Ranging Algorithms for Ultrawideband Communication Systems

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Abstract: In this paper we present ranging algorithms for Ultrawideband (UWB) communications systems and evaluate their performance in indoor propagation environment. Using the UWB transmission technique for ranging is motivated by position accuracy that varies with the inverse of the bandwidth; the larger the bandwidth, the finer the time resolution and therefore the greater the obtained accuracy. We start by explaining the transmitter and receiver architectures based on Impulse Radio (IR) UWB, that are envisaged for the ranging technique. Then, we present the lower performance bound that can be reached by the ranging procedure in terms of Cramer-Rao Bound (CRB). Simulations results based on the IEEE 802.15.4a Personal Area Network (WPAN) standard are presented to illustrate the performance of the proposed ranging algorithms.

Key words: Ultrawideband, Ranging Algorithms, Cramer-Rao Bound.

INTRODUCTION

Location aware applications are becoming increasingly important. Such applications rely on accurate and reliable localisation and tracking. In principle, the accuracy varies with the inverse of the bandwidth; the larger the bandwidth, the finer the time resolution and therefore the greater the accuracy that can be reached. In this paper¹ we present ranging algorithms that can be suited for IR UWB communication systems and illustrate their performance.

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Outdoor navigation systems offer potential for accuracy on the order of a few meters. The case of indoor localisation is complicated by multipath delay variations, which increase time uncertainty and dilute location accuracy and reliability. In such environments, existing outdoor positioning systems does not perform well. Today, narrowband wireless systems, such as Bluetooth, are capable of achieving indoor location accuracies on the order of a few meters indoors. This is sufficient for locating a person in a room, but is certainly not sufficient for future applications, such as virtual reality games and assisted surgery, where precise localisation may be required to centimetres, or even millimetres. Moreover, it is not only the accuracy that is important, but also the percentage of the time that it can be reliably achieved. Although it
may be possible to locate a person or object to within 1 meter using narrowband Received Signal Strength Indicator (RSSI) based solution with current technology, the reliability is low. Ultrawideband (UWB) offers the potential for substantial improvement over narrowband solutions. For example, an UWB system with 1 GHz bandwidth offers a thousandfold potential improvement over a narrowband system with 1 MHz of bandwidth. Furthermore, techniques other than RSSI may be exploited in UWB receivers; perhaps especially, Impulse Radio UWB (IR-UWB) [1].

We focus in this paper on the ranging procedures for IR-UWB communication systems in terms of suitable algorithms and performance bounds.

1. UWB Transmitter

A fully UWB digital transmitter design was introduced in [2]. We will just review its main characteristics (for more details on the transmitter design and its circuit implementation see [2]). The fully digital transmitter generates digital wavelets with programmable centre frequency and bandwidth. The digital wavelet generator uses a counter whose clock frequency is locked by a PLL to a quartz oscillator. By changing the PLL division number, the UWB centre frequency can be adjusted. Gating of the clock signal yields the digital UWB wavelet, whose duration can be changed by reprogramming the counter. The raw pulse transmission rate equals 10 MHz and modulation is simple OOK. In the Low Data Rate (LDR) mode (100 kbit/s) each data bit is mapped upon 100 pulses, allowing for a receiver without pulse synchronisation. In the Medium Data Rate (MDR) mode (5 Mbit/s), synchronisation wavelets are interleaved with the data to ease synchronisation in the receiver. The wavelet \( W(t) \) used in our approach is a sine wave burst wavelet with half-cosine envelope mathematically described by

\[
W(t) = V_p \sin(2\pi f_c t) \cos\left(\frac{\pi t}{\tau}\right)
\]

\(-\tau/2 < t < \tau/2 \) and 0 elsewhere

This results in a spectrum \( W(f) \) given by

\[
W(f) = W_c [\text{sinc}(\tau - f_c + 0.5) + \text{sinc}(\tau - f_c - 0.5)]
\]

Figure 1 (left hand side) shows a 4-cycle sine wave burst wavelet with a duration \( \tau = 4/f_c \).

