Ultra-Wideband Local Positioning for Smart Home Applications

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Abstract- Due to the inherently fine temporal resolution of UWB, arriving multi-path components can be sharply timed at a receiver to provide accurate time of arrival estimates. This characteristic makes UWB ideal for high precision radio-location applications. This paper focuses on feature UWB technology that makes it attractive for location precise. A Time-of-Arrival (TOA) based ranging scheme using UWB radio link is proposed. The problem of ToA estimation in multipath channels and sources of estimation error are discussed. Simulation results based on channel measurement data in indoor environment are presented. Results show that the accuracy enhancement depends on two principal factors: the strength of multipath components \(\theta_p\), and the variance of non-line-of-sight (NLOS) delays \(\delta\). For network synchronization, initial acquisition scheme for UWB multipath environments are investigated.

Index Terms— Ultra-Wideband, TOA, NLOS, Time acquisition, Smart home.

I. INTRODUCTION

Ultra-wideband (UWB) radios employ very short pulse waveforms that spread their energy over a broad swath of the frequency spectrum. The combination of high bandwidth wireless communications with the ability to achieve accurate positioning opens all of possibilities for wireless smart home networks. Location enabled networks can be used for smart home applications in self-organizing sensor networks, ubiquitous computing, location sensitive billing, context dependent information services, tracking and guiding old people and babies, etc. Many location systems have been developed. GPS is a space-based system where satellites are used as reference points. GPS does not function well indoors as the building structure itself hampers reception of the satellite signals. Local positioning systems (LPS) measure the physical properties of the radio signal between a device and a lattice of pre-deployed access points. Angle of arrival (AOA) received signal strength indicator (RSSI), time of arrival (TOA), and time difference of Arrival (TDOA) can be utilized to find link distances between nodes. However, due to the multipath fading and scattering near antennas, the delay based methods of TOA and TDOA are preferred in wireless networks such as CDMA. A TDOA based method for position location does not require synchronization between the transmitter and the receiver [1]. An UWB ranging technique that uses round trip time of flight measurements has been reported in [2]. An UWB location system that achieves 1 to 2 meters root-mean-square (RMS) accuracy in an open space cargo hold was described in [3]. An UWB positioning system where devices achieve location using shared ranging information is reported in [4]. A relative location system is presented in [5], in which the sensor location estimation problem is explored for sensors that measure range via RSSI and TOA between themselves and neighboring sensors. Previous research analyzed the location error with a Rayleigh channel model under the assumption of the existence of the line-of-sight (LOS) path and detection of the first multipath.

In this paper we present and evaluate via simulation the performance of UWB location precise for indoor wireless network. Initial acquisition scheme for impulse based UWB signal synchronization in multipath environments are investigated. This paper is organized as follows. Section 2 describes UWB ranging for MAC layer, section 3 discusses our proposed system model for UWB radio-location, section 4 considers the location for UWB networks, simulation results in section 5, and conclusions are given in section 6.

II. UWB RANGING FOR MAC FUNCTIONS

UWB ranging precision is useful in the short-range scenarios expected for smart home networks where positioning is effective only if high precision can be achieved. Ranging information can be exploited in several ways in resource management. Examples are: a) Definition of distance related metrics for both MAC and higher layers, enabling the development of power-aware protocols, b) Evaluation of initial transmission power levels, required in distributed power control protocols c) Introduction of distributed positioning protocols in order to build a relative network map starting from ranging measurements. This map could enable location-based enhancements in several MAC and network functions, such as position-based routing, and position-aware distributed code assignment protocols in multiple channels MAC, in order to minimize MUI.

III. UWB SYSTEM MODEL

In this work, an ad hoc network scenario is considered, in which a connecting station has to
identify the node acting as master station (or cluster head). The organizations of the network include time periods (beacons) reserved to synchronization, alternated to the time-division multiplexed downlink/uplink connections. In general, the uplink communication is characterized by the coexistence of asynchronous users. Each user is assigned a time-hopping sequence, typically corresponding to a PN code, translating into a pulse train, which spans several time frames. For physical layer signal transmission UWB is used. In UWB the fractional bandwidth \( \eta \) is greater than 25% of a centre frequency \( f_c \). The transmitted UWB signal consists of a train of short pulses, which dithered by a time-hoping (TH) sequence to facilitate multiple accesses and reduce spectral lines. The polarities of the transmitted pulses are also randomized by using a direct sequence (DS) spreading code to mitigate multiple access interference (MAI). The generalized UWB signal of Gaussian pulse \( \psi(t) \) is the received waveform corresponding to a single pulse. The received signal from a single user can then expressed as a series of 2\(^nd\) derivatives of Gaussian pulse \( \psi(t) \).

\[
\psi(t) = \sqrt{\frac{4}{3\pi \eta}} \left(1 - \frac{t^2}{t_n^2}\right) \exp\left(-\frac{1}{2} \left(\frac{t}{t_n}\right)^2\right)
\] (2)

The parameter \( t_n \) determines the effective time width of the pulse \( t_p \), and, hence, its bandwidth (shown in figure 1).

