A Realtime Testbed for Performance Evaluation of Indoor TOA Location System

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***Abstract*—Performance evaluation is an essential step in the development and deployment of an indoor TOA location system, in order to see the influence of multipath condition on ranging and localization accuracy. For field testing approach, multipath condition is invisible, uncontrollable and unrepeatable. Also it is usually not convenient due to system deployment. This paper presents a multipath visible, controllable and repeatable realtime testbed for indoor TOA location performance evaluation, based on RF channel emulator and Ray-tracing software. The testbed can provide accurate performance evaluation in specific indoor environments or specific multipath conditions without deployment. We evaluate the performance of an IEEE 802.15.4a Standard location system in typical office building with this testbed. The result was compared with the performance obtained in field testing to validate the feasibility of the testbed approach.**

Keywords-Time of Arrival; TOA; indoor localization; testbed; performacne evaluation;

I. Introduction

Position is one of the most important properties of an object. Outdoor location system, such as GPS, has already widely applied in transportation, public safety and military applications [1, 2]. Indoor location system can be widely used to tracking people or facilities in warehousing, airport, museum, factories and underground urban structures or inside disaster areas and underground mines. It is also an important assistive technology of some emerging technologies, such as body area network, which can improves health care by remotely monitoring the physiological characteristics[3].

Since GPS cannot work properly in indoor area, wireless indoor location became a popular research topic. Time-of-arrival (TOA) is the most frequently used distance measurement method for achieving accurate indoor localization by measuring the flight time of waveform between transmitter and receiver [2,8]. Serious multipath condition caused by reflection and blockage in indoor area is the major challenge of TOA-based indoor location system. The fading of the direct path signal and the combining among multipath signals cause the difficulty of the measurement on the flight time of the direct path pulse between transmitter and receiver, which represents the exact distance[12]. A number of TOA ranging algorithms, TOA devices and localization algorithms were developed to address this problem. The realtime performance evaluation of TOA-based indoor location system, is a serious challenge for system designers, due to the wide variety of multipath conditions, the diversity and complexity of the algorithms for implementation of the systems, and the challenges in creating visible, controllable and repeatable multipath conditions.

The current methods for evaluating TOA ranging and localization performance are software simulation [5][14] and field testing [4][13]. It is hard to achieve accurate performance using software simulation, due largely to the difficulties in simulating the influence of device and system implementation. In particular, software simulation cannot be used to evaluate the performance of most commercial devices and systems, since the implementation details are not open to the user. Field testing provides the performance similar to real application. But the multipath condition in field testing is invisible and uncontrollable. Therefore the influence of multipath cannot be exactly estimated in field test, which is very important to the research and development of TOA devices and TOA-based indoor location system. In addition, field test is not convenient to shift the deployment for evaluating the performance in multi environments.

In this paper, we present a hardware based realtime testbed for performance evaluation of indoor TOA location systems. In this testbed, multipath condition and waveform propagation is emulated by a RF channel emulator based on the impulse response channel model, in which, the multipath condition is visible, controllable and repeatable. The specific multipath condition in test filed is simulated by a Ray-tracing software, which produces the specific impulse response channel model between the transmitter and the receiver based on the floor plan of the building and the positions of the transmitter and receiver. With this testbed, the performance of TOA-based indoor location system can be evaluated accurately in visible and controllable multipath conditions without physical deployment in the application field.

The remainder of this paper is organized as follows. Section II describes the design of the testbed and the implementation of a testbed for IEEE 802.15.4a [8] based location systems. Section III validates the testbed by evaluating the ranging and localization performance in typical application scenarios. Section V presents our conclusions and comments on future work.

II. Testbed Design and Implementation

For TOA-based indoor location system, ranging accuracy and localization accuracy in specific multipath conditions or specific application scenarios are the most important performance to the system designers. This testbed allow precise ranging and localization performance evaluation of a TOA-based indoor location system in visible, controllable and repeatable multipath conditions and scenarios. In this section overall architecture of the testbed is described first, and then, the implementation of a testbed for IEEE 802.15.4A based TOA location system is introduced.

