ENHANCED POSITION LOCATION WITH UWB IN OBSTRUCTED LOS AND NLOS MULTIPATH ENVIRONMENTS

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ABSTRACT

We propose an enhanced directional beacon based position location procedure for UWB systems. Unlike previous work that relies on strongest return and therefore prone to errors in obstructed line of sight (OLOS) and non-LOS (NLOS) environments, our procedure identifies the LOS return by detecting the earliest arrival. To overcome synchronization problems, we propose a correlation based window algorithm to detect the earliest arrival and hence the LOS component across a 360° rotation of directional beacon. We extend the algorithm to non-LOS (NLOS) case and estimate position by minimizing the norm between the sets of measurements. To assess the performance over realistic UWB channels, we modify the UWB channel model to incorporate the effect of directional transmitting antennas. From simulation results we claim position location accuracy of around 34 cm with a pragmatic 4-element antenna array using 2.4GHz UWB pulses and 4-bit A/D converter at 24dB SNR.

1. INTRODUCTION

With the rise in need for seamless data connectivity and the role of automation in everyday life, WPAN (wireless personal area networks) are becoming increasingly popular. The standard for low speed WPAN (IEEE 802.15.4 [1]) is being revised and ultra wideband (UWB) has been proposed as the underlying physical layer communication technology. Among several other requirements, the revision of IEEE 802.15.4 standard requires more precise position location technique.

Position location in WPANs has found a number of applications that range from commercial and residential to public safety and military applications [2]. The position of a desired node can be determined in a variety of ways, such as Angle of Arrival (AOA), Time of Arrival (TOA), Time Difference of arrival (TDOA), or Received Signal Strength (RSS) [2]. However, the unique nature of the propagation environment of UWB signals poses certain challenges in position location.

The fine time resolution of UWB signals makes it more appropriate for position location systems. UWB signals have been employed in position location systems [3, 4, 5, 6]. Lee and Scholtz [3] proposed time of arrival based ranging technique using an UWB radio link. The ranging scheme utilizes generalized maximum likelihood and implements a search algorithm for the detection of direct path. In [4], a UWB based ranging method that utilizes TOA of the strongest path is investigated. We show in this work that ranging based on strongest path incurs severe errors in obstructed LOS environments. Use of directional beacons with UWB for position location was first evaluated by Chung *et. al* [5]. Multipath returns are poorly handled in the scheme and could lead to erroneous position location in realistic UWB channels. Our work is different from [5] in several aspects. Firstly, our scheme looks for the earliest arrival in order to determine the LOS component and does not rely on strongest arrival that deteriorates the performance, in general. Particularly in OLOS environments the use of earliest arrival to mark LOS component is more appropriate. Secondly, we propose a computation efficient scheme to eliminate the errors due to NLOS measurements. Thirdly, we consider a realistic UWB channel proposed for IEEE 802.15.3a [7] and modify it to account for directional transmitting antennas. Use of standard UWB channel model provides benchmarking results that can be compared with future studies on position location. We also evaluated the effect of practical concerns on the scheme like generation of directional beam.

The paper is organized as follows: Section 2 gives system details and outlines the localization principle. Section 3 presents the UWB channel model with proposed modification. The proposed algorithm to detect direct path component is discussed in Section 4 and the simulation results are provided in Section 5. Section 6 concludes the paper.

2. SYSTEM MODEL AND LOCALIZATION PRINCIPLE

2.1 The System Model

This section provides the details of the system model and localization principle used for UWB signals. Consider a situation where we need to obtain the position of node Q surrounded by three reference nodes RN-1, RN-2 and RN-3 as shown in Fig 1. In this paper, we are interested in determining the coordinates of Q, (x,y), relative to a specified origin. The reference nodes are capable of generating a UWB pulse periodically that will be transmitted using a directional antenna. The signal from reference nodes can be considered as *beacon* in radar terminology. We consider UWB pulses in the form of Gaussian monocycles and implement directional beam using M-element uniform linear antenna array as this is the simplest array structure to produce directional beams. The received UWB pulse can be written as

