Performance of Ultra-Wideband Time-of-Arrival Estimation Enhanced With Synchronization Scheme

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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 is discussed. Coarse synchronization scheme was used. 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, UWB, ranging, multipath, TOA, MAT

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 on 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, which 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 makes 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. Localization 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 that 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

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error. In this paper we investigate the estimation error in ranging when the line-of-sight path is blocked. In this paper, we concentrate on ranging aspects in ad-hoc networks for indoor environment i.e., 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, in which we will investigate the positioning problem from a UWB perspective and present performance bounds and estimation algorithms for UWB ranging. An initial acquisition scheme for impulse based UWB multipath environments also investigated, which reduction of acquisition time with minimization of false alarm and miss probabilities by properly adjusting the decision threshold and the number of hypothesized phases was studied.

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

2. RANGING TECHNIQUES

There are four types of positioning techniques, the angle of arrival (AoA), the received signal strength (RSS) or time delay information can be used in order to determine the location of a node. 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, which an accuracy propagation model is required to reliably estimate distance.

The other two are time-based positioning techniques include Time-of-Arrival (ToA) and Time-Difference-of-Arrival (TDoA) 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.

Since the achievable ranging accuracy for UWB under ideal conditions is very high, clock synchronization 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).

$$\eta = \frac{2\left(f_H - f_l\right)}{\left(f_H + f_l\right)} \tag{1}$$

where f_H and f_l are high and low frequency respectively. For a multi-user (device) scenario, the format of the transmitted Time Hopping -Spread Spectrum (TH-SS) Impulse Response (IR) UWB signal, $s_{tx}^{k}\left(t\right)$, corresponding to the kth user is given by:

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

where $w\left(t\right)$ is the transmitted unit-energy pulse, T_f 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,. . .,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 $R_b = 1/N_s T_f$ [11].

A known radio signal $s\left(t\right)$ is emanated from 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

$$x\left(t\right) = \alpha s\left(t - \tau_d\right) + n\left(t\right) \tag{3}$$

where the parameters τ_d and α are the arrival time and strength of the direct path signal, respectively. The waveform $s\left(t\right)$ denotes the canonical single-path signal, used as a correlator template, with a width of T_p seconds, and $n\left(t\right)$ 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 maximizes the correlation function of received signal $x\left(t\right)$ and transmitted signal $s\left(t\right)$ as follows:

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

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 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 distance based on the estimation of the propagation delay between transmitter and receiver, which we can use the ML estimator, which is defined as follows:

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

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. Where the accuracy of estimation expressed by the variance of the TOA estimation error $\sigma^2_{\widehat{\tau}}$, which it is related to the bandwidth and SNR at the receiver. According to ML, the lower limit for $\sigma^2_{\widehat{\tau}}$ is given by Cramer-Rao lower bound (CRLB):

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

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

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

where the power gain $(G_0) = 3.31 \times 10^{-29}$ J/Hz for ad-hoc nodes with UWB power constraint (-41 dBm).Since the achievable accuracy under ideal conditions is very high, clock synchronization 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 estimation 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 used parameters are: the second derivative of Gaussian pulse with width $T_p = 1.562$ ns and, modulation method is disjoint BPPM, multiple access technique for inter-piconet; TDMA, for intra-piconet; TH-UWB and DS-CDMA, the maximum threshold time delay (θ_τ) was 100 nsec for the search region. Saleh-Valenzuela model [11] for channel model is adopted and 15mx15m area per piconet is used, which two piconets are 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 of non-impulse OFDM signals combined with Frequency Hopping (FH) with four different operation 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, where group B and D have been reserved for future use, and 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 Fig. 1, the accuracy of a time-based approach improves with increases 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 20cm can be obtained at SNR=0dB. Also 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 $\sigma^2_{\widehat{\tau}}(s)$
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 Band)	3.1-10.6 GHz	$7.2933e^{-29}$

