A Novel Indoor Localization Scheme

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***Abstract*—Ultra-wideband (UWB) receivers can resolve individual multipath components (MPCs), due to the signal occupied a large bandwidths, so they are capable of accurately estimating the time of flight of the signal. To realize high-accuracy indoor localization, a novel UWB locating scheme through estimating the round trip time (RTT) of UWB signal is proposed. Each reference station (RS) transmits the baseband pulse modulated UWB signals. The signals are received by the user terminals (UT) and sent back to the original RS using a different carrier frequency. We can easily calculate the position of the UT by detecting the time gap between the feedback signal and the origin signal. Meanwhile, the multi-path detection algorithm for RTT estimation is presented and the localization performance of the proposed scheme is tested under IEEE 802.15.4a channel models. Experiments demonstrate that the proposed scheme can realize high accuracy localization with an error around the centimeter level.**

I. INTRODUCTION

High resolution localization is an important and novel emerging technology for commercial, public safety, and military applications[1]. Recently, there is increasing interest in accurate location finding techniques and location-based applications. The Global Positioning System (GPS)[2] and wireless enhanced 911(E-911) services[3] also address the issue of location finding. However, these technologies cannot provide accurate indoor localization, which has its own independent market and unique technical challenges.

UWB techniques, which make use of the extremely low power and narrow pulses to convey information, have attracted wide interests in wireless communications[4][5]. So it was considered as a potential candidate for high speed and short-range wireless communications[6]. UWB technology is a viable solution for high-rate short-range wireless communications, as well as for low-rate moderate range communications with ranging capabilities. In particular, it is believed that the impulse radio version of UWB (IR-UWB) can provide centimeter accuracy in ranging and can be exploited in a variety of applications aimed at localizing valuable assets in hospitals, industrial areas, airports etc. [7]. UWB localization technique have attracted more and more attentions in recent years, IEEE 802.15.4a Working Group has already regarded UWB as the first choice for high accuracy indoor localization[8].

Generally speaking, UWB positioning estimation methods can be divided into three categories: Received Signal Strength (RSS), Angle of Arrival (AOA), and Time/Time Difference of Arrival (TOA/TDOA)[9]. The RSS measurements provide information about the distance between two nodes based on certain channel characteristics. This method highly depends on path loss model, so it is quite sensitive to channel environment. AOA method provides information about the direction of an incoming signal[10]. Commonly, antenna arrays are employed in order to measure the AOA of a signal. The angle information is obtained at an antenna array by measuring the differences in arrival times of an incoming signal at different antenna elements, which results in highly complex arithmetic. TOA/TDOA method using a signal traveling from one node to another to estimate the distance between those two nodes, provides very good localization accuracy due to high time resolution of UWB[11]. So they are more commonly used in practice.

TOA and TDOA methods are can provide high accuracy localization in theory, however, there are many challenges in developing a real-time indoor UWB localization system[12]. These challenges include clock synchronization, signal acquisition, multipath interference, sampling rate limitations etc. TOA systems needs to setup a very precise timing reference between RSs with UTs[13]. In TDOA estimation, all of the base stations or receivers need to be synchronized. GPSs use ultra-high-precision atomic clocks to measure the time-of-flight[14], but it's unpractical for an indoor localization system to use high accuracy atomic clocks. So the most difficult problem is the physical layer and the medium access layer being optimized for communication but suboptimal for localization.

In this paper, we propose a novel of indoor localization scheme. In order to reduce complexity and improve the accuracy, we obtain TOA from Round Trip Time (RTT), which avoided high accuracy clock synchronization and complex beamforming. The UWB architectrue we used is a kind of carrier-based impulse radio (IR), where the transmitted UWB signal is up-converted through a microwave carrier, then is converted and retransmitted back to the RS by the UN. We obtain the TOF through detecting the time gap between the feedback signal and the origin signal. Meanwhile, the detection algorithm for UWB multipath signal for RTT estimation is discussed and the effect of multipath error and Non-Line-of-Sight (NLOS) error on localization performance is analyzed. We conduct simulations under the LOS and NLOS environment according to IEEE.802.15.4a channel model. The experiment results demonstrate the effectiveness of our proposed scheme.

The remainder of this paper is structured as follows. In section II, we describe the proposed localization scheme and UWB signal model. In section III, we discuss the UWB RTT multipath detection algorithm. Simulation results are presented in section IV.

II. Localization Scheme and Signal Model

A. localization Scheme

In order to realize high accuracy indoor positioning, we proposed a locating scheme through estimating the RTT of frequency-conversion retransmitted signal, which not only takes the advantage of UWB high time resolution effectively but also avoids clock synchronization and complicated beamforming technique.