A. Overall Arictheture

In TOA-based location system, ranging accuracy and localization accuracy is sensitive to multipath conditions between Tag and Base stations (BSs) and the implementation of the system. Multipath conditions depend on the architecture of the building and the positions of Tag and BSs. The implementation of the system includes the implementation of TOA devices, localization protocol and localization algorithm [4]. To achieve the precise ranging and localization performance in controllable and repeatable multipath conditions, the overall architecture of the testbed is designed as Fig.1. The core of the testbed is the RF channel emulator, which can emulate multichannel simultaneously using impulse response channel model. Ray-Tracing is instrumented to produce the site-specific impulse response channel model between Tag and BSs, which is emulated by RF channel emulator, according to the floor plan of the building and positions of Tag and BSs. Tag, BSs and Location Engine constitute the location system to be evaluated. Distance and Position Error Statistics can be evaluated after ranging and location data are gathered.

The RF channel emulator [7] utilizes the impulse response method to emulator the process of radio waveform propagation in wireless channel as follows: The RF input signal is down-converted to analog complex baseband signals; These signals are filtered, then converted to digital format using A/Ds; The multipath fading and simulation and summing of impulse components are done with DSP technology; The resulting fading signal is D/A-converted and up-converted to the original RF frequency. By combining different types of fading with the impulse response channel model, the channel emulator can emulate radio waveform propagation for a wide range of application environments. Since the input and output signal of channel emulator are both RF signals, Tag and BSs of the location system can be connect to the channel emulator by RF cable instead of antennas without any further change. Therefore the influence of system implementation is accounted for exactly.

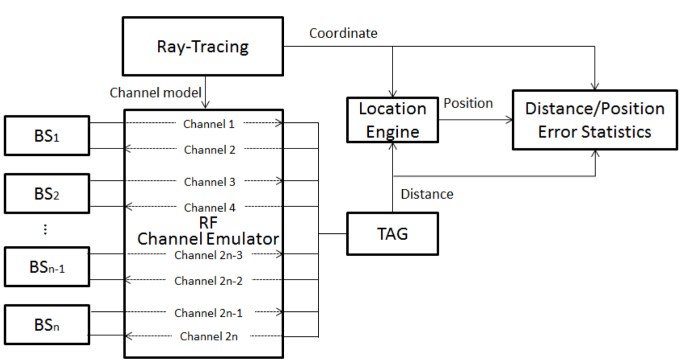


Figure 1. Architecture of the testbed

Ray-Tracing[6][13] is one of the most accurate site-specific algorithms available to predict radio waveform propagation in indoor environments. According to the building floor plan , the reflection and transmission coefficients of each wall, the positions of transmitter (Tx) and receiver (Rx), Ray-Tracing constructs the site-specific impulse response channel model between the Tx and Rx, based on the number of arriving paths, their respective amplitudes, delays and phases. It can also include details of the test environment, such as tables, cabinets, , etc. The influence of multipath and blockage is accurately included in the channel model produced by Ray-tracing. Since Ray-Tracing can only provide the channel model for one instantiation of a dynamic channel, to achieve needed statistical accuracy, we combine each channel model with Rayleigh fading, which is the typical type of fading in indoor wireless propagation. The positions of the BSs and Tag can be set manually in Ray-Tracing software.

Because the emulated channel model of RF channel emulator and is the visible and controllable, the floor plan of the building and the positions of Tags and BSs are also editable, the location system runs in controlled multipath condition and physical scenario, which is defined before performance evaluation.