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 w1ould degrade the ranging precision. Indeed, dense multipaths 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 matched, which occurs 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

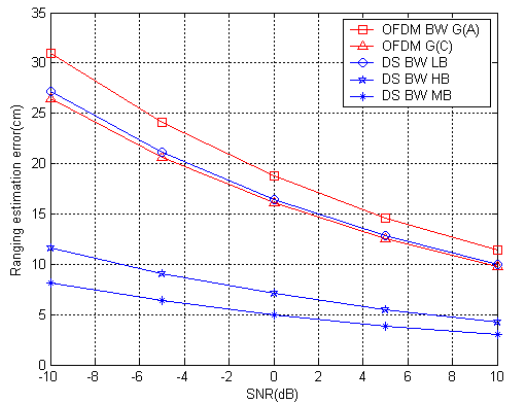

Fig.1: *Ranging error based on the CRLB for various types of UWB IEEE802.15 standards.*

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 by

$$x(t) = \alpha s(t - \tau_d) + \sum_{k=1}^{L_p} \alpha_k s(t - \tau_k) + n(t)\,; t \leq \frac{T_p}{2} \quad (8)$$

where $\tau_d < \tau_1 < \tau_2 < \ldots < \tau_{L_p}$. The parameter τ_k and α_k are those of the k-th reflected signal component. The number of multipath signals 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. 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 normalized and shift the received signal as

$$\begin{aligned} \delta_d &= \tau_{peak} - \tau_d \\ \rho_d &= \alpha_d / \left|\alpha_{peak}\right|, \end{aligned} \quad (9)$$

The search duration δ of arrival of the direct path signal is limited to prevent the high probability of false matched (PFM). By defining θ_s as the threshold on δ so that the direct path signal is searched over portion of the received signal $x(t)$ satisfying $t \geq -\theta_s$. 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:

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

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

$$\begin{aligned} P_{FM} = &\int_0^{\theta_\delta} \left(1 - e^{-(\theta_\delta - \delta - T_p + B_\gamma)/C}\right) f_\delta(\delta | \delta \neq 0)\, d\delta \\ &.(1 - P_0) + \left(1 - e^{-(\theta_\delta - \delta - T_p + B_\gamma)/C}\right) P_0. \end{aligned} \quad (11)$$

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 $T_p = 1.562$ ns, B and C are 6.5757 and $1.375e^{-11}$ respectively; and $\gamma = \theta_\rho.\sqrt{SNR_p}$.

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

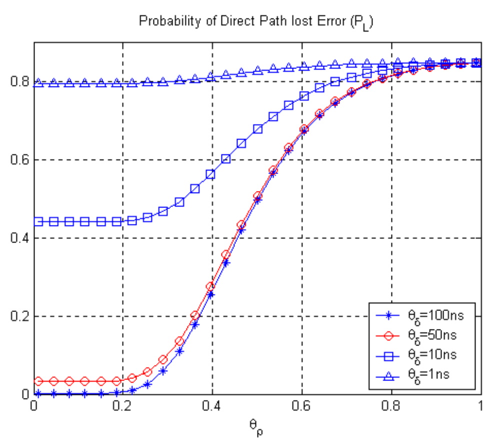

Fig.2: *Probability of a direct path lost error (PL) with a peak SNR of 18 dB.*

Fig. 3 shows the probability of false matched (PFM) with delay threshold (θ_δ) 100 nsec and different values of SNR, which shows that the ToA technique performance is proportion to SNR_p, as a result the probability of false matched direct path (PFM) will decreased.

Fig. 4 shows when the duration of the search region for the time of arrival of the direct path signal be limited, this will prevent the probability of false matched (PFM) 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 lost represent the receiver-operating characteristic (ROC) of the matched filter energy detector. The ROC curves indicate the tradeoff between false alarm and detection probability at different SNR's are plotted in Fig. 5. Generally the more concave the ROC curve, the better is the performance of the detector.

