A Testbed for Evaluation of the Effects of Multipath on Performance of TOA-based Indoor Geolocation

Jie He, Student Member, IEEE, Kaveh Pahlavan, Fellow, IEEE,
Shen Li, Student Member, IEEE, and Qin Wang

Abstract—Real-time performance evaluation of time-of-arrival (TOA) based geolocation systems in multipath rich indoor areas has posed a serious challenge for the research community. This is due to the wide variety of performances observed with these systems under different multipath conditions in indoor areas, the diversity and complexity of the localization algorithms, sensitivity of the design to device implementation, and the challenges encountered in creating controllable and repeatable multipath conditions. In this paper we present a real-time performance evaluation system for TOA-based indoor geolocation devices operating in different multipath conditions using instrumentation and measurements in a laboratory testbed. This testbed is capable of producing repeatable multipath conditions. The heart of this testbed is a multi-channel real-time radio propagation emulator capable of emulating up to eight multipath fading channels simultaneously. We define four different multipath scenarios occurring in a typical office building at the Worcester Polytechnic Institute, Worcester, MA exhibiting a wide range of expected performance for the TOA-based geolocation systems. We use ray tracing software to simulate different multipath conditions caused by these scenarios and we map the multipath conditions into the real-time channel emulator to add the effects of fading. Then we measure the performance of a typical commercial product in this laboratory environment. To show the validity of this method, we compare the results of measurements in the testbed with empirical data obtained from actual measurements made in the same building.

Keywords-Time of Arrival; TOA; indoor geolocation; testbed; performance evaluation;

I. INTRODUCTION

A CURATE indoor geolocation is an important and novel emerging technology for commercial, public safety, and military applications [1], [2]. It has many potential uses in different environments such as navigation in shopping centers, airports, hospitals, factories and museums as well as localization inside disaster areas and underground mines [2]. Indoor geolocation is also instrumental in the growth of other areas of research, such as health monitoring, by associating the sensory information collected from body area networks with the geographical locations where the sensor data are collected [3].

Since the satellite based Global Positioning System (GPS) does not provide satisfactory performance in indoor areas, new wireless technologies for indoor geolocation have been investigated since late-1990s [4]. The received signal strength (RSS) base wireless localization techniques, currently used in smart devices, have their own limitations on accuracy [5], thus for more accurate localization researchers resort to TOA-based systems, used in GPS [2], [26]. The TOA-based systems, however, suffer from the effects of intensive multipath conditions in indoor areas [4]. As a result, a number of algorithms have been proposed and implemented for the design of these systems for indoor geolocation [6]. Complexity and diversity of TOA-based algorithms, sensitivity of the design to device implementation and serious difficulties caused by uncontrollable multipath conditions [7], [8] have posed a serious challenge for realistic performance evaluation of these systems [9]. Real-time testbeds for performance evaluation of RSS-based indoor geolocation systems are reported in [10]. In this paper we present a real-time testbed for performance evaluation of TOA-based systems and we compare the results with actual empirical data collected in the same environment.

In indoor environments, performance of TOA-based ranging and localization algorithms and systems is significantly influenced by the extensive multipath conditions in the channel between a device to be localized and the Reference Nodes or fixed Reference Points in known locations that are used to locate the device [12][19]. Since each deployment of infrastructure for the Reference Points has a specific architecture resulting in a specific multipath condition among Reference Points and the targeted device, the ranging and localization performance of TOA location systems can vary widely across different indoor environments. As a result, it is essential to evaluate the localization performance of a system before large scale deployment to verify that it can meet the application requirements. For the designer of the devices and researchers working on the algorithms, it is necessary to evaluate the ranging and consequently localization performance in different propagation and interference environments in order to design a system with an optimal performance.

The current methods provided in the literature for performance evaluation of TOA-based ranging and localization systems are software simulation [13] and field testing [12]. It is difficult to rely on the results of performance evaluations using software simulation, because of the difficulties in simulating the influence of the details of device implementation such as synchronization and signal detection algorithms used for practical implementation of the direct transmission path between a transmitter and a receiver. In addition, using software simulations we cannot evaluate the performance of most commercial devices and systems, since
the implementation details are not ordinarily released by manufacturers [14], [15].

Field testing suggests itself as a more reliable method for comparative performance evaluations in real-time and using the actual devices. However, in a field test we cannot fully control the interference in the environment and the effects of moving objects between and around the Reference Points and the target device. Due to changes in movement patterns and interference levels, the arrival time of the multipath components and the statistics of the fading for each arriving path are difficult to control and repeat. Consequently, it is difficult to use field testing to evaluate the performance of a TOA-based indoor geolocation system in a specific multipath condition. In addition, field testing is not convenient in large scale deployments, as it requires installing a large number of nodes. Since the performance of TOA-based localization techniques is very sensitive to multipath conditions [16], [17] to have a fair evaluation we need to compare the performance in different environments with a variety of multipath conditions among the Reference Points and the desired device. Field testing becomes very expensive and cumbersome for performance evaluation in different environments, because it requires multiple movements of physical deployments of the infrastructure of the Reference Points to different locations.

We believe using a real-time channel emulator and Ray-tracing [26] software to emulate the physical environment, as presented in this paper, can resolve a number of these difficulties in comparative performance evaluation of TOA-based location systems [24]. Ray-tracing provides the controllability and repeatability of multipath scenarios occurring in indoor areas [17], [18]. A real-time channel emulator can accurately emulate the radio propagation conditions based on the arrival times of the multipath components, the fading characteristics of the amplitude of each path [9], [10], [20] and at the same time provide for a controllable and repeatable testing environment.

