UWB-TOA GEOLOCATION TECHNIQUES IN INDOOR ENVIRONMENTS

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ABSTRACT

Ultra-wideband (UWB) radio is a new carrierless communication scheme using impulses and is a candidate technology for future communication and ranging applications. In this paper, we consider the problem of node localizing in ad-hoc networks, in which positioning algorithm only exploits the high precision ranging capabilities offered by UWB and does not rely on GPS. A Time-of-Arrival (ToA) based ranging scheme using UWB radio link is proposed. In this paper, the problem of ToA estimation in multipath channels, source of estimation error are discussed. Two-way ranging (TWR) scheme was used for network synchronisation. Results show that the accuracy enhancement depends on two principal factors: the strength of multipath components and the variance of non-line-of-sight (NLOS) delays, which it shows that DS-UWB is best suited for ranging, due to its larger bandwidth and its higher frequencies of operation.

Keywords: *Indoor, Multipath, Ranging, TOA,UWB*

1. INTRODUCTION

With the emergence of location-based applications, location finding techniques are becoming increasingly important [1]. Both indoor and outdoor coverage are required in the process of positioning. The Global Positioning System (GPS) delivers reliable radio frequency (RF) location using a combination of orbiting satellites to determine position coordinates. GPS works fine in most outdoor areas, but the satellite signals are not strong enough to penetrate inside most indoor environments. As a result, new indoor positioning technologies are beginning to appear in the market. Such technologies make use of 802.11 wireless LANs or Bluetooth, but the obtained accuracy is not good enough [2].

An alternative system that can provide the accuracy and robustness needed by indoor positioning systems and having an advantage of low power and low cost is the Ultra-Wideband (UWB) technology. UWB allows up to a few centimeters ranging accuracy ranging, and involve short discrete transmission pulses instead of continuously modulating a code into a carrier signal [3]. This technology offers high data rates for radio communications, extremely high accuracy for location systems and good resolution for radars by using an inherently low cost architecture and only milli-watts of power [4].

Ultra wideband (UWB) has been the focus of much research and development recently [5]. UWB offers solutions to applications such as see-through-the-wall, security applications, family communications and supervision of children, search-and-rescue, medical imaging, control of home appliances, which make UWB an ideal candidate for wireless home network. Recently, impulse-based UWB ranging methods have been investigated [6].

UWB transmission offers the potential of accurate user location [7]. The location information can be used for transmission synchronization, power and rate allocation, and traffic routing in ad-hoc environment.

Localisation of radio signals indoors is difficult because of the presence of shadowing and of multipath reflections from walls and objects [8]. The wide bandwidth of UWB signals implies a fine time resolution that gives them a potential for high-resolution positioning applications, provided that the multipaths are dealt with.

Time-of-arrival (TOA) is one of the most widely used location metrics in geolocation systems. The basic problem of TOA-based techniques is to accurately estimate the propagation delay of the radio signal arriving from the direct line-of-sight (DLOS) propagation path. Estimation of TOA falls into the field of signal parameter estimation, and it was studied in the literature for sonar, radar, and GPS applications [2,3]. In those traditional applications, the radio propagation channel is normally assumed to be single path, only disturbed by additive white Gaussian noise (AWGN). But the major challenge in indoor geolocation systems to achieve accurate and acceptable performance is when the direct path from the transmitter to the receiver is intermittently blocked. This is the non line-of-sight (NLOS) or obstructed line-of-sight (OLOS) problem, and it is known to be a major source of error in estimating location since it erroneously causes the node to appear farther away than it actually is, thereby increasing the positioning error.

Here, we concentrate on ranging aspects in ad-hoc networks for indoor environment e.g., future smart home. We will also discuss the ranging technique based on ToA estimation where the nodes can adopt a two-way ranging scheme in the absence of a common clock, where upon we will investigate the positioning problem from a UWB perspective and present performance bounds and estimation algorithms for UWB ranging. This includes the estimation error in ranging when the line-of-sight path is blocked.

The remainder of this paper is organised as follows: In section 2, several ranging techniques are described; in section 3, positioning techniques for UWB systems based on ToA with two-way ranging are presented, followed by simulation results in section 4. Finally, concluding remarks are summarised in section 5.