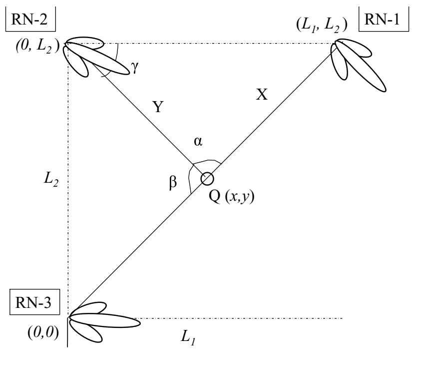

Figure 1: Arrangement of three beacon nodes

$$r(t) = w(t) \star h(t) \tag{1}$$

where $w(t)$ is the transmitted UWB pulse and $h(t)$ is the channel model that will be discussed in detail in Section 3. The UWB receiver needed for the proposed scheme is simply a filter matched to $w(t)$ followed by a comparator to detect the peaks.

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2.2 Localization Principle

The beacon signals are designed to enable node Q or any other node to determine its angular bearing with respect to the reference nodes. For this purpose, the reference nodes need to change their beam direction such that the beam from each reference node will be pointed to node Q once in a complete rotation. A rotational directional beam may be implemented by a directional antenna that is mechanically rotated, or it could be generated by an electronically steerable smart antenna [8]. It is necessary that the transmissions from different reference nodes is distinguishable, which may be achieved by using different pulse shapes for each beacon or by using a coded sequence of pulses. It is not important that the beacons from reference nodes should be pointing in the same direction at the start, however, there should be a constant angular separation (ϕ) between the directional beams.

The localization principle is based on observing the times when the node Q receives different beacon signals, and evaluating its angular bearings and location with respect to the reference nodes by triangulation [9]. If the times at which Q receives beacons from RN-1, RN-2 and RN-3 are t_1, t_2 and t_3, respectively, the bearings can be obtained as:

$$\alpha = \phi - \omega(t_2 - t_1) \quad \text{and} \quad \beta = \phi - \omega(t_3 - t_2) \tag{2}$$

where ω is the angular speed of the rotating directional beam in degrees/s and ϕ is a constant angular separation between the directional beams of reference nodes. From (2) it is clear that absolute timings are not required as we are dealing with time differences in calculating the bearings. Using simple trigonometry, it can be shown that the coordinates (x, y) of the node Q can be computed as

$$x = \frac{L_2 \cos\gamma}{\sin\beta}\cos(\beta - \gamma) \quad \text{and} \quad y = \frac{L_2 \cos\gamma}{\sin\beta}\sin(\beta - \gamma) \tag{3}$$

where

$$\gamma = \tan^{-1}\left(\frac{L_2 \cot\beta - L_1}{L_1 \cot\alpha - L_2}\right)$$

The symmetric arrangement of the reference nodes in Fig 1 leads to a simple relation in (2), however, the localization principle in (3) is valid for any arrangement of the reference nodes.

3. UWB CHANNEL MODEL

A distinguishing feature of UWB system is their ability to resolve multipath components of wireless propagation channel with extremely high time resolution. Based on measurements and statistical modeling several models have been proposed in the literature (see [7] for a list of contributions). For this paper we focus on the standardized UWB channel model for IEEE 802.15.3a [7] as it is claimed to better match the measurements. The model accounts for multipath as well as clustering phenomena. The impulse response of the channel model has the form

$$h(t) = X \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l}\, \delta(t - T_l - \tau_{k,l}) \tag{4}$$

where $\alpha_{k,l}$ and $\tau_{k,l}$ are the multipath gain and delay of the k^{th} ray in l^{th} cluster, respectively. T_l represents the delay of the l^{th} cluster and X indicates the log-normal shadowing effect. Detailed distribution functions of different variables in (4) can be found in [7].