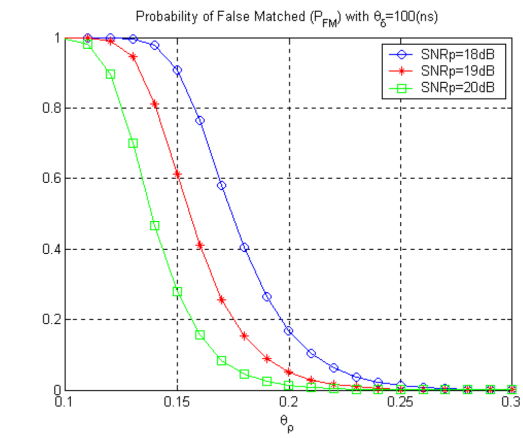

Fig.3: *Probability of false matched (PFM) with delay threshold (θ_δ) 100 nsec.*

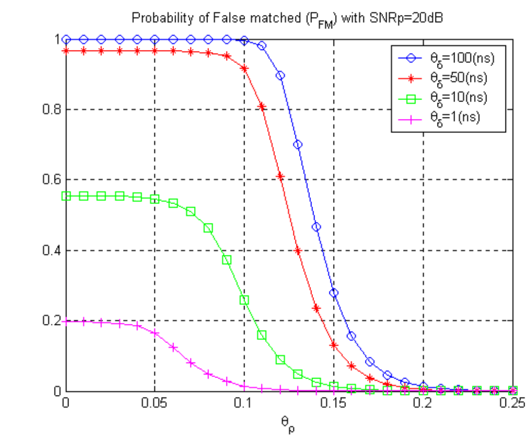

Fig.4: *Probability of false matched (PFM) with SNR_p = 20 dB.*

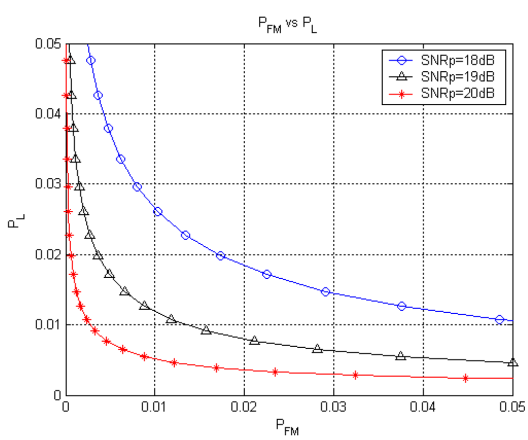

Fig.5: *False matched probability versus probability of direct path lost for different peak SNRs.*

4.2 Mean Acquisition Time

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 is given by

$$T_{acq}\left(n,j,k\right) = nT_d + jNT_d + kT_{fa} \qquad (12)$$

Hence, the mean overall acquisition time is

$$\overline{T}_{acq} = \sum_{n=1}^{N}\sum_{j=0}^{\infty}\sum_{k=0}^{K} T_{acq}\left(n,j,k\right)P\left(n,j,k\right), \qquad (13)$$

Where

$$P\left(n,j,k\right) = P\left(k|n,j\right)P\left(j|n\right)P\left(n\right) \qquad (14)$$

As a result

$$\overline{T}_{acq} = \sum_{n=1}^{N}\sum_{j=0}^{\infty}\frac{1}{N}\left(1-P_{DET}\right)^{j}P_{DET}\cdot$$

$$\sum_{k=0}^{K} P_{FA}^{k}\left(1-P_{FA}\right)^{K-k}\left(nT_d + jNT_d + kT_{fa}\right) \qquad (15)$$

Fig. 6 gives the mean acquisition time versus signal-to-noise ratio with different values for number of hypothesized phases, which shows the large number of hypothesized phases the large of mean acquisition time.