B. Implementation

Figure 2 shows the testbed for an IEEE 802.15.4a standard-based indoor location system, which includes PlaceTool, PROPSim C8 and StarLOC[9]. PlaceTool[6] is a 2D Ray-Tracing software developed by the Center of Wireless Informantion Network Studies (CWINS) at Worcester Polytechnic Institute (WPI). Figure 3(a) shows the user interface of PlaceTool and Figure 3(b) shows the impluse reponse channel model of PlaceTool. PROPSim C8[7] is a real-time wideband multichannel emulator produced by Elektrobit. StarLOC is TOA-based indoor location system, which is develped by Microarchitecture and IC design laboratory (MICL) at University of Science & Technology Beijing (USTB) using IEEE 802.15.4A standard TOA RF chip, NanoLOC. The hardware of StarLOC node is shown in Figure 2. The TOA ranging algortihm and localization algorithm used in StarLOC will be introduced in the Section III and the details of the implementation of the StarLOC is introduced in our previous work [4, 9].

In this testbed, PROPSim C8 converts the input signal to output signal according to[7] :

$$y(t) = x(t) \otimes h(t) \tag{1}$$

where $y(t)$ is the output baseband signal, $x(t)$ is the input baseband signal, and $h(t)$ is the impulse response channel model.

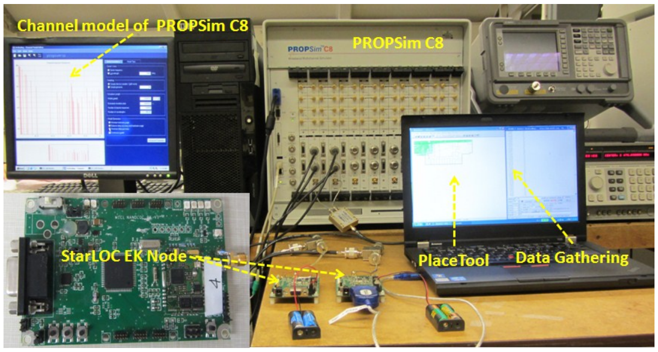
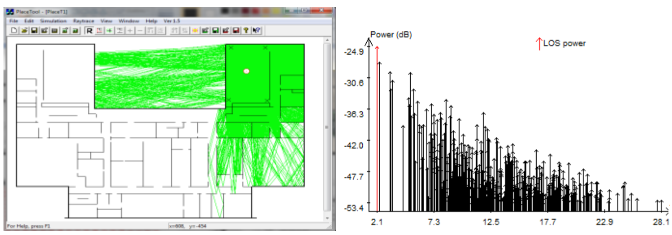


Figure 2. Testbed for IEEE 802.15.4A Standard TOA location system



(a) Uer interface of PlaceTool (b) impulse response channel model

Figure 3. PlaceTool

The channel model produced by PlaceTool is transformed to the impulse response channel model, which is the standard channel model of PROPSim C8:

$$h(t,\tau)=\sum_{i=1}^{L}\beta_i(t)e^{j\phi_i(t)}\delta[\tau-\tau_i] \tag{2}$$

where $\beta_i(t)$ and $\phi_i(t)$ represent the amplitude and phase of the i^{th} path arriving at delay τ_i.

PROPSim C8 applies Rayleigh fading to each channel impulse according to the channel model given by PlaceTool. The probability density function of Rayleigh fading is given by:

$$P(r)=\frac{r}{\sigma^2}\exp\left(-\frac{r^2}{2\sigma^2}\right) \tag{3}$$

where $P(r)$ is the probability density, r is amplitude of the impulse and σ^2 is known as the fading envelope of the Rayleigh distribution and is set at 0.5.

III. Validation

In this section, we use the testbed for the performance evaluation of an IEEE 802.15.4a recommended device in a typical office building at the Atwater Kent Laboratories, WPI. The ranging and localization accuracy from the testbed are compared with the results of actual field test with the same deployment to demonstrate the feasibility of this approach for performance evaluation of TOA-based indoor location systems.