Figure 1 (right hand side) shows the spectrum with its maximum at frequency \( f_c \) and first zeroes at \( f_c \pm 1.5/\tau \). For a carrier frequency \( f_c = 4.224 \) GHz (132 x 32 MHz) and duration \( \tau = 947\) ps, this yields a UWB signal centred at 4.22 GHz.

2. UWB Receiver

It is the task of the UWB receiver to detect the UWB signals that may be below the thermal noise. Figure 2 shows the received signal for a line-of-sight (LOS) link with transmission power of -11 dBm (1 GHz bandwidth at -41 dBm/MHz) as well as the receiver noise floor for 1 GHz bandwidth and a receiver noise figure of 5 dB. This yields a noise floor at -174 + 90 + 5 = -79 dBm. Clearly, processing gain is required to make the system work for negative SNR values.

The main challenges for UWB receiver designers are

- High sensitivity,
- Low power consumption,
- Synchronisation,
- Interference mitigation.

Figure 3 shows a simple receiver architecture for impulse radio applications. It comprises a square law detector followed by a low-pass filter and a decision circuit. The modulation used in this simple system is on/off keying. Synchronisation is at symbol level. A drawback of the energy detection receiver is that it does not distinguish between the wanted UWB signal and any other signal present at the same time as the UWB pulse. Using this receiver architecture for ranging purposes, would introduce a serial block for ranging purposes that has as input the received signal (RXD).
Figure 3: Energy detection receiver with pulse synchronisation.

Figure 4 shows a more sophisticated correlation receiver architecture. The received UWB wavelet is multiplied by a signal from a template generator. After low-pass filtering a decision is taken whether the received wavelet represents a logical 0 or a logical 1. The synchronisation loop acts on the template generator.

This system uses differential BPAM modulation, and differential encoding removes the polarity ambiguity. For example, rotating the antenna 180 degrees, will probably invert the raw received data (RXD).

An issue with the correlation receiver is matching of the wavelet template with the received pulse. Since the antennas and channel are frequency selective (thereby causing dispersion and ringing) the transmitted pulse becomes severely distorted, and hence it is unlikely that the received pulse corresponds to the template pulse. Moreover, the channel transfer function strongly depends on the antennas and the environment, which is a dynamic phenomenon in general.

This receiver architecture can also hold ranging functionality by introducing a serial ranging processing block that will operate on the received signal (RXD).

Figure 4: Correlation receiver with pulse synchronisation.

The transmitted reference scheme proposed by Hctor and Tomlinson [3] does not suffer from the above problems. The core part of the transmitted reference scheme receiver, also known as “autocorrelation receiver”, is shown in Figure 5 [4].

In this approach, two pulses per symbols are sent separated by delay time \( \tau_d \). The first pulse acts as the reference and the second pulse is modulated by the data. The receiver delays the first pulse by the delay time \( \tau_d \) multiplies it with the second pulse and integrates the result.

The data is contained in the relative polarity of the two pulses and the delay between them acts as a synchronisation mechanism. The autocorrelation receiver can detect the two consecutive pulses properly as long as they have corresponding waveforms (except for their polarity). This receiver architecture can also be used for ranging purposes by introducing a serial ranging processing block that will operate on the received signal (RXD).

The main challenge in UWB impulse radio receivers is pulse synchronisation. Synchronisation allows to filter in the time domain and to sample the incoming signal only during a short sampling window, thus eliminating all the interference outside that time window. The price to be paid for this robustness is complexity and also power consumption. From a receiver complexity point of view, one would like to get rid of the pulse synchronisation.

3. Ranging for UWB Systems

We focus here on ranging in the case of Line Of Sight (LOS) propagation environment in UWB communication systems. This would necessitates the estimation of the first delay introduced by the multipath propagation channel effect, using the received signal.