2. RANGING TECHNIQUES

There are three types of positioning techniques that can be used in order to determine the location of a node, viz., the angle of arrival (AoA), the received signal strength (RSS) and time of arrival (ToA) and time difference of arrival (TDoA). The AoA technique measures the angles between a given node and a number of reference nodes to estimate the location by means of antenna arrays, with increased system cost [10], while RSS relies on a path-loss model; the distance between two nodes can be calculated by measuring the energy of the received signal at one node, where an accurate propagation model is required to reliably estimate distance.

The other two are time-based positioning techniques including Time-of-Arrival (ToA) and Time-Difference-of-Arrival (TDoA) which rely on measurements of travel times of signals between nodes. The accuracy of a time-based approach can be improved by increasing the signal-to-noise ratio (SNR) or the effective signal bandwidth, β. Since UWB signals have very large bandwidths, this property allows extremely accurate location estimation.

However, since the achievable ranging accuracy for UWB under ideal conditions is very high, clock synchronisation between the nodes becomes an important factor that affects ToA estimation accuracy. Hence, clock jitter must be considered in evaluating the accuracy of a UWB positioning system.

3. TIME-OF-ARRIVAL (TOA) TECHNIQUES FOR UWB SYSTEMS

The Ultra Wide-Band (UWB) radio communications can be viewed as an extreme form of spread spectrum communication systems. UWB radios transmit using very short impulses spread over a very large bandwidth. UWB radios are generally defined to have a fractional bandwidth (η) higher than 0.25 (i.e. a 3dB bandwidth which is at least 25% of the centre frequency used).

$$\eta = \frac{2(f_H - f_l)}{(f_H + f_l)} \quad (1)$$

where f_H and f_l are the high and low out frequency off, respectively. For a multi-user (device) scenario, the format of the transmitted Time Hopping –Spread Spectrum (TH-SS) Impulse Response (IR) UWB signal, $s^k_{tx}(t)$, corresponding to the k[th] user is given by:

$$s_{tx}^{(k)} = \sum_{j=-\infty}^{j=+\infty} w(t - j.T_f - c_j^{(k)}.T_c - \delta.b_{j/N_s}) \quad (2)$$

where $w(t)$ is the transmitted unit-energy pulse, Tf is the pulse repetition time (typically a hundred or a thousand times the monocycle width), δ is the pulse time shift for Pulse Position Modulation (PPM), the time shift element of the time-hopping code word assigned to the k^{th} user chosen from the set $\{0,1,\ldots,N_{b-1}\}$, N_b is the number of time delay bins in a T_f, T_c the time delay bin, N_s is the number of impulses or impulse dedicated to the transmission of one bit. The bit rate associated to one code word is then $R_b = 1/(N_sT_f)$ [11].

A known radio signal emanates transmitter and the signal is monitored at a spatial separated receiver which estimates the propagation delay of the signal from the transmitter to receiver. The AWGN radio propagation channels between nodes are considered with single-path, then the received signal can be mathematically expressed as

$$x(t) = \alpha s(t-\tau_d) + n(t) \quad (3)$$

where the parameters τ_d and α are the arrival time and strength of the direct path signal, respectively. The waveform $s(t)$ denotes the canonical single-path signal used as a correlator template with a width of T_p seconds, and $n(t)$ is AWGN with double-sided noise spectral density, $N_0/2$. The Maximum Likelihood (ML) estimation of the arrival time delay (τ) can be obtained by finding the value of τ_d that maximises the correlation function of received signal $x(t)$ and transmitted signal $s(t)$ as follows:

$$r_{xs}(\tau_d) = \frac{1}{T_0}\int_{T_0} x(t)s(t-\tau_d)dt \quad (4)$$

Where T_0 is the auto-correlation duration, which is equal $T_p/2$ where T_p is pulse width. In practice, the delay profile can be measured at the receiver using a sliding correlator or matched filter. The performance of the ML estimator is bounded by the Cramer-Rao lower bound (CRLB), which is the minimum variance of ToA estimation errors about the true time delay.