As illustrated in Figure.1, Unknown terminal (UT) only carries out retransmission frequency-conversion UWB signal without any baseband processing. UT could distribute in any location in localization area. RS_0, RS_1, RS_2, RS_3 represent four different referenced stations (RS) respectively. According to geometric relationship in Figure.1, the location of UT can be determined if we know d_0, d_1, d_2, d_3. Let RS be fixed, The coordinates of RS_0, RS_1, RS_2 and RS_3 are (0, 0, 0), (K, 0, 0), (0, K, 0), (0, 0, K) respectively. (x_{UT}, y_{UT},z_{UT}) denotes the coordinates of UT. We can obtain the position relation as follow

$$c \cdot t_{RTT}^{0} = 2\sqrt{(x_{UT})^2 + (y_{UT})^2 + (z_{UT})^2} + c \cdot t_{\Delta} \tag{1}$$

$$c \cdot t_{RTT}^{1} = 2\sqrt{(x_{UT} - K)^2 + (y_{UT})^2 + (z_{UT})^2} + c \cdot t_{\Delta} \tag{2}$$

$$c \cdot t_{RRT}^{2} = 2\sqrt{(x_{UT})^2 + (y_{UT} - K)^2 + (z_{UT})^2} + c \cdot t_{\Delta} \tag{3}$$

$$c \cdot t_{RTT}^{3} = 2\sqrt{(x_{UT})^2 + (y_{UT})^2 + (z_{UT} - K)^2} + c \cdot t_{\Delta} \tag{4}$$

where t_{RTT}^{i} denoted the i-th RTT estimate value, t_{Δ} is time estimation error, t_{RTT}^{i} =2TOA^{i}+t_{Δ}, $c = 3 \times 10^8 m/s$. The

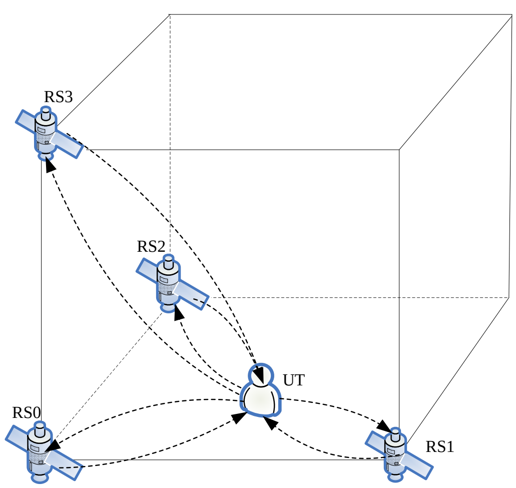

Fig. 1. UWB localization scheme

procedure of the localization algorithm can be summarized as follows.

Each RS transmits the baseband pulse modulated UWB signals using different pseudonoise (PN) sequence. We call this kind of origin signal from RS to UT the downlink signal.UT receives Analog downlink UWB Signal and convert the signal using the carrier in another center frequency, then retransmitted the converted signal to the original RS. We call this kind of feedback signal from UT to RS the uplink signal. RSs receive the uplink feedback signal, then detect the time gap between the feedback signal and the origin signal.The detection method will be discussed in detain in section III. Each RS naturally developments a self-synchronization system, for each RS uses a same crystal oscillator to generate the clock signal.Calculate the position of UT according to geometric relationship described in Equation (1)-(4).

B. Signal Model

The proposed RTT estimator is based on the transmission of a training sequence type.We call this kind of signal as DS-UWB. The downlink signal generated by Each RS is

$$\begin{aligned} s_{dl}(t) = &\sum_{m=0}^{\infty} \sum_{i=0}^{N-1} \varepsilon_{dl}(m) \cdot c(i) \\ &\cdot g(t - kT_f - jT_c - \tau_0) \cdot \cos(\omega_{dl} \cdot t) \end{aligned} \tag{5}$$

where ε_{dl} is the energy per pulse, $c(i)$ is the code chip value, $c(i) \in \{+1, -1\}$, The length of PN sequence is N, T_f is the frame time, each frame consists of integer number $N_f = T_f/T_c$ of pulse slots, T_c is the chip duration, τ_0 is the pulse time jitter, $g(t)$is the Gaussian pulse waveform, $\omega_{dl} = 2\pi f_{dl}$, f_{dl} is the frequency of downlink carrier. The uplink signal retransmitted by UT is

$$\begin{aligned} s_{ul}(t) = &\sum_{m=0}^{\infty} \sum_{i=0}^{N-1} \varepsilon_{ul}(m) \cdot c(i) \\ &\cdot g(t - kT_f - jT_c - \tau_0) \cdot \cos(\omega_{ul} \cdot t) \end{aligned} \tag{6}$$

where $\varepsilon_{ul}(m)$ is the amplitude of the m-th impulse, f_{ul} is the frequency of uplink carrier.