Since the ranging procedure is equivalent to the estimation of the first delay, all the delay estimation techniques should apply. Such techniques include simple techniques like correlation based ones to optimal estimation methods like the Maximum Likelihood (ML) algorithms.

4. Cramer-Rao Lower Bound

Cramer-Rao Lower Bound (CRLB) allows establishing achievable performance using an ideal unbiased estimator. This performance is not attainable using a real estimator, but the bound allows understanding the trend of the estimator. The Cramer-Rao lower bound provides the minimal achievable error variance for an unbiased estimator \( \sigma^2 \).

In order to individuate the characteristics of an UWB signal that minimize CRLB, let us consider a received signal \( r(t) = s(t; q, \Delta) + w(t) \) obtained as the sum of a signal \( s(t; q, \Delta) \), function of the time \( t \) and of a
set of unknown parameters \( \{a_k\} \), and of thermal noise \( w(t) \). The overall frequency occupation of
the signal being \( B \), the power of thermal noise can be defined as follows:
\[
\sigma_n^2 = FkTB/2
\]

The signal at the receiver is sampled at a frequency \( Bt/T_s = B \). The sequence of useful samples is
\( s_n = s(nT_s; \{a_k\}) \), while noise and received signal samples are \( w_n = w(nT_s) \) and
\( r_n = s_n + w_n \), respectively.

The Cramer-Rao theorem indicates that, for any
unbiased estimator, the minimal achievable variance \( \sigma_i^2 \) is \( \sigma_i^2 \geq F_n^{-1} \), where \( F_n \) is the
Fisher information matrix, defined as follows:
\[
F_n = -E\left( \frac{\partial}{\partial \theta} \left( \ell(X; \theta) \right) \right) - E\left( \frac{\partial^2}{\partial \theta^2} \ell(X; \theta) \right)
\]

where \( \ell(X; \theta) \) is the log likelihood function with respect to parameter \( \theta \). The log likelihood
function is the logarithm of the probability of the estimation error, conditioned to the knowledge of
\( \tau \) and \( \{a_k\} \), which is defined as follows:
\[
p(r | \tau; \{a_k\}) = \frac{1}{(2\pi)^{\frac{N}{2}}} \exp \left\{ -\frac{1}{\sigma_n^2} \sum [r - s(nT_s - \tau; \{a_k\})]^2 \right\}
\]

To evaluate CRLB ([7], [8]) we need the first and
second derivatives of log likelihood function, that is:
\[
\frac{\partial}{\partial \tau} \ln[p(r | \tau, \{a_k\})] = -\frac{2}{\sigma_n^2} \sum [r - s(nT_s - \tau, \{a_k\})] \tilde{s}(nT_s - \tau, \{a_k\}) - \frac{\partial^2}{\partial \tau^2} \ln[p(r | \tau, \{a_k\})] = \frac{2}{\sigma_n^2} \sum [r - s(nT_s - \tau, \{a_k\})] \tilde{s}(nT_s - \tau, \{a_k\}) - [r - s(nT_s - \tau, \{a_k\})] \tilde{s}(nT_s - \tau, \{a_k\})
\]

The next step is the evaluation of the average value
of the second derivative of the log likelihood function, which corresponds to the Fisher
information matrix:
\[
F_n = \frac{4}{N_0} \int \tilde{s}^2(t; \{a_k\}) dt
\]

The minimal achievable variance for any unbiased estimator (CRLB) is thus:
\[
\sigma_i^2 = \frac{1}{F_n} = \frac{N_0}{4} \int \tilde{s}^2(t; \{a_k\}) dt = \frac{1}{2} \left( \frac{2E}{N_0} \right) \beta^2
\]

where
\[
\beta^2 = \int \frac{s^2(t; \{a_k\}) dt}{\int s^2(t; \{a_k\}) dt} = -4\pi^2 \int \frac{f^2 S^2(f; \{a_k\}) df}{\int S^2(f; \{a_k\}) df}
\]

and hence the maximum theoretical ranging accuracy achievable with the proposed UWB signal formats can be obtained by considering the corresponding signal \( s(t) \).

