Performance analysis of an indoor UWB ranging system∗

Zhang Tingting1, Zhang Qinyu2, Zhang Naitong1 & Xu Hongguang2
1. School of Electrical and Information, Harbin Inst. of Technology, Harbin 150001, P. R. China;
2. Harbin Inst. of Technology Shenzhen Graduate School, Shenzhen 518055, P. R. China
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Abstract: To evaluate the ranging performance of impulse radio ultra wideband (IR-UWB) signals, an experiment is performed in a typical indoor environment. In order to mitigate the ranging error caused by theoretical algorithm and practical circuits, one way-time difference of the arrival (OW-TDOA) ranging method and corresponding approaches are proposed and carried out according to the structure of UWB transceivers. Generalized maximum likelihood (GML) estimator based on energy detection is applied for the time of arrival estimation. The obtained results show that this UWB ranging system can achieve a relative high ranging accuracy in a multipath environment (e.g. about 5 cm at ranges up to 6 m), which is practical and meaningful for many sensor applications.

Keywords: ranging, impulse radio ultra wideband, time of arrival, energy detection, multipath.

1. Introduction

Impulse radio ultra wideband (IR-UWB) systems utilize very short pulses with the duration of less than 1 ns. The short duration of the UWB waveform enables the system to provide high data rate communication as well as accurate positioning. While the accuracy of conventional indoor positioning techniques such as the one with wireless LAN terminals is several meters, the accuracy of the UWB positioning is on the order of centimeters.

To exploit the fine time resolution most, ranging techniques based on the time of arrival (TOA) estimation of the received signals are most reasonable. TOA estimation algorithms have been extensively studied of late years[1−3], including those considering high sampling rate, matched filtering (MF) based coherent algorithms, and those considering lower sampling rate, energy detection based non-coherent algorithms. Many applications pose constraints on device complexity and power consumption, which makes energy detection a preferred option[4−6].

According to Refs. [7–8], ranging accuracy could be limited theoretically by the presence of noise, multipath components (MPCs), the effect of system bandwidth, and the presence of non-line-of-sight (NLOS) conditions. Besides these factors, the implementation of system circuits should be taken into account, while most researches are based on simulations, which restricts the applications of these algorithms.

In this paper, a digital UWB ranging system is developed, by which the ranging results are collected and analyzed. According to the structure and complexity of the system, a generalized maximum likelihood (GML) estimation based on energy detection is proposed and realized. One way-time difference of arrival (OW-TDOA) ranging is utilized because the transceivers are simplex. A simple method is proposed for the NLOS error mitigation. From the measured results, it can be seen that this digital UWB ranging system can achieve a relative high accuracy, which is practical in most sensor applications, and can be the basis of localization implementation.

2. Channel and signal model

UWB multipath channel is well modeled by a double-exponential channel impulse response (CIR) in order to take into account the clustering of multipath components (MPCs)[9]. The clustering CIR based on the

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A conventional S-V channel model\(^{[10]}\) can be expressed as follows

\[
h(t) = \sum_{k=1}^{K} \sum_{l=1}^{L_k} \alpha_{k,l} \delta(t - T_k - \tau_{k,l})
\]

where \(\delta(\cdot)\) is the Dirac delta function, \(K\) is the total number of clusters, \(L_k\) is the total number of MPCs within the \(k\)th cluster, and \(\tau_{k,l}\) is the delay of the \(l\)th MPC relative to the \(k\)th cluster arrival time \(T_k\).

For ranging and geolocation purposes, it has been shown that the direct path (DP) within the first cluster \(\tau_{1,1}\), and not the later arrivals, is significant to the accuracy of ranging systems. Therefore, without loss of generality, the clustering UWB multipath channel can be simplified as a sum of CIRs given as follows

\[
h(t) = \sum_{l=1}^{L} \alpha_l \delta(t - \tau_l)
\]

where \(L\) is the total number of MPCs, while \(\alpha_l\) and \(\tau_l\) are the multipath gain coefficient and the TOA of the \(l\)th MPC respectively.