The model reported in the standard deals with omnidirectional antennas. To incorporate the use of directional transmitting antennas, we first invoke the independence between time and angle of departures *i.e.*

$$h(t, \theta) = h(t)h(\theta)$$

where $h(\theta)$ accounts for the beam pattern of the directional antenna. Thus, we can write the channel impulse with directional transmitting antennas as

$$h(t, \theta) = X \sum_{l=0}^{L} \sum_{k=0}^{K} \chi(\theta - \theta_l - \psi_{k,l})\, \alpha_{k,l}\, \delta(t - T_l - \tau_{k,l}) \tag{5}$$

where $\chi(\cdot)$ refers to antenna beam pattern. θ is the angle of node Q, θ_l is the mean angle of the l^{th} cluster and $\psi_{k,l}$ is the angle of the k^{th} ray relative to the l^{th} cluster angle. All angles are measured according to a defined reference on the beam pattern.

Exploiting the symmetry, we propose that the angle of departures (AOD) of the rays (θ_l and $\psi_{k,l}$) can be statistically characterized using the AOA statistics reported in [10]. The clusters are modeled as uniformly distributed around the transmitter such that the mean angle of each cluster, θ_l, is a uniform random variable on the interval $[0, 2\pi)$. The ray angle within a cluster, $\psi_{k,l}$, is modeled as zero mean Laplacian distribution with standard deviation ζ. Fig. 2 shows a typical beam pattern for 4-element uniform linear antenna array. In Fig. 3, we show a single realization of UWB channel model 1 (valid for LOS case with 0-4 m distance) using directional antenna with pattern in Fig. 2. The figure shows each cluster individually and then their combined effect.

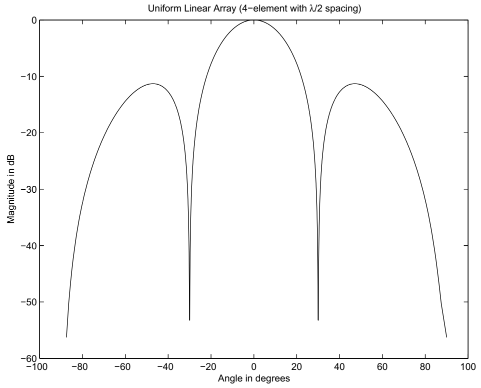

Figure 2: Beam pattern for 4-element antenna array

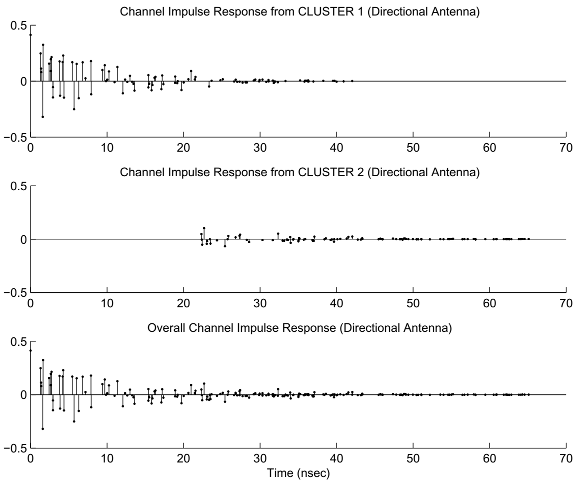

Figure 3: Impulse response of 3A UWB Channel Model 1 (Directional)

4. PROPOSED ALGORITHM

The proposed algorithm requires the detection of LOS component to mark the instant when the transmitting beam is aligned with the receiver. Due to the very nature of indoor multipath propagation environment the direct line of sight component gets either deteriorated or completely blocked [2]. The former situation is commonly termed as OLOS and the latter is known as NLOS. We pay attention to the two cases separately in the sequel.

4.1 Obstructed LOS (OLOS) Environments

To detect LOS component in OLOS environment - where the strongest arrival is not necessarily LOS - we rely on earliest arrival in case of perfect synchronization. To perform synchronization, we propose a correlation based window algorithm to detect the earliest arrival. Let's consider each case individually.

