Accuracy Enhancement for UWB Indoor Positioning Using Ray Tracing

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Abstract—An ultra-wideband (UWB) system is known to be a viable solution for accurate positioning in dense multipath environments because of the exceptionally fine time resolution of the signal. However, the presence of a line-of-sight (LoS) blockage can degrade the positioning accuracy for two reasons. Firstly, it makes estimation of the time of arrival (ToA) of the direct path signal difficult by complicating the multipath structure of the propagation channel. Secondly, the higher dielectric constant of the LoS blocking material than that of free space introduces excess propagation delay which will bias the range estimation. In this paper, methods based on ray tracing to reduce the ranging error resulting from the second reason are posed. We take two different approaches; a statistical approach and a map-aided method. In the statistical approach, we establish a conditional distribution of the excess propagation delay caused by LoS blockages using a ray tracing technique. The lower bound of the ranging performance based on this model is estimated. The ray tracing method is also used for the map-aided ToA positioning approach. UWB propagation measurement data taken in an office environment is used to examine the performance of this method.

Index Terms—Ultra-wideband (UWB), ranging, ray tracing, delay estimation, multipath channel

I. INTRODUCTION

Accurate position location is one of the promising applications of ultra-wideband (UWB) radio. Technical issues with UWB ranging and positioning have been identified and discussed by several researchers [1]-[6]. Most research so far has focused on the method for time of arrival (ToA) estimation of the direct path signal which is a key technique for accurate ranging. Another issue is the potential ranging error caused by the line of sight (LoS) blockage material, which was identified in [1] and [7]. In non-LoS channels, the shortest path between the transceivers might be longer than the actual range due to refraction. Furthermore, the propagation speed of the signal is generally lower inside a lossy medium than that in free space. For these reason, excess propagation delay is introduced in non-LoS propagation, which gives a range estimation error.

To tackle this problem, we used a ray tracing method. Ray tracing has been widely used for indoor channel characterization as well as localization [8]-[10]. We developed a path-tracer which has a capability to find the potential shortest path between the transceivers. Here, we used path simulator in a map-aided method as well as to establish a statistical model.

II. SIMULATOR DESIGN

We designed a two-dimensional path-tracer which has a capability to find the potential shortest path between transceivers in non-LoS environments. An iterative polar search using a bisection method [11] is performed to identify the shortest path and once it is found, the excess propagation delay can be calculated. Material constants such as the dielectric constant are embedded in the simulator. All dielectric interfaces are assumed to be plane surfaces. When a ray traveling through medium 1 encounters medium 2, refraction occurs, expressed in the statement [12]

\[
\frac{\sin \theta_2}{\sin \theta_1} = \sqrt{\frac{\varepsilon_2}{\varepsilon_1}},
\]

(1)

where \(\theta_1\) and \(\theta_2\) represent angles of incidence and transmission, respectively. Parameters \(\varepsilon_1\) and \(\varepsilon_2\) denote the dielectric constants of materials 1 and 2, respectively. It was assumed that the propagation speed, \(v\), of the signal inside a dielectric
medium with a dielectric constant of $\epsilon$ is given by [13]

$$v = \frac{c}{\sqrt{\epsilon}},$$

(2)

where $c$ is the speed of light. We also took critical reflection into account, which is known to occur when [13]

$$\epsilon_1 > \epsilon_2, \quad \theta_1 > \sin^{-1}\left(\sqrt{\frac{\epsilon_2}{\epsilon_1}}\right),$$

(3)

is satisfied. Fig. 1 shows an example of path tracing. The line between nodes a and b represents the potential shortest path between them found by polar search.

To verify the credibility of the algorithm used in the simulation, we made a set of through-wall propagation measurements. Measurements were taken using an Anritsu’s vector network analyzer and an UWB antenna set made by Skycross, Inc., whose passband is approximately 2 GHz to 8 GHz. Transmitting and receiving antennas were hooked up to the two ports of the vector network analyzer, positioned on tripods, approximately 5 feet above the floor. The $S_{21}$ parameter was measured, which represents the transfer function of the antenna system, which describes the successive transfer of signal from the transmitting antenna, through the propagation channel, to the receiving antenna. Fig. 2 shows the measurement plan. The receiving antenna was fixed and the transmitting antenna was moved on a linear path such that each angle of incidence would be increased by 5 degrees. Measured frequency response was converted to time domain response by taking an inverse Fourier transform after which the time of the earliest arrival was measured. Simulated and measured ToA of the earliest arrival is compared in Fig. 3.