The ToA technique computes the distance based on the estimation of the propagation delay between transmitter and receiver in which we can use the ML estimator, defined as follows:

$$\hat{\tau}_{ML}(r) = \arg\min_{\tau\in\Re}\left(e^{-\frac{1}{N_o}\int_{T_{obs}}(r(t)-s(t-\tau_d))^2 dt}\right) \quad (5)$$

where N_0 is the bilateral Power Spectral Density (PSD) of the noise and T_{obs} is the observation interval over which the estimation is performed. The accuracy of estimation expressed by the variance of the TOA estimation error $\sigma^2_{\hat{\tau}}$, which is related to the bandwidth and SNR at the receiver. According to ML, the lower limit for $\sigma^2_{\hat{\tau}}$ is given by Cramer-Rao lower bound (CRLB):

$$\sigma^2_{\hat{\tau}} = \frac{N_0}{2\int_{-\infty}^{+\infty}(2\pi f)^2 \,|\, P(f)|^2 \, df} \quad (6)$$

where $|P(f)|^2$ is the constant bilateral Energy Spectral Density (ESD) for the UWB pulse p(t), which can be expressed as:

$$P(f)|^2 = \begin{cases} G_0 & for \quad f \in [f_L, f_H] \cup [-f_L, -f_H] \\ 0 & outside \end{cases} \quad (7)$$

where the power gain $(G_0) = 3.315\text{x}10^{-29}$ J/Hz for ad-hoc nodes with UWB power constraint (-41dBm).Since the achievable accuracy under ideal conditions is very high, clock synchronisation between the nodes becomes an important factor affecting ToA estimation accuracy. Hence, clock jitter must be considered in evaluating the accuracy of a UWB positioning system.

4 SIMULATION RESULTS

To investigate the UWB location system for ad hoc network in an indoor environment, a custom-made simulation tool was developed. The simulation investigated the estimated time delay for signal between transmitter and receiver. In accordance with the regulations of the FCC the chosen frequency band is shown in Table 1. The propagation aspects of the wireless channel were modeled using the residential indoors NLOS environment. The parameters used are: the second derivative of Gaussian pulse with width $T_p = 1.562_{ns}$ with disjoint BPPM modulation method multiple access technique for inter-piconet are: TDMA, for intra-piconet; TH-UWB and DS-CDMA, the maximum threshold time delay (θ_δ) was 100nsec for the search region. Saleh-Valenzuela model [11] for channel model adopted and 15mx15m area per piconet used in which two piconets considered.

4.1 ERROR ESTIMATION FOR TOA TECHNIQUE

a) ML ESTIMATION FOR DIRECT LOS SIGNALS

The two proposals considered in this paper are: a Multi Band OFDM approach, based on the transmission is non-impulse OFDM signals combined with Frequency Hopping (FH) at four different groups of bands; group A with band from 3.1-4.9 GHz, group B from 4.9-6.0 GHz, group C from 6.0-8.1 GHz, Group D from 8.1-10.6 GHz, Group B and D have been reserved for future use, and the second method is the direct-sequence (DS) UWB approach, based on impulse radio transmission of UWB DS-coded pulses with two different bands; lower band from 3.1-5.15 GHz and upper bands from 5.8-10.6 GHz. [14].

As shown in Figure 1, the accuracy of a time-based approach improves with the increase of SNR or the effective signal bandwidth. Since UWB signals have very large bandwidths, this property allows extremely accurate location estimation. For example, for a received UWB pulse of 1.8 GHz bandwidth, an accuracy of less than 20 cm can be obtained at SNR=0dB. Also the figure shows that DS-UWB overcome MB-OFDM in ranging accuracy due to large bandwidth in DA-UWB.