4.1.1 In case of perfect synchronization

The algorithm details for the system in Fig. 1 are as follows:

Step 1. Reference node RN-1 will transmit a UWB pulse while it's main beam is at angle φ_i measured from some reference.

Step 2. The receiver (node Q) uses a matched filter to detect the peaks of received multiple returns (multipath components of the transmitted pulse). At discrete time index n, the matched filter output is converted to

$$z_{\varphi_i}[n] = p_{\varphi_i}[n] + \eta[n]$$

where p_{φ_i} is the peak of the multipath return and η denotes the samples of AWGN.

Step 3. With perfect synchronization, the earliest arrival ($\mathscr{F}_{\varphi_i}$) from RN-1 at angle φ_i is the first detected peak, *i.e.*, $\mathscr{F}_{\varphi_i} = z_{\varphi_i}[1]$.

Step 4. Rotate the beam of RN-1 by $\Delta\varphi$ and repeat *Steps 2-3*. Store the time and amplitude information of first arrivals for one complete rotation of the beacon ($0 \leq \varphi_i \leq 2\pi$) in $f[n]$, *i.e.*,

$$f[n] = \sum_{i=0}^{I-1} \mathscr{F}_{\varphi_i} \delta[n - n_i]$$

where $\varphi_i - \varphi_{i-1} = \Delta\varphi$ is the rotation step so called angular resolution of the directional beacon and I is the total steps needed by RN-1 to make one complete rotation. n_i is the time index of the first arrival when the main beam of RN-1 is pointing at φ_i. Clearly, $n_0 = 1$.

Step 5. Determine the maximum absolute value of $f[n]$ that represents the instant when the beacon from RN-1 is aligned with the receiver, *i.e.*,

$$n' = \arg\max |f[n]| \quad \text{and hence} \quad t_1 = n' T_s$$

where T_s is the sampling time.

Step 6. Repeat the above steps for other reference nodes to obtain t_2, t_3 and so on. Finally, use (2) and (3) to obtain the coordinates of node Q .

4.1.2 In case of imperfect synchronization

The receiver is said to be synchronized if the first arrival is received at $n = 1$. In order to synchronize, we need to find the length of time-slot that corresponds to the reception of all the returns for a single pulse transmission from RN-1. Let W denotes the length of the time slot that has support in discrete time $n \in [n_a, n_b]$ such that $W = n_b - n_a$. Once synchronized the receiver will receive the first arrival at n_a. Here we describe the steps to get W, n_a and n_b.

Step 1. Store a few detected peaks $z_{\varphi_i}[n]$ for $i = 1$ to 5, and form a concatenated vector $Z = [\underline{z}^T_{\varphi_1}, \underline{z}^T_{\varphi_2}, \cdots, \underline{z}^T_{\varphi_5}]$

Step 2. To get W, calculate the autocorrelation of Z. The autocorrelation will be a periodic sequence with period W. Thus, the separation of the first two consecutive peaks of the autocorrelation gives the window size (W).

Step 3. To mark the start of the window, n_a, we will make use of the rms delay spread (τ) of the channel[1]. For $n > n_a + \tau$ the received signal strength is almost zero. With this condition we can properly mark the start of the window at $n = n_a$ and hence achieve the synchronization. It is important to note that the transmission from the transmitting beacon that occurs in discrete time intervals need to be adjusted appropriately so that $W \gg \tau$.

Step 4. After synchronization, repeat *Step 1-6* of Sec 4.1.1 to estimate the position.

