pulses increases.
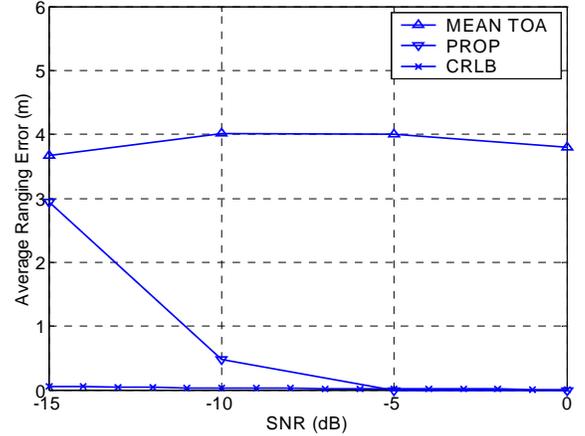
(a) Ranging Error (m) vs. SNR in dB
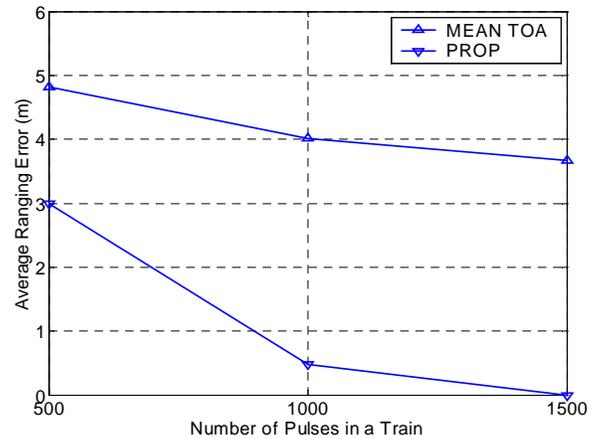
(b) Ranging Error (m) vs. the Number of Pulses in a Train
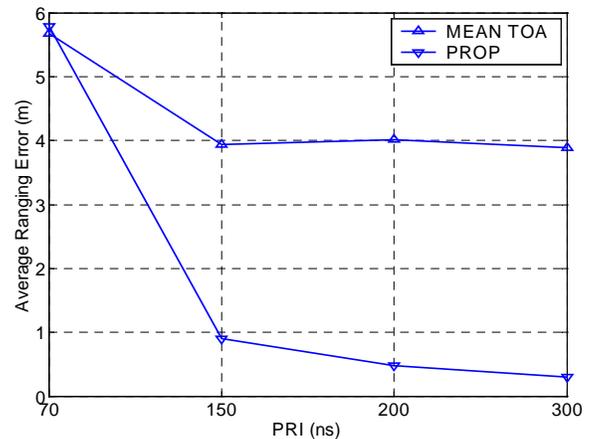
(c) Ranging Error (m) vs. PRI (ns)

Figure 6: Ranging Errors

TABLE I. STATISTICS OF RANGING ERROR FOR VARIOUS SNR VALUES

SNR	-15 dB		-10 dB		-5 dB		0 dB	
Statistics	Mean	Std_dev	Mean	Std_dev	Mean	Std_dev	Mean	Std_dev
MEAN_TOA	3.67	0.30	4.01	0.25	4.00	0.13	3.80	0.16
PROP	2.94	2.95	0.48	1.51	0.00	0.00	0.00	0.00

VI. CONCLUSION

In this paper, we investigated a ranging method using impulse-based carrierless UWB pulses under a multipath environment. Our method is based on estimation of the TOA for the first multipath, and the major assumptions involved in our method are:

(i) There exists the LOS path. So that the strongest path is the first multipath.

(ii) A perfect synchronization between the transmitter and the receiver,

Under the two assumptions, we aim to reduce the ranging error due to AWGN and ISI. We take the time average of a train of received pulses over multiple PRIs, and the averaging process eliminates AWGN due to its statistical zero-mean property. We adopted Cassioli's channel model for our system. We observed over 95% of pulses dissipate entire of their energy after about 120 ns. So we virtually eliminate ISI by setting the PRI to 200 ns for our methods.

We draw three conclusions for our method based on our simulation results. First, the ranging error for our method rapidly approaches the theoretical low bound proposed by Cramer and Rao as the SNR increases, and the error is virtually zero for SNR ≥ -5 dB. As the number of pluses used for the averaging process increases, the ranging error reduces. This implies that the averaging process reduces the impact of AWGN effectively. Third, if the PRI reduces beyond a threshold value, the ranging error increases rapidly due to increase of ISI. Finally, it is important to note that our method eliminate the ranging error due to AWGN and multipaths, but there are still other factors such as imperfect synchronization and non existence of LOS can cause ranging error.

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