Table 1: Lower bound estimation error variance for varies type of UWB standards

Standard	BW (GHz)	Variance σ_τ^2 (s)
MB-OFDM G(A)	3.1-4.9 GHz	$8.7721e^{-28}$
MB-OFDM G(C)	6.0-8.1 GHz	$2.44321e^{-28}$
DS-UWB (Lower Band)	3.1-5.15 GHz	$7.24163e^{-28}$
DS-UWB (Upper Band)	5.8-10.6 GHz	$7.7584e^{-29}$
DS-UWB (Multi Bands)	3.1-10.6 GHz	$7.2933e^{-29}$

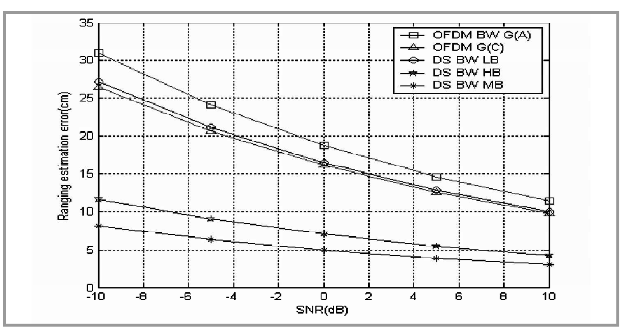

Figure 1: Ranging error based on the CRLB for various types of UWB IEEE802.15 standards

b) DIRECT PATH SIGNAL ESTIMATION FROM MULTIPATH SIGNALS

Despite the promising performances of UWB systems, indoor radiolocation is a tough task on its own. Since the ranging transactions usually require TOF estimation, it is obvious that the propagation channel would degrade the ranging precision. Indeed, dense multipath channels may adversely affect the distance estimate. It is specifically the case when the LOS is present but undetectable, or when it is purely absent of the channel impulse response (CIR) due to severe blockage situations.

Then we can classify the ToA error into two categories; one is direct path false match, which occur when a false detection in the noise only portion of the signal is regarded as that of direct path signal. The other is direct-path lost error, which occurs when the actual direct path signal is lost and a multipath signal is falsely declared to be direct path signal.

For a signal transmitted through a multipath channel, the received signal *x(t)* can be represented as

$$x(t) = \alpha s(t-\tau_d) + \sum_{k=1}^{L_p} \alpha_k s(t-\tau_k) + n(t) \qquad t \le \frac{T_p}{2} \tag{8}$$

where $\tau_d < \tau_l < \tau_2 < \ldots < \tau_{L_p}$. The parameter τ_k and α_k are those of the k-th reflected signal component. The number of multipath signals is unknown a priori. *x(t)* was truncated to which it is the observation of the signal prior to $T_p/2$ and including the arrival of the strongest path. Let τ_{peak} and α_{peak} be the arrival time and amplitude of the shortest path, determined by correlation in the receiver. Then the signal is received normalised and shifted the received signal as

$$\begin{aligned} \delta_d &= \tau_{peak} - \tau_d \\ \rho_d &= \alpha_d / |\alpha_{peak}|, \end{aligned} \tag{9}$$

The search duration δ of the arrival of direct path signal is limited to prevent the high probability of false matched (P_{FM}). By Define θ_δ as the threshold on δ so that the direct path signal is searched over portion of the received signal *x(t)* satisfying $t \geq -\theta_\delta$. The iterative search process stops when no more paths satisfying $\rho \geq -\theta_\rho$ are detected in the search region, where θ_ρ is the threshold of ρ.

The probability of direct path lost error can be evaluated as:

$$\begin{aligned} P_L &= P_r(\delta > \theta_d \quad or \quad \rho < \theta_\rho) \\ &= 1 - P_0 - (1-P_0) \int_{\theta_\rho}^{1} \int_{0}^{\theta_\delta} f_{\delta\rho}(\delta, \rho \mid \delta \neq 0) \, d\delta d\rho. \end{aligned} \tag{10}$$

where P_0 is the probability that the direct signal is the strongest signal, is $P_0 = \Pr(\delta = 0) = \Pr(\rho = 1)$. The probability of direct path false match (PFM) can be evaluated as:

$$\begin{aligned} P_{FM} &= \int_0^{\theta_\delta} (1 - e^{-(\theta_\delta - \delta - T_p + B\gamma)/C}) f_\delta(\delta \mid \delta \neq 0) d\delta . (1-P_0) \\ &+ (1 - e^{-(\theta_\delta - \delta - T_p + B\gamma)/C}) P_{0.} \end{aligned} \tag{11}$$

where the constants B and C depend on the structure of the signal template *s(t)* and the signal model. For second derivative of Gaussian with pulse width $T_p = 1.562ns$, B and C are 6.5757, and $1.375e^{-11}$ respectively; and $\gamma = \theta_\rho . \sqrt{SNR_p}$.