Based on Eq. (2), the received signal \(r(t)\) after the multipath channel is given by

\[
r(t) = \sum_{l=1}^{L} \alpha_l p(t - \tau_l) + n(t)
\]

where \(p(t)\) is the transmit signal pulse with duration \(T_p\), while \(\{\alpha_l\}_{l=1}^{L}\) and \(\{\tau_l\}_{l=1}^{L}\) are the received amplitudes and the TOAs of \(p(t)\), respectively. And \(n(t)\) is the additive white Gaussian noise (AWGN) with zero mean and two-sided power spectral density \(N_0/2\).

The received signal concerning the MPCs for TOA estimation starts within a window of duration \(T_u\) that represents the uncertainty on the arrival time of the received signal, i.e. \(\tau_l \in (0, T_u)\).

A discrete signal model can be obtained by sampled at the Nyquist rate\(^{[10–11]}\),

\[
r(t) = \sum_{i=-\infty}^{\infty} r_i \sin c \left( t - \frac{i}{2W} \right)
\]

where \(r_i = \frac{1}{\sqrt{2W}} p \left( \frac{i}{2W} \right)\). Based on this discrete representation, the starting position of the MPCs can take a finite number of values so that \(\delta_i \in \{1, \ldots, 2WT_u\}\) represents the discrete index value associated with \(\tau_l\) after ADC.

3. GML TOA estimator for digital UWB transceivers

3.1 Digital UWB system

In the experiments described in Refs. [1,13], the receiver applied is a digital oscilloscope, connected with the receiving antenna, by which the waveforms are collected, and the algorithm performance is evaluated. During our measurements, both transmitter and receiver boards are fulfilled by digital circuits, which makes it flexible and practical to multiple applications. The transmitter structure and photograph (Fig. 1) are shown in Fig. 1. The transmitted pulse is generated by the carry signal of a high speed emitter coupled logical (ECL) counter, which is configured and preset by field programmable gate array (FPGA). The pulse repetition period \((T_f)\) can be modified easily by setting different parameters.

The receiver board is shown in Fig. 2, including a
low noise amplifier (LNA), a high speed analog digital converter (ADC) and FPGA. After passing through LNA, the receiving signal is sampled by 2 G/s, and 8-bit quantified. Then the rest baseband processing including the integration of signal energy, transceiver synchronization and TOA estimation, are all carried out in FPGA. The estimation results will be demonstrated in a monitor connected to the receiver board.

![Fig. 2 UWB receiver structure and photograph](image)

### 3.2 GML estimation

In most sensor applications, considering the low complexity and computational ability of sensor nodes, the TOA estimation based on energy detection is preferred.

By maximum likelihood estimation\(^{[14-15]}\), the likelihood function is

\[
p(r|\delta, h) = \frac{1}{\sqrt{2\pi}\sigma} \exp \left[\sum_{i=1}^{2T_iW} (r_{i\delta} - h)^2\right]
\]

where \(h\) is the discrete channel response, remains unknown. \(T_i\) is the integration interval, during which the signal energy is collected for TOA estimation.

The log-likelihood function of Eq. (5) is

\[
\Gamma(r|\delta, h) = \sum_{i=1}^{2T_iW} (-2r_{i\delta}h_i + h_i^2)
\]

The estimate \(\hat{h}_i\) in the ML sense is obtained by forcing to zero the derivative of the likelihood function.

\[
\frac{d}{dh}\Gamma = 0, i.e. \hat{h}_i = r_{i\delta}.
\]

This means that the generalized maximum likelihood function of the observed value is an energy detector (shown in Fig. 3), and the discrete time of arrival is

\[
\delta_l = \arg \max_{\delta_l \in \{1, 2, ..., 2T_uW\}} \{\Gamma(r|\delta_l, h)\} = \arg \max_{\delta_l \in \{1, 2, ..., 2T_uW\}} \sum_{i=1}^{2T_iW} r_{i\delta_l}^2
\]

![Fig. 3 GML estimator structure and realization](image)

According to the digital receiver, the GML energy detector is fulfilled as a process of sliding window (SW), and the sliding step is the sampling interval (0.5 ns).