4.2 NLOS Environments

In case of NLOS, the receiver makes erroneous estimation of position due to the biased measurement of time of arrival. Here we consider the scenario when NLOS measurements exist with a few LOS measurements. For instance, consider five reference nodes (RN-1 to RN-5) located around node Q whose position is required. From the discussion in Sec 2.2 it follows that the position of Q can be determined by using any three consecutive reference nodes (*e.g.* RN-1,2,3 or RN-2,3,4 or so on). This results in five possible sets of consecutive reference nodes ($\{1,2,3\}$,$\{2,3,4\}$,$\{3,4,5\}$,$\{4,5,1\}$,$\{5,1,2\}$) and in turn five possible estimates of the position of Q. If we assume that all the reference nodes have LOS except RN-2 then this leads to biased measurement of t_2 as obtained from *Step 5* of Sec 4.1.1. It is obvious from (2) that an error in t_2 will render incorrect bearings α and β. Thus, the estimation of position from the set of reference nodes $\{1,2,3\}$ that uses α and β will be incorrect. Similarly, the position estimates from sets $\{2,3,4\}$ and $\{5,1,2\}$ are also incorrect as they use β and α, respectively. However, for this particular case, the estimates of position from sets $\{3,4,5\}$ and $\{4,5,1\}$ will be similar except for the error due to additive noise. The simulation results of this scenario are presented in Sec 5. In general, with N reference nodes we can form N subsets of measurements from three consecutive reference nodes. Each subset will lead to an estimate of position such that the biased measurements of TDOA or bearings, due to NLOS, result in different estimates and cause ambiguity in position location.

To resolve the ambiguity from NLOS measurements, our algorithm requires at least two subsets of LOS measurements which in turn need four consecutive reference nodes with LOS component. In general, out of N reference nodes at most $N - 4$ can have NLOS component. Since the estimates of position from each subset are different except for the ones that have LOS. We propose a computation efficient technique to distinguish between the LOS and NLOS estimates by observing the fact that the estimates from LOS measurements lie close to each other as compared to the estimates from NLOS measurements. The property is elaborated in Fig. 5. To quantify the proximity of estimates we use vector norm, *i.e.*, if $(\hat{x}_i, \hat{y}_i)$ and $(\hat{x}_j, \hat{y}_j)$ are the position estimates from two consecutive sets of bearing measurements then norm is defined as

$$||\mathscr{N}_{i,j}||^2 = (\hat{x}_i - \hat{x}_j)^2 + (\hat{y}_i - \hat{y}_j)^2$$

The estimate of the position is the arithmetic mean of the pair with minimum norm, *i.e.*,

$$(\hat{x}, \hat{y}) = \left(\frac{\hat{x}'_i + \hat{x}'_j}{2}, \frac{\hat{y}'_i + \hat{y}'_j}{2} \right) \quad \text{where} \quad (\hat{x}'_{i,j}, \hat{y}'_{i,j}) = \min_{(\hat{x}_{i,j}, \hat{y}_{i,j})} ||\mathscr{N}_{i,j}||$$

Use of directional beacons for position estimation in NLOS environments provides an inherent advantage over TOA techniques. In TOA schemes, a small error in time acquisition produces quite large error in position location because of high propagation speeds ($\Delta d = c\Delta t$ where $c = 3 \times 10^8$ m/s is the speed of electromagnetic wave). For directional beacons, it can be shown that an error in time acquisition translates into error in angles (see (2)) that causes error in position estimation but with much less severity.

5. SIMULATION RESULTS

The performance of the proposed UWB position location system using directional beacon is evaluated by computer simulations. We assume a scenario depicted in Fig. 1 with $L_1 = L_2 = \sqrt{32}$ m. For simplicity, we set node RN-1, RN-2 and RN-3 at coordinates (L_1, L_2), $(0, L_2)$ and $(0, 0)$, respectively. For simulations, we used Gaussian monopulses with bandwidth 2.4 GHz and 4-bit A/D converter with sampling rate of 0.167 ns.

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[1] for UWB it's of the order of 50ns in indoor environment

The position location algorithm estimates the coordinates of node Q $(\hat{x},\hat{y})$ and obtain the algorithm's performance by computing the distance (ε) between the actual and the estimated coordinates *i.e.* $\varepsilon = \sqrt{(x-\hat{x})^2-(y-\hat{y})^2}$. To emphasize the importance of detecting direct path from earliest arrival we compare the results in Tables 1 and 2. Table 1 lists the estimated position and the error in position for LOS and OLOS environments when signal strength is used to detect the direct path. As discussed earlier, use of signal strength in OLOS environments incurs significant error in position. Table 2, that uses earliest arrival to detect the direct path, endorses the importance of the proposed scheme.