A. *Evaluated System*

In StarLOC, Two-Way ranging (TWR) TOA algorithm [2, 6, 7], which is illustrated in Fig. 4, is used to estimate distance between two nodes. The distance is given by:

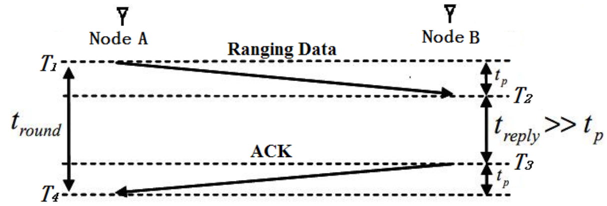


Figure 4. Principle of TWR TOA

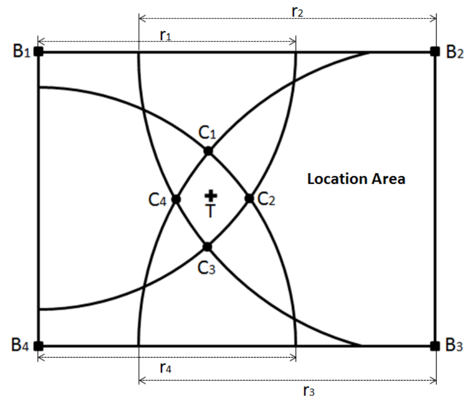


Figure 5. Trilateral-Centroid localization algorithm

$$\hat{d}=t_p\times C=\frac{t_{round}-t_{reply}}{2}\times C=\frac{(T_4-T_1)-(T_3-T_2)}{2}\times C \tag{4}$$

where $\hat{d}$ is the measured distance, t_p is the flight time of radio waveform between Node A and Node B , and C is the speed of radio waveform propagation in air. T_1 is the T_4 The T_1 denotes the time that Node A sends the ranging waveform, T_2 is the time Node B receives ranging waveform, T_3 is the time Node B sends the acknowledgement (ACK), and T_4 is the time Node A received ACK.

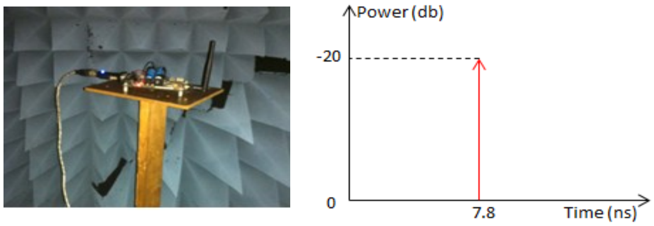
Trilateral-Centroid localization algorithm, as illustrated in Fig. 5 is used to localize Tag. As shown in Fig. 5, L is the location area; B_i is BS$_i$ in the location area; r_i is the estimated distance between Tag and B_i ; R_i is a circle with B_i at its center and r_i as its radius. Assume Tag ranging with n BSs in within the location area. Since the ranging error magnitude with StarLOC must be larger than 0m, the Tag's calculated coordinate is defined as follows:

$$(\hat{x},\hat{y})=Centroid\ of\{L\cap R_1\cap R_2\cap\ldots\cap R_n\} \tag{5}$$

As shown in Fig. 5, Tag's calculated position (T) is the centroid of area $C_1C_2C_3C_4$.

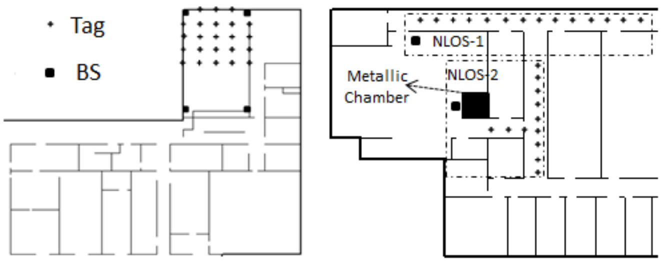
B. *Scenarios*

In this subsection, the typical test scenarios of TOA-based indoor location system, which are Free space, Line of Sight (LOS) and Non-line of sight (NLOS), are defined for both testbed approach and field test approach. The ranging accuracy is evaluated in all three scenarios and the localization accuracy is evaluated in LOS scenario.