### 4. Measurements and data analysis

#### 4.1 Experiment environment

Field measurements have been conducted in a typical indoor environment, shown in Fig. 4 which is a part of our laboratory, which is divided into 3 parts by obstacles. Then both of LOS/NLOS ranging measurements can be carried out. The TX and RX are placed as described in Fig. 4. The TX-RX separation ranges from 0–10 m for convenience and power constraints. Both antennas have the same height. There is weak narrow band interference such as GSM signals existed in the lab, but it doesn’t affect the signal detection severely.
4.2 One way-time difference of arrival ranging method

Because the UWB system is simplex, the measure method applied is one way ranging, as depicted in Fig. 5. A wire is connected between the transceivers for synchronization. When a transmitting pulse is generated, a falling edge signal is sent to the receiver board in the wire as the trigger simultaneously.

As shown in Fig. 5, when a pulse is sent from the transmitting antenna, a falling edge signal is generated on the wire simultaneously, for receiver acquisition. If the length of wire between transceivers is \( l \), the distance to be measured is \( d_R \), then \( \delta_{DP} = (d_R - l)/c \), and

\[
\begin{align*}
\delta_{DP} &= (d_R - l)/c, \\
\end{align*}
\]

During the one way ranging process, there are two main error sources that degrade the performance. One is the theoretical error \( \epsilon_{DP} \) introduced by the GML estimation, which is proposed in the LOS situation originally. Though it is proved in Ref. [14] that GML also works well in non-severe NLOS situations, the performance decreases correspondingly if the signal energy of some other components are close to the DP’s. The other error \( \epsilon_L \) is caused by the receiver board. Since the clock frequency is limited, the falling edge in the wire can only be acquired in the next clock period.

In order to solve these problems, a TDOA ranging method is applied. As in the experiment, a reference point of the known distance is required. When the TOA difference between the reference point and unknown RX point to be tested is obtained, the ranging results can be achieved easily. Considering the random feature of circuit errors, a simple way to promote the ranging accuracy is to take multiple detecting pulses to average the transmission delay and sampling jitter. The more pulses are applied, the smaller the uncertainty of ranging results achieves.

4.3 Data analysis

During the experiment, the generated pulse width \( T_p \) is 1.3 ns, the pulse repetition period applied is 160 ns, by which the inter frame interference (IFI) can not be observed in the oscilloscope in Fig. 6. Integration interval \( T_i \) applied is 8 ns according to the channel power delay profile (PDP). 10 and 60 pulses are applied to average the ranging uncertainty respectively. And the measured range between TX and RX differs from 0.6 m to 5.4 m. The measurements are taken at LOS/NLOS channel situations, and the data analysis is carried out respectively.
LOS between TX and REF1. The waveform obtained is shown in Fig. 7.

![Fig. 7 Received waveform in LOS situation](image)

It can be seen from results in Fig. 8 that the ranging accuracy is independent with the ranging distance. When the realization times increase from 10 to 60, the ranging performance promotes obviously from 10 cm to 5 cm level. It’s suggested to obtain better ranging performance by adding the detecting pulses when the complexity and cost is limited.

![Fig. 8 LOS ranging error with respect to different realization times](image)

In NLOS situations, it is different depending on the materials of the NLOS blockage. In this paper, two different obstacles are considered. One is a 3 cm-thick wood door, and the other is a 20 cm-thick plaster wall. The transceivers are placed at TX and RX2, and REF1 is still taken as the reference point. The receiving waveforms are shown in Fig. 9. It’s easy to tell that the pulse penetrating the plaster wall distorts much more severely than the wood door.