### III. A Statistical Approach

In this paper, we assume it is possible to measure the ToA of the earliest arrival exactly. In other words, it is assumed that ranging error is only caused by an excess propagation delay. The propagation time, namely $\tau$, between transceivers is given by

$$\tau = \frac{r}{c} + \chi,$$

(4)

where $r$ is range between the transceivers and $\chi$ is the excess propagation delay. We can apply various statistical estimation methods once the statistics of $\chi$ is available. We used the simulator introduced in the previous section to establish a statistical model for $\chi$. Floor maps of 5 different buildings were used for the simulation and Fig. 4 shows one of them.
which is the floor plan of the Jesus hospital. We assumed the indoor structure consists of materials listed in table I. The points on the map represent potential node locations, and all such locations are separated by at least 1.5 m. The potential shortest path between the transceivers were traced for every possible combination of point-pairs that showed a non-LoS path. Pairs of nodes more than 30 m apart were discarded. The iterative polar search process was stopped once the end point falls within a 5 cm range. Paths including critical reflection was also discarded.

Fig. 5 shows normalized histograms of simulated excess delay. The conditional density of $\chi$ given range can be modeled as a lognormal density, that is

$$f_{\chi|r}(\chi|r) = \frac{1}{\sigma(r)\sqrt{2\pi}\chi} \exp \left[ - \left( \frac{\ln \chi - \mu(r)}{2\sigma^2(r)} \right) \right].$$  \hspace{1cm} (5)$$

Parameters $\sigma(r)$ and $\mu(r)$ are functions of range and can be modeled as

$$\sigma(r) = a_1 r + b_1, \hspace{1cm} (6)$$

$$\mu(r) = a_2 \ln r + b_2, \hspace{1cm} (7)$$

where $a_1 = -0.0062$, $b_1 = 0.68$, $a_2 = 1.17$, and $b_2 = -22.10$. Assuming that the excess propagation delay is the only cause for ranging error, the Cramer-Rao lower bound (CRLB) of error variance, namely $\sigma^2$, is computed as

$$\sigma^2 \geq \frac{1}{E \left[ \left( \frac{\partial}{\partial \tau} \ln f_{\tau|r}(\tau|\tau) \right)^2 \right]},$$

where

$$f_{\tau|r}(\tau|\tau) = f_{\chi|r} \left( \tau - \frac{r}{c} \right).$$

The CRLB of standard deviation of the range estimation error is shown in Fig. 6.

IV. MAP-AYED APPROACH

The path-tracer introduced in section II can be also used for map-aided indoor positioning. We tested the feasibility of this technique using a set of swept frequency propagation measurement data. The measurements were taken with the same experimental setup described in section II. Fig. 7 is the floor plan of the 3rd floor of the Electrical Engineering building, Handong University, where measurements were taken. Signals were measured at 2 different locations with the transmitting antenna being placed at 3 different locations, which are assumed to be those of known reference nodes. The signal propagation time was calibrated using a LoS measurement at 2 meters. The location of each mobile node was estimated using a ToA-based positioning algorithm. Fig. 8 and Fig. 9 show the trajectories obtained using the measured propagation time from each reference node with and without considering the presence of LoS blockages. The position of the mobile node was estimated according to least square error criterion. We can notice that the positioning error is considerably improved by ray tracing.
V. CONCLUSIONS

The CRLB obtained in section III provides a measure of the effect of excess propagation delay on ranging accuracy. Considering the inherent range resolution of an UWB signal, it can be an important limiting factor for accurate ranging. The statistical model presented here is based on simulation results. A model for excess delay based on measurement data would enable more sound estimation approaches. Considerable accuracy improvement was observed in the map-aided positioning experiment. A more novel path tracing would be possible by considering propagation effect on a non-plane surface.

REFERENCES