Variance of time estimation error \( \sigma_t^2 \) is in fact related to the distance estimation error as follows:
\[
\sigma_t^2 = c^2 \cdot \sigma_x^2
\]

where \( c \) is the propagation speed of the signal.

Figure 6 shows the CRB on the ranging error in terms of SNR for four different bandwidths, 0.5GHz, 0.75GHz, 1GHz and 3.3GHz. The figure indicates that theoretical low bounds are less than 5 cm for the entire range of the SNR experimented under the bandwidth of 3.3GHz. From the above figure, UWB is a good candidate for accurate ranging. Larger BW or/and higher Signal to Noise Ratio (SNR) will reduce the uncertainty.

5. Simulation Results

For the simulations presented here, we used the
IEEE802.15.4a WPAN standard channel model [6]. Results are averaged over 100 realizations and curves illustrating standard deviation and ranging error at different SNRs, are shown. We use the UWB transmitter illustrated in Section 1. The UWB receiver of Section 2, should be augmented with ranging algorithms used in the ranging processing block, that we explain in the following sections.

5.1. IEEE802.15.4a Channel

Figure 7 illustrates the channel model of the IEEE
803.15.4a standard [6].
Figure 7: IEEE802.15.4a Standard channel response

Figure 8 and Figure 9 illustrate the noiseless and noisy received signal, respectively at the UWB receiver. This former should use the noisy received signal in order to perform ranging through the estimation of the first delay.

5.2. Leading Edge Detection Algorithm

Using the received signal, we do first correlation and then normalize it (see Figure 10). The threshold is set to 0.7. The first signal crossover the threshold gives time of arrival, which measuring the distance between transmitter (TX) and receiver (RX) as long as they are synchronized (see Figure 11).

We can also set the threshold adaptively. The threshold is based on the noise floor:

\[ T = K_T \cdot \sigma_n \cdot \sqrt{E_w} \]  

- \( K_T \) is a constant. 
- \( \sigma_n \) is the standard deviation of the noise 
- \( E_w \) is the energy of the transmit signal

In [9], the parameter \( K_T \) is set equal to 3.5. To find the optimal value of \( K_T \), we set the range of \( K_T \) between 3.0 and 3.9. From the simulation results, we find the system have better performance when \( K_T \) equals to 3.4.

But this threshold does not lead to good results in low SNR environments (5dB to 10dB).

5.3. Peak Detection Algorithm

This algorithm is used to find the peak of correlation between the received signal and transmitted one (see Figure 12). The corresponding time is the time of arrival. The first arrival path is not always the strongest one. This algorithm does not need threshold. It is very simple but it does not give good results in low SNR environments.
The simulation results for this algorithm are illustrated in Figure 13 and Figure 14.

From the above results, we can conclude the following:
- When the SNR is greater than 20dB, the standard deviation of range error is less than 1 meters. We can also find when SNR is equal to 30dB, the standard deviation of Range Error is about 0.01 meter.
- When the SNR is less than 20dB, the standard deviation of Range Error is much greater than 1 meter.

We can conclude that noise factor generates more errors than the multipath factor. If we want to decrease the standard error of range error between 5 dB and 20dB, we need to decrease the noise of received signal.

6. Conclusions

In this paper we presented ranging algorithms that can be suited for IR UWB communication systems and illustrate their performance bounds in terms of CRBs. As a general conclusion, the considered algorithms (Leading Edge Detection Algorithm and Peak Detection Algorithm) lead to satisfactory results when the envisaged indoor positioning application requires medium accuracy.

For ranging applications where the positioning accuracy should be optimized, enhanced delay estimation leading to optimal delay estimates, should be used. Indeed, accuracy in ranging can be significantly enhanced when using sophisticated estimation techniques based on ML formulation. Algorithms using properly this formulation and the obtained related results are given in [10].

REFERENCES