Figure 2 shows the probability of a direct path lost (PL) with different values of θ_δ. The P_L is increased when delay threshold (θ_δ) decreased, hence the increase of θ_δ estimation error range for the node location.

Figure 3 shows the probability of false matched (P_{FM}) with delay threshold (θ_δ) 100nsec and different values of SNR,

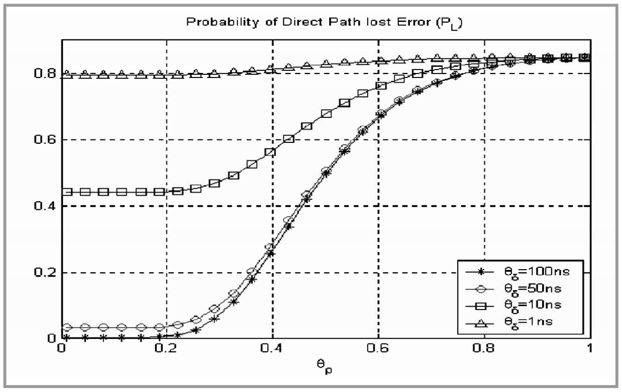

Figure 2: Probability of a direct path lost error (P_L) with a peak SNR of 18 dB

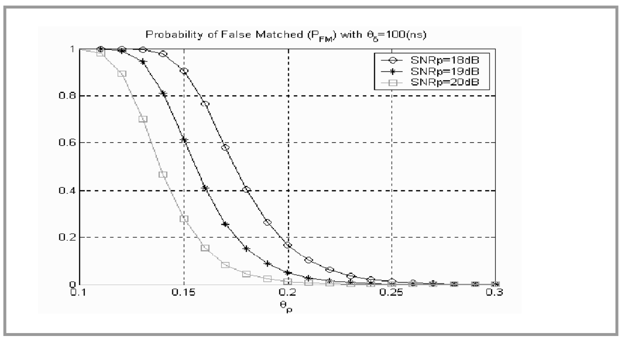

Figure 3: Probability of false matched (P_{FM}) with delay threshold (θ_δ) 100nsec

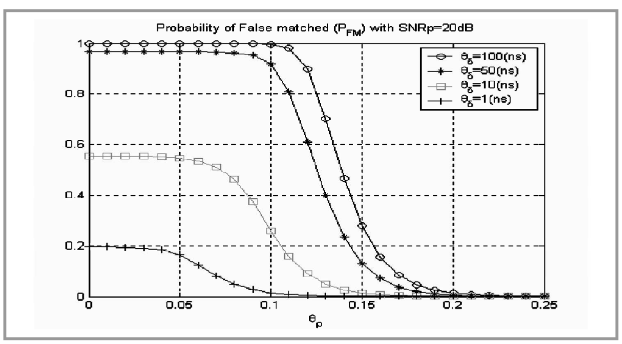

Figure 4: Probability of false matched (P_{FM}) with SNR_p=20dB

which shows that the ToA technique performance is proportional to SNR_p, as a result the probability of false matched direct path (P_{FM}) will decreased.

Figure 4 shows P_{FM} when the duration of the search region for the ToA of the direct path signal is limited, this will prevent the probability of false matched (P_{FM}) to be too large in the noise only portion of the observed signal.

The relationship between the false matched probability PFM and the direct path loss P_L represent the receiver-operating characteristic (ROC) of the matched filter energy detector. The ROC curves indicate the trade-off between false alarm and detection probability at different SNR's plotted in Figure 5. Generally the more concave the ROC curve, the better is the performance of the detector.