Fig. 4 shows the effect of AWGN on the performance of the algorithm. It also depicts the effect of number of antenna elements on the performance. For high SNR ($\sim$ 40dB) the error in position (ε) is as small as 30 cm for 2-element antenna system. The figure also shows that increasing the number of antenna elements from 2 to 4 results in reduced position error for all values of SNR, though the gain is more pronounced at low SNR.

For NLOS case, we simulate the scenario discussed in Sec 4.2 where we consider five reference nodes such that four of them possess LOS component and one reference node is deprived of LOS component. From the five time measurements (t_1,t_2,t_3,t_4,t_5) bearings are computed and used to estimate the position of node Q. As explained in Sec 4.2, the estimates from three measurement subsets are biased while the other two subsets produce very close estimates as shown in Fig. 5. The final coordinates of node Q are calculated using the method outlined in Sec 4.2 and are listed in Table 2.

Table 1: Position location based on strongest received pulse [original coordinates = $(2.828, 2.828)$, M=4, SNR = 24dB]

Environment	Estimated Coordinates	Avg Range Error
LOS	(2.98, 2.52)	34.4 cm
OLOS	(-1.22, -2.66)	682 cm

Table 2: Position location based on proposed algorithm [original coordinates = $(2.828, 2.828)$, M=4, SNR = 24dB]

Environment	Estimated Coordinates	Avg Range Error
LOS	(2.98, 2.52)	34.4 cm
OLOS	(3.01, 3.12)	34.4 cm
NLOS	(3.12, 2.64)	34.7 cm

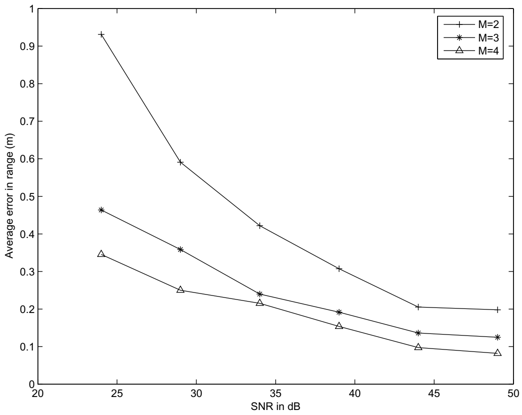

Figure 4: Error in range for M=2,3 and 4

6. CONCLUSION AND FUTURE WORK

We proposed a directional beacons based position location scheme for UWB systems in OLOS and NLOS multipath environments. Different from the previous works, we proposed LOS detection through earliest arrival. Correlation based window algorithm to detect the earliest arrival and hence the LOS component is devised to overcome synchronization problems. We evaluated the performance over realistic UWB channels that were modified to incorporate the effect of directional transmitting antennas. Simulation results demonstrate the robustness of the algorithm for OLOS and NLOS environments. The accuracy of the proposed algorithm depends on beamwidth, though considerable accuracy ($\approx$34 cm) in position location can be achieved with 4-element antenna array. In future, we would like to determine the effect of angular resolution and width of the rotational beam on the system performance.

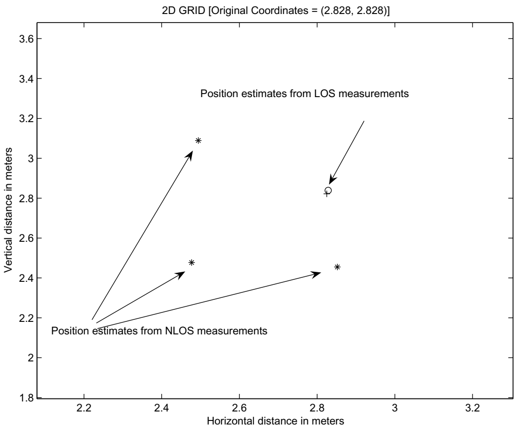

Figure 5: 2D Grid showing position estimates in NLOS case

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