III. RTT Estimation

According to 802.15.4a channel model, the propagation occurs on an L-path channel whose response to $g(t)$ can be expressed as

$$g_s(t) = \sum_{l=1}^{L} \alpha_l g(t - \tau_l) \tag{7}$$

where α_l is the time-varying gains, $g(t)$ is the transmitted pulse waveform, τ_l is the time delay of the L-th path.

So the baseband signal received by reference stations can be written as

$$\begin{aligned} s_r(t) = &\sum_{m=0}^{\infty} \sum_{i=0}^{N-1} \varepsilon_r(m) \cdot c(i) \\ &\cdot g(t - kT_f - jT_c - \tau_m) + n(t) \end{aligned} \tag{8}$$

where $n(t)$is zero mean AWGN with double sided power spectral density $N_0/2$. Suppose the local spread spectrum PN sequence is

$$PN(t) = \sum_{i=0}^{N-1} c_0(i) \tag{9}$$

where $c(i)$ is the code chip value, $c(i) \in \{+1, -1\}$, N denotes the length of PN sequence.

Calculate the cross-correlation using the ADC sampling signal with PN sequence in T_f with the interval T_s.

$$\begin{aligned} R(k;t) &= \int_{kT_s}^{(k+N-1)T_s} s_r(t) \cdot PN(t)\, dt \\ &= \int_{kT_s}^{(k+N-1)T_s} g(t - kT_f - jT_c - \tau_m) \\ &\quad \cdot \left(\sum_{i=0}^{N} c(i) \cdot c(i+k) \right) dt \end{aligned} \tag{10}$$

Find the maximum correlation peak in $R(k;t)$, record the k value. $k_{temp} = \underset{0 \le k \le N_f - 1}{\arg\max}\ R(k;t)$, $k_{temp}T_s$ is the synchronization point. So the RTT estimation value is

$$t_{RTT} = k_{temp} \cdot T_s = \left\{ \underset{0 \le k \le NK-1}{\arg\max}\ R(k;t) \right\} \cdot T_s \tag{11}$$

Substitute four different t_{RTT} tested value into equation (1)-(4) to calculate the accuracy coordinates of the UT.

IV. Simulations and Performance Evaluation

The position deviations are mainly caused by multipath and NLOS errors[15]. According to the analysis in [16][17], the multipath error and NLOS error are independently Gaussian-distributed random variables. IEEE 802.15.4a work group has developed a standard channel model for UWB-based low-data-rate communications with ranging capability, they developed a UWB channel model that is valid over larger distances than the 802.15.3a model. The model is parameterized for LOS as well as NLOS situations in indoor residential, office indoor, outdoor, and industrial environments. So we can obtain eight different kinds of Scenarios. To evaluate the performance of proposed scheme four channel models CM1 (indoor residential LOS), CM2 (indoor residential NLOS), CM5 (outdoor LOS), and CM6 (outdoor NLOS) in IEEE 802.15.4a are considered in experiments. In each channel model, 200 channel responses were considered. Figure.2 and Figure.3 represent the channel impulse response (CIR) in CM1 and CM2 respectively. In CM1, direct path (DP) carries more energy than other multi-path components (MPCs) in LOS channel. So we can consider strongest path (SP) as the DP signal. In CM2, it is clear that the SP is not the path arrives first, which arrives about 10ns earlier than SP. The localization deviation between estimated with actual coordinates can be described as

$$\Delta d = \sqrt{(x_e - x_a)^2 + (y_e - y_a)^2 + (z_e - z_a)^2} \tag{12}$$

where (x_e, y_e, z_e) are the estimated coordinates of the UT in a postioning measurement. (x_a, y_a, z_a) denote the actual coordinates of the UT. We use the Root of Mean Square Error (RMSE) to evaluate the system performance.