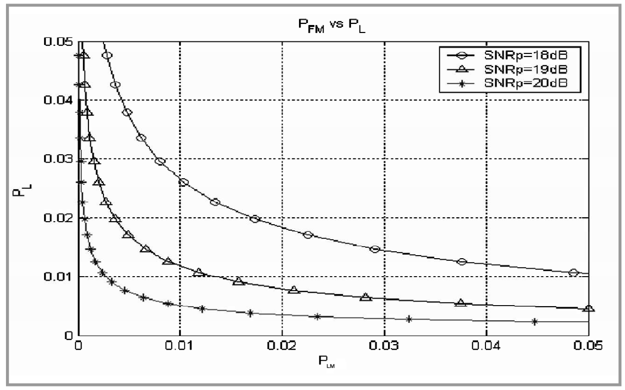

Figure 5: False matched probability versus probability of direct path lost for different peak SNRs.

4.2 NETWORK SYNCHRONISATION

UWB ad-hoc ranging system can estimate the range by measuring signal round-trip time without a common timing reference, where a pair of nodes is time-multiplexed with half-duplex packet exchanges. This procedure relies on a typical mechanism for fused location and communication such as requestor sends packets to a responder, after synchronizing it with packets containing synchronous timing information. The receipt of this response allows the requestor to determine the round-trip TOF information (shown in Figure 6).

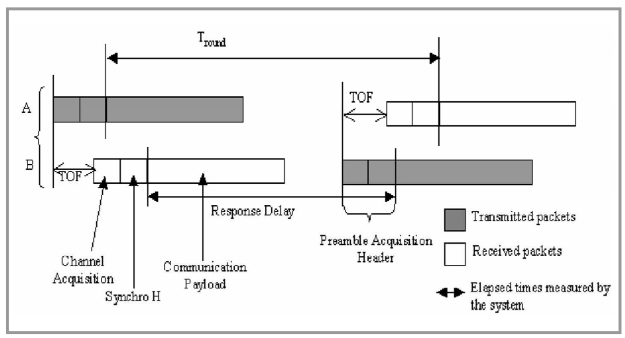

Figure 6: Two-way Ranging (TWR) transaction enabling to estimate the round-trip Time-OF-Flight between two asynchronous terminals (feeding TOA-based positioning algorithms)

Figure 7 shows the ranging error estimation for a single TWR between the node and cluster-head due to the clock drift, node mobility, and absent of the base station (lack of infrastructure). Here the ToF is maintained below 50ps for ε (frequency offset) up to 10^{-5} if the ACK occurs within duration less than 10msec. This corresponds to uncompensated drift situations when the value of ε is too large. Otherwise, when considering traditional values of 10^{-6}, the constraints on the ACK collapse down to 100μsec.

5 CONCLUSIONS

The target of this work is to design UWB ranging system with a decent multipath immunity for indoor applications, such as smart homes. A ToA based ranging scheme was adopted to detect direct path signal, which 93.12% probability of

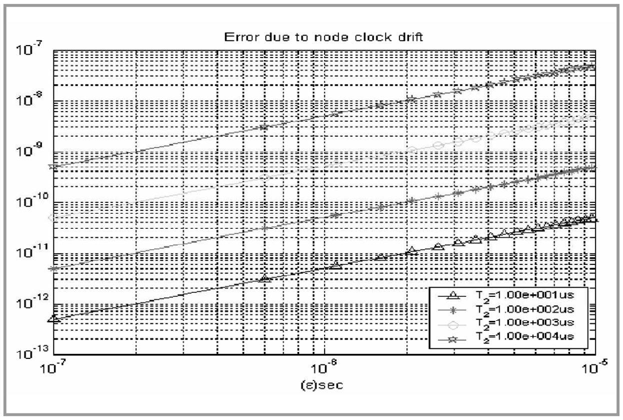

Figure 7: Ranging Error with a single TWR between the node and cluster-head estimation

detection with 50 ns NLOS delays was achieved resulting 25 cm ranging estimation error compared with 30 meters in GPS. The UWB ranging system designed utilising the ToA algorithm based on two-way ranging (TWR) scheme.

In this scheme we assume that the clocks are locked. So the clock synchronisation, timing acquisition, and clock jitter are important issues for future study. ■

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