The normalized threshold, θ_ρ, sets the detection and false alarm probabilities, as well as the mean acquisition time. For Fig. 7 shown below, normalized thresholds of θ_ρ= 0.25, 0.50, and 0.75 are assumed.

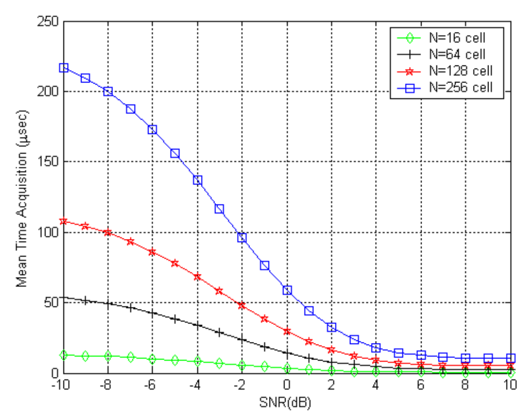

Fig.6: *Mean acquisition time for different number of hypothesized search cells, $\theta_\rho = 0.75$.*

The differences in Fig. 6 and 7 show the acquisition performance as a function of detection and false alarm penalty time (with different parameters for the receiver design). As the signal-to-noise ratio increases the numbers of detections increase and false alarms

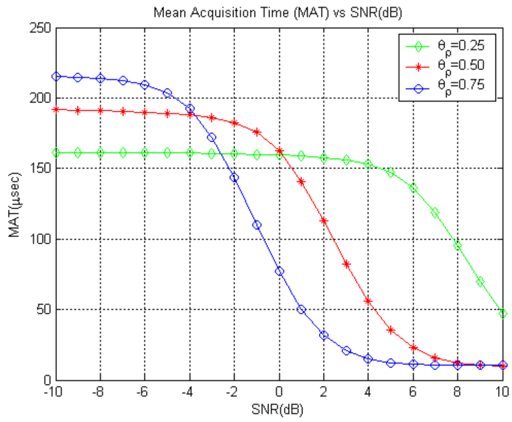

Fig. 7: *Mean acquisition time for different normalized signal strength threshold values.*

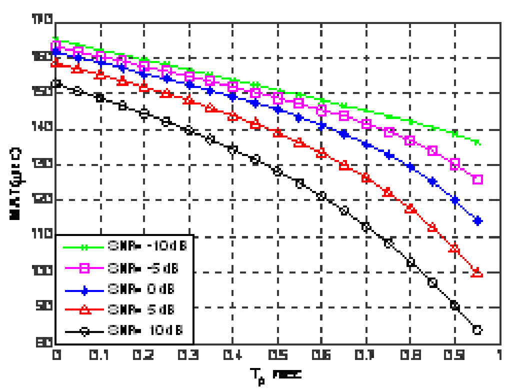

Fig. 8: *MAT versus pulse waveform width, with different SNR and $N = 265$.*

decrease, both graphs converge to the same mean acquisition time.

Fig. 8 shows the affects of pulse width in MAT with different values of SNR with $N = 256$ and $\theta_\rho = 0.50$. For short pulse width (e.g. high signal bandwidth); the large signal bandwidth results in very fine time resolution, increasing the number of phases in the search space of the acquisition system.

The thresholds, θ_ρ and θ_δ, which are used in MAT method have to be determined so that they meet the performance criteria. The two criteria false alarm and missed probabilities.

5. CONCLUSION

The target of this work is to design UWB ranging system with a decent multipath immunity for in indoor applications, i.e., smart home. A ToA based ranging scheme is adopted to detect direct path signal, which 93.12% probability of detection with 50 ns NLOS delays was achieved and only 25 cm ranging estimation error compared with 30 meters in GPS. The UWB ranging system is designed utilizing the ToA algorithm based on coarse synchronization scheme, serial search technique is considered and the performance measure is the mean time acquisition (MAT), which shows how the design of the correlation parameters affects the time to achieve synchronization.

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