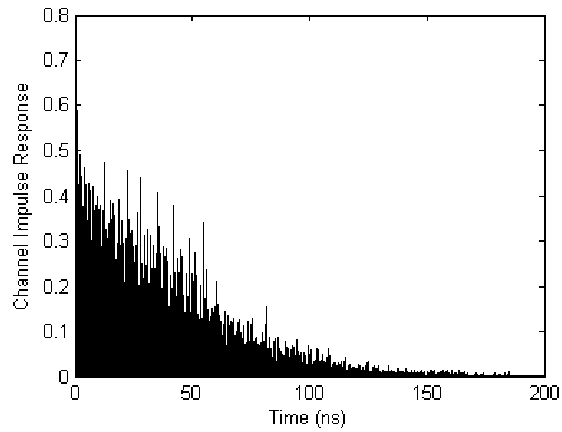

Fig. 2. CM1 Impulse response realizations

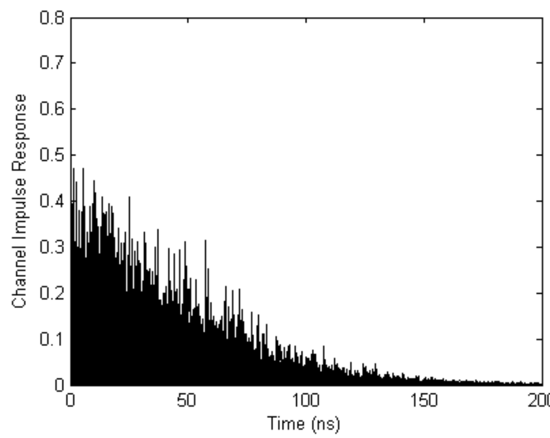

Fig. 3. CM2 Impulse response realizations

$$RMSE = \sqrt{E\{(\Delta d)\}^2} = \sqrt{\frac{1}{N} \sum\nolimits_{n=1}^{N} (\Delta d)^2} \tag{13}$$

The RMSE of localization deviation versus SNR in LOS and NLOS channels will be tested in different environment. In the simulations, the transmitted signal waveform we used is the second derivative of the Gaussian pulse. And the pulse width is truncated to 4ns, which includes the main lobe and two side lobes. Its bandwidth is 512MHz. The DS-UWB proposal foresees two different carrier frequencies, located at 3.75GHz (Uplink) and 5.25GHz (Downlink) respectively. The ADC sampling rate is 4GHz. We assumed that the transmitted signal contains a preamble sequence that is long enough to carry out accurate synchronization. Simulation results are the RMSE of 1000 different realizations. Fig.4 shows The RMSE of localization deviations vs. SNR in CM1 and CM2. The curve shows that the RMSE of localization deviations is difference between CM1 and CM2 increases with SNR in favor of CM1. The necessary SNR in LOS channel is lower than that in

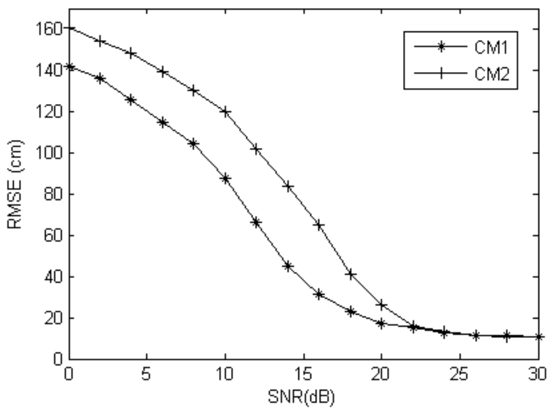

Fig. 4. indoor residential

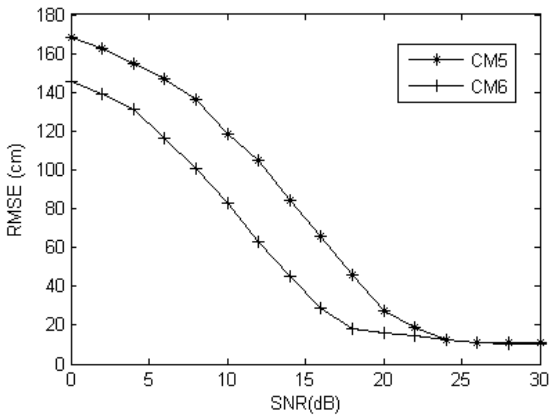

Fig. 5. outdoor environment

NLOS channel for the same localization estimation deviation. For example, SNR=13dB in CM1 while 17dB for CM2 in the residential scenario. This indicates that direct path (DP) carries more energy than other multi-path components (MPCs) in LOS channel, thus the proposed methods obtain better result. Fig.5 illustrates the outdoor scenario. At low SNR, multiple clusters of the arriving signal are buried in noise. The RMSE of localization deviations has a waterfall shape with the increase of SNR. However, when the SNR is larger than 22dB, the performance will not be improved with an increase of SNR. Comparing Fig.4 with Fig.5, we can find that the performance in CM5 is superior at low SNR, moreover, a higher signal-to-noise ratio results in a better performance of the proposed scheme. An accuracy of about 8cm is asymptotically achieved in these four channels.

V. Conclusion

A novel of indoor UWB positioning scheme has been presented, which combines the single-channel carrier-based UWB system and IR-UWB positioning system. We determine the positioning of UT by estimating RTT of frequency-conversion retransmitted signal. A strongest path detection method based on convolution of UWB multipath components is developed. Meanwhile we have evaluated the performance of the proposed scheme with the standard deviation of propagation distance under IEEE 802.15.4a channel models. The simulation results show the feasibility of the proposed scheme, which can provide a high accuracy of positions to within centimeters.

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