Fig. 1. Second derivative of Gaussian pulse

Then the transmitted signal is given by

\[
x(t) = \sum_{l=-\infty}^{\infty} b_l^{[l/N_s]} a_l^{[l/N_d]} \psi(t - lT_f - c_l^{[l/N_d]}T_c) - n(t)
\] (3)

Where \( N_s \) is the number of consecutive pulses modulated by each data symbol \( b_l \), \( T_f \) is the pulse repetition period (PRP), \( T_c \) is the chip duration, which is the unit of additional time shift provided by the TH sequence and \( [+][+] \) denote the integer division reminder operation and the floor operation, respectively. The pseudorandom TH sequence \( \{c_l\}_{l=0}^{N_{th}-1} \) has length \( N_{th} \), where each \( c_l \) takes integer values between 0 and \( N_{th} - 1 \), where \( N_{th} \) is less than the number of chips per frame \( N_f = T_f / T_c \). The DS sequence \( \{a_l\}_{l=0}^{N_{ds}-1} \) has length \( N_{ds} \) with each \( a_l \) taking the value +1 or –1.

B. Channel model

The UWB indoor propagation channel can be modeled by a stochastic tapped delay line [5], which can generally be expressed in terms of its impulse response

\[
h(t) = \sum_{k=0}^{N_{tap}-1} h_k f_k (t - t_k)
\] (4)

Where \( N_{tap} \) is the number of taps in the channel response, \( h_k \) is the path gain at excess delay \( t_k \) corresponding to the \( k \)-th path. Due to the frequency sensitivity of the UWB channel, the pulse shapes received at different excess delays are path-dependent. The function \( f_k(t) \) models the combined effects of transmitting and receiving antennas and propagation channel corresponding to the \( k \)-th path of the transmitted pulse. The received signal from a single user can then expressed as

\[
r(t) = \sum_{l=-\infty}^{\infty} b_l^{[l/N_s]} a_l^{[l/N_d]} w_r(t - lT_f - c_l^{[l/N_d]}T_c - \tau) + n(t)
\] (5)

where

\[
w_r(t) = \sum_{k=0}^{N_{tap}-1} h_k \psi(t - t_k)
\] (6)

is the received waveform corresponding to a single pulse. Here \( \psi_k(t) = f_k(t) * \psi(t) \) is the received UWB pulse from the \( k \)-th path. The duration of the received pulse \( T_r \) is assumed to be less than the chip duration \( T_c \). The propagation delay is denoted by \( \tau \) and \( n(t) \) is a zero mean noise process. Given the received signal, the acquisition system attempts to retrieve the timing offset \( \tau \).

IV. UWB LOCATION DESIGN

A. False Alarm and Miss Probabilities

ToA errors can classify into two categories, one is an early false alarm \( P_{Fa} \), which occur when a false detection in the noise only (related to the variance of the input noise) portion of the signal is regarded as that of a direct path signal. The missed probability \( P_M \) occurs when the actual direct path signal is lost...
and a multipath signal is falsely declared to be direct path signal.

If the signal is transmitted through the multipath channel, as described in previous section, the received signal \( x(t) \) can be represented by

\[
x(t) = ax(t - \tau_d) + \sum_{k=1}^{L_p} \alpha_k s(t - \tau_k) + n(t) \quad t \leq \frac{T_p}{2}
\]

where \( \tau_d < \tau_1 < \tau_2 < \ldots < \tau_{L_p} \). The parameter \( \tau_k \) and \( \alpha_k \) are those of the \( k \)-th reflected signal component. The number of multipath signals \( L_p \) is unknown a priori. \( x(t) \) has been truncated to \( T_p / 2 \) which it is the observation of the signal prior to and including the arrival of the strongest path, \( T_p \) is the pulse repetition time. Let \( \tau_{peak} \) and \( \alpha_{peak} \) be the arrival time and amplitude of the shortest path, which have been determined by correlation in the receiver [6], and normalize and shift the received signal as

\[
\delta_d = \tau_{peak} - \tau_d \\
\rho_d = \alpha_d / |\alpha_{peak}|
\]