![Fig. 9 Received waveform in NLOS situation](image)

In order to obtain better performance, 60 realizations are applied during the NLOS ranging. From the results in Fig. 10, the ranging error of the wood door case is limited within 30 cm, which is a little larger than the results under LOS conditions. The performance of plaster wall ranging deteriorates severely, and all the ranging errors are positive, which can be explained by that the TOA obtained by GML esti-
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mation is not the DP component, but the maximum component. The error is caused by the time difference between DP and the maximum component. The measured results are also consistent with the conclusions drawn by Refs. [14–15].

Instead of some complex NLOS mitigation algorithms, a simple method to solve this problem is to choose a reference point which shares the same channel model as the TX-RX radio link. As depicted in Fig. 4, REF2 is taken as the reference point, which is also behind the plaster wall, like RX2. The ranging performance increases obviously to the 10 cm level.

![Fig. 10 NLOS ranging error with respect to different materials and reference points](image)

According to Refs. [1–3,6], the pulse position is regarded as the middle of the selected energy block by approximation, while the real pulse position is uniformly distributed within $T_{\text{step}}$. Absolute error $\varepsilon$ is illustrated in Fig. 11.

![Fig. 11 Ideal MAE illustration](image)

The expectation of the mean absolute error is

$$E(\varepsilon) = c \int_0^{T_{\text{step}}/2} \varepsilon f(\varepsilon) d\varepsilon =$$

$$c \int_0^{T_{\text{step}}/2} \varepsilon \frac{1}{T_{\text{step}}^2} d\varepsilon =$$

$$c T_{\text{step}}^2 \left( \frac{T_{\text{step}}}{2} \right)^2 = c T_{\text{step}}^4$$  \hspace{1cm} (9)

When the sliding step $T_{\text{step}}$ is 0.5 ns based on the ADC sampling rate, the theoretical mean absolute error is obtained

$$E(\varepsilon) = \frac{T_{\text{step}}}{4} = 0.01875 \text{ m}$$  \hspace{1cm} (10)

Although the ranging performance doesn’t reach the expectation value according to SNR, channel interference, etc, the experiment results show that the UWB ranging system can achieve a relative high accuracy performance, which is practical and meaningful to many sensor applications.

5. Conclusion

A ranging experiment is performed in a typical indoor environment with digital UWB transceivers. At first, the structure of the system is introduced based on which the TOA estimation algorithm is proposed consequently. Then the experiment background including the environment and measure method is illustrated. In order to mitigate the ranging error caused by theoretical algorithm and practical circuits, the OW-TDOA ranging method and corresponding approaches are proposed and carried out. The obtained results show that this UWB ranging system can achieve a relative high ranging accuracy in a multipath environment, which is practical for many sensor applications, and can be the basis for localization in the wireless sensor network.

References


**Zhang Tingting** was born in 1980. He received B.S. and M.S. degrees from Harbin Institute of Technology (HIT) in 2003 and 2005 respectively. Since Sept. 2005, he was a Ph.D. candidate of HIT. His research interests are UWB communications and applications. E-mail: ztt_44@163.com

**Zhang Qinyu** was born in 1972. He is now a professor and doctoral advisor at the Harbin Institute of Technology Shenzhen Graduate School. His research interests are UWB, wireless communication network, bio-medical engineering and deep space communication, etc.

**Zhang Naitong** was born in 1934. He is an academician at the Chinese Academy of Engineering, and a professor and doctoral advisor at the HIT. His research interests are UWB, satellite communication, trunked radio system, and C4ISR network, etc.

**Xu Hongguang** was born in 1963. He is now an associate professor at the Harbin Institute of Technology Shenzhen Graduate School. His research interests are embedded system, UWB communication, high speed circuits design, etc.