(a) (b)

Figure 6. Scenario of free space



(a) (b)

Figure 7. LOS and NLOS scenarios

In Free Space scenario, a Tag and a BS are deployed at a separation of 2.34m. In field test, the nodes are deployed in an anechoic chamber, as shown in Fig. 6 (a). The corresponding channel model emulated in testbed is shown Fig. 6 (b). In LOS scenario, as shown in Fig. 7 (a), 4 BSs are deployed in the corners of a classroom located on the second floor of Atwater Kent Laboratory and Tag is deployed in 25 locations to evaluate both ranging accuracy and localization accuracy. In NLOS scenario, as shown in Fig. 7 (b), two conditions of NLOS are define on the third floor of Atwater Kent Laboratory. In NLOS-1, the Tag and the BS are separated by an office wooden wall. In NLOS-2, the Tag are separated from the BS by a metal-walled chamber, which cuts off the direct path.

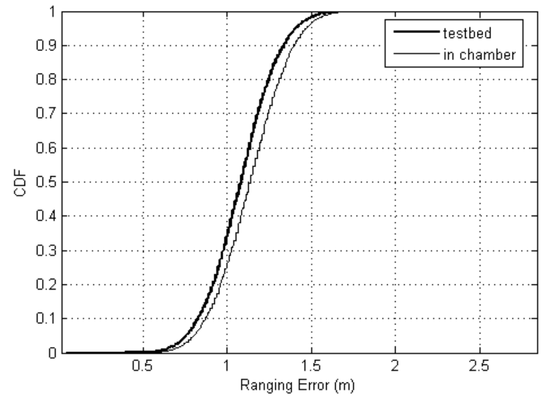
C. *Results*

1) *TOA ranging accuracy*

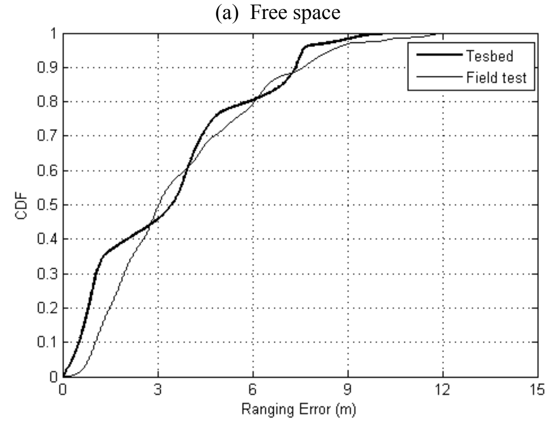
Ranging error is defined as follow:

$$e_R = \hat{d} - d \tag{6}$$

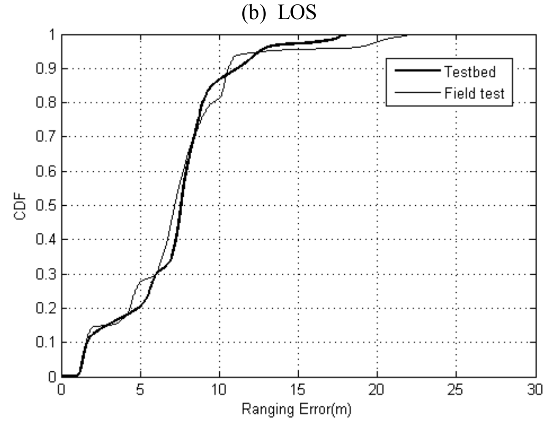
Fig. 8 (a) through (d) compares the CDF of ranging error obtained from the evaluation experiment with testbed and actual measurement in field test. From these comparisons, we can see that the ranging error distributions observed in the testbed results are very similar to those observed in the field test results. Table I shows the mean and standard deviation observed in each of these tests. From Table I we can see that the means and stand deviations found in the testbed results are also similar to those found in the field test results. Both the results of testbed and field test clearly indicate the ranging accuracy variation observed in different test scenarios, as the multipath condition changes. From the result of Free Space case, we can see that the best resolution obtainable with the StarLOC node in non-multipath condition. The influence of multipath caused by reflection to the ranging accuracy can be figured out by comparing the ranging error of LOS case with ranging error of Free Space. We can also see the influence of