(8)
The duration of the search region for the time \( \delta \) of arrival of the direct path signal is limited to prevent the probability of false alarm \( P_{FA} \) from becoming too large. Defining \( \theta_\delta \) is as a limiting threshold on \( \delta \) so that the direct path signal is searched over the portion of the received signal \( x(t) \) satisfying \( t \geq -\theta_\delta \). Then the iterative search process stops when no more paths satisfying \( \rho \geq \theta_\rho \) are detected in the search region, where \( \theta_\rho \) is the normalized detection threshold of \( \rho \).
The probability of missed \( P_M \) can be evaluated as:

\[
P_M = pr(\delta > \theta_\delta \ or \ \rho < \theta_\rho)
= 1 - Pr(0 \leq \delta \leq \theta_\delta \ and \ \theta_\rho \leq \rho \leq 1)
= 1 - P_0 - (1 - P_0) \int_{\theta_\rho}^{\theta_\delta} \int_0^\infty f_{\delta\rho}(\delta, \rho) \rho \neq 0) d\delta d\rho.
\]

(9)
where \( P_0 \) is the probability that the direct signal is the strongest signal, where \( P_0 = Pr(\delta = 0) = Pr(\rho = 1) \) and \( P_D = 1 - P_M \) is the probability of detection.

Probability of false alarm \( P_{FA} \) can be evaluated as:

\[
P_{FA} = \int_{\theta_\delta}^{\theta_\rho} \left(1 - e^{-(\theta_\delta - \delta + B\gamma + By)}/C\right) f_{\delta\rho}(\delta, \rho \neq 0) d\delta (1 - P_0)
+ (1 - e^{-(\theta_\delta - \delta + B\gamma + By)}/C) P_0
\]

(10)
where the constants \( B \) and \( C \) depend on the structure of the signal template \( s(t) \), and \( \gamma = \theta_\rho \sqrt{SNR} \) [7].

B. Network Synchronization

The extremely short duration pulse offers great possibilities for precise position location, but makes the timing synchronization task more complex. Since we are mostly interested in low signal-to-noise ratio environments (in the presence of strong interfering signals or deep noise, for example), in this paper, we shall consider serial search techniques [8]. Let us assume that we cycle through and test a total of \( N \) different hypothesized phases in each search cycle until the correct phase is detected. We associate a penalty time of \( T_{fa} \) seconds \( T_{fa} >> T_d \) with a false alarm. The penalty time associated with a miss is \( NT_d \), where \( T_d \) is the dwell time. If the correct phase is in the \( n \)-th hypothesized position, and there are \( j \) misses and \( k \) false alarms, the overall acquisition time [9] is given by:

\[
T_{acq}(n, j, k) = nT_d + jNT_d + kT_{fa}
\]

(11)
Hence, the mean overall acquisition time is

\[
\overline{T}_{acq} = \sum_{n=1}^N \frac{\sum_{j=0}^\infty \sum_{k=0}^j \left(T_{acq}(n, j, k)\right) P(n, j, k)}{N}
\]

(12)
Where

\[
P(n, j, k) = P(k \mid n)P(j \mid n)P(n)
\]

(13)
As a result

\[
\overline{T}_{acq} = \sum_{n=1}^N \frac{\sum_{j=0}^\infty (1 - P_{DET})^j P_{DET}}{N}
\]

(14)
V. SIMULATION RESULTS

To investigate the UWB location system for indoor environment, which nodes connect as ad-hoc network a custom-made simulation tool has been developed. The simulation investigates the estimation time delay for signal between transmitter and receiver. For simulation, nodes were distributed randomly on area (15 m x 15 m), 2nd derivative of Gaussian with pulse width \( T_p = 1.562 ns \) was used, and set the SNR=10 dB.

Figure 2 shows the probability of false alarm \( P_{FA} \) with different values of \( \theta_\delta \) and \( \theta_\rho \), SRN is 10dB, \( P_{FA} \) increased with decrease of SNR.

Figure 3 shows that the probability of direct path detection \( P_D \) with different values of \( \theta_\delta \). The \( P_D \) increased with the variance of non-line-of-sight (NLOS) delays \( \theta_\delta \) and with decreased the strength of
multipath components $\theta_\rho$, hence increases the range estimation error for the node location.

![Fig. 2. Probability of false alarm with SNR of 10 dB plotted over $\theta_\rho$ and $\theta_\delta$](image)

The detection and false alarm probabilities, as well as the mean acquisition time. Normalized thresholds of $\theta_\rho = 0.75$ is assumed.

VI. CONCLUSIONS

UWB ranging with a decent multipath immunity for applications in indoor multipath environments, i.e., smart home have been presented. A ToA based ranging scheme was adopted and the detection of direct path signal and false alarm probabilities were developed. The extremely short duration pulses that employ to offer great possibilities for precise position location make the timing synchronization task more complex, we discussed the initial synchronization time for UWB in presence of multipath.

REFERENCES