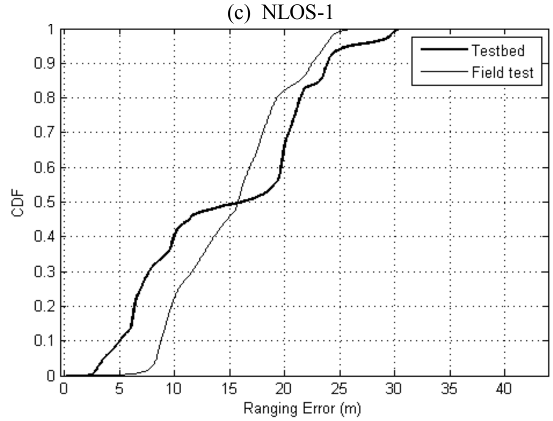
(a) Free space



(b) LOS



(c) NLOS-1



(d) NLOS-2

Figure 8. Comparison of ranging accuracy

the wooden wall and the metallic chamber to the ranging accuracy by comparing the ranging error of NLOS-1 and NLOS-2 with Free Space and LOS.

2) TOA localizaiton accuracy

Localization error is defined as follows:

$$e_L = \sqrt{(\hat{x} - x)^2 + (\hat{y} - y)^2} \quad (7)$$

where e_L is the localization error, $(\hat{x}, \hat{y})$ is the Tag's calculated coordinate location and (x, y) is Tag's actual coordinate location.

Fig. 10 compares the CDF of localization error observed in the testbed and field test results. Table II compares the mean error, stand deviation and 90% error between the testbed and field test results. The distribution of localization error obtained from the tesbed shows close agreement with the results of the field tests.

IV. CONCLUSION AND FUTURE WORK

Performance evaluation is an essential step in the development and deployment of an indoor TOA localization system, in order to verify that the system can meet the requirements. It is difficult to achieve exact performance using software simulation, due largely to difficulties in simulating the influence of device and system implementation. To address these problems, we have designed a controllable and repeatable realtime testbed for indoor TOA location performance evaluation. The testbed provides accurate performance evaluation for specific indoor environments, including a variety of realistic propagation situations, without the need for actual system deployment. Our testbed provides controllable and repeatable test scenarios, thus helping the researcher and developer to better understand the sources of location estimation error and to improve the performance of the localization algorithms, devices and systems. Our performance evaluation experiments using StarLOC validate the testbed. From the test result, we can clearly see the localization performance achievable in different scenarios. Comparisons made between the testbed results and field test results show excellent agreement.

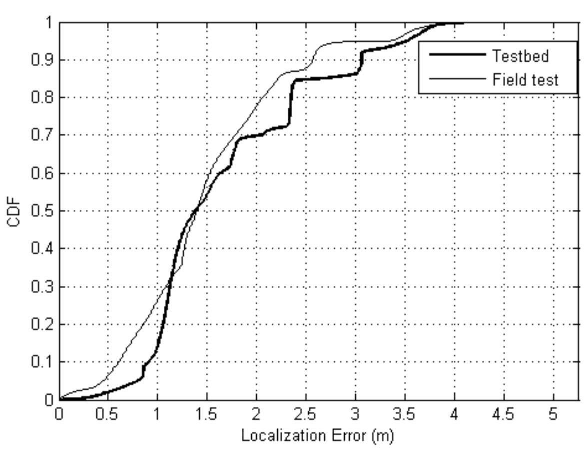


Figure 9. Comparison of localization accuracy

TABLE I. RANGING PERFORMANCE COMPARISON

Channel Condition		Free space	LOS	NLOS-1	NLOS-2
Field test	Mean(m)	1.13	3.70	7.22	15.25
	Std deviation(m)	0.65	2.58	3.97	4.96
Test-bed	Mean(m)	1.08	3.32	7.22	14.66
	Std deviation(m)	0.62	2.50	3.35	7.75

TABLE II. LOCALIZATION PERFORMANCE COMPARISON

Method	Mean (m)	Std deviation (m)	90% Error (m)
Field test	1.50	0.78	2.56
Testbed	1.69	0.71	3.06

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