In this paper, we classify multipath conditions into four categories and use a Ray-Tracing (RT) [26] software to simulate these multipath conditions. Then, a real-time RF channel emulator hardware is used to map the multipath conditions to an existing TOA-based geolocation system developed based on commercially available TOA-ranging devices [12][21]. We compare the results of the measurement made in this controlled environment with actual empirical data collected for the same scenarios in a typical office area at the Worcester Polytechnic Institute, Worcester, MA. The testbed can provide accurate performance evaluation in specific indoor propagation and interference environments prior to system deployment. In addition, since we can control and repeat multipath propagation features, the testbed can also help researchers to better understand the causes of unsatisfactory performance and find ways to improve the ranging and localization algorithm, device, and system.

The remainder of this paper is organized as follows. Section II describes the challenge for TOA-based location system caused by different multipath conditions and divides these conditions into four categories. Section III describes a real-time laboratory testbed used for performance evaluation of a typical system in an indoor area. This section describes the architecture of the testbed, description of the real-time channel emulator and the ray tracing software used for simulation of multipath conditions. Section IV describes the results obtained from the testbed under four different multipath conditions in indoor areas and validates the results of the testbed by comparing the testbed results with an actual field test in the same building. Section V summarizes this work and presents our conclusions.

II. MULTIPATH CONDITION AND TOA-BASED LOCALIZATION

For a TOA-based geolocation system, the time of flight of the direct path between a transmitter and a receiver is used to determine the intervening distance. A pulse is transmitted and the difference between the time of occurrence of the peak of the transmitted pulse and the first peak of the received pulse is used to measure the TOA [26]. Reflections and blockage in indoor environment caused by walls, furniture and people moving inside the building result in rapid fluctuations of the power of the direct path and severe multipath conditions. In a multipath environment, the received waveform is combination of the pulse arriving on the direct path and pulses arriving on other paths between the transmitter and receiver. As a result, the shape of the transmitted waveform and the expected time of occurrence of the first peak of the received waveform are not preserved at the receiver and consequently the measured TOA of the direct path suffers from inaccuracies [4].

The direct path can be blocked by large metallic objects [22] and large concrete walls or its first peak used for time of flight measurements may shift due to multipath components arriving close to the direct path [2]. These errors in the TOA estimation cause ranging errors that are a function of the environment and bandwidth of the measurement system [23]. For realistic performance evaluation of TOA-based indoor geolocation systems, it is traditional to classify different multipath conditions and physical situations causing these conditions [16].

A. Multipath Conditons and Ranging Error

In a multipath rich indoor area, the overall channel impulse response between a transmitter and a receiver, \( h(t, \tau) \), is given by:

\[
h(t, \tau) = \sum_{i=1}^{N} \beta_i e^{i\phi} \delta(t - \tau_i)
\]

(1)

where \( \beta_i \) and \( \phi_i \) represent the amplitude and phase of the \( i^{th} \) path arriving at delay \( \tau_i \) [26]. The parameter \( N \) is the number of paths between the transmitter and the receiver. If the transmitted waveform is represented by \( x(t) \) the received waveform, \( y(t) \), is given by

\[
y(t) = x(t) \otimes h(t) = \sum_{i=1}^{N} \beta_i e^{i\phi} x(t - \tau_i)
\]

(2)
This received signal is often referred to as the channel profile. In indoor geolocation the Hanning pulses are commonly used as the transmitted waveform. The Hanning pulses have very low side lobes allowing detection of more multipath components and they are defined as:

\[ w(t) = \begin{cases} \frac{1}{T} \left(1 + \frac{\cos \frac{\pi t}{T}}{2}\right), & |t| \leq T \\ 0, & |t| > T \end{cases} \]  

(3)

where \( T \) is length window.

Fig. 1 shows two typical measured channel profiles in an office area at the Atwater Kent Laboratory, Worcester Polytechnic Institute, using Hanning pulses. If we normalize the peak of the transmitted pulse at time zero, the peak of the first arriving pulse is the measurement of the TOA. The estimated distance between the transmitter and the receiver is 

\[ \hat{d} = \tau_t \times c, \]  

in which \( c \) is the speed of radio wave propagation in the medium. In free space it is the same as speed of light and in other media such as inside the human body it will vary with the conductivity of the medium [25].

For TOA-based indoor geolocation, multipath conditions can be classified into two categories based on the availability of direct path (DP) between the transmitter and the receiver [4]. The first category is detectable direct path (DDP), in which the amplitude of the direct path pulse is higher than the threshold of the receiver and is detectable, as shown in Fig. 1(a). The second category is undetectable direct path (UDP), shown in Fig. 1(b), in which the power of the direct path pulse is lower than the threshold of the receiver and thus the direct path pulse is undetectable. If the amplitude of the direct path in the received multipath profile is represented by \( \beta_{DP} \), the DDP and UDP are defined as:

\[ y(t) = \begin{cases} \text{DDP}; & \beta_{DP} \geq \beta_T \\ \text{UDP}; & \beta_{DP} < \beta_T \end{cases} \]  

(3)

where \( \beta_T \) is the power threshold of the receiver.

In DDP condition, shown in Fig. 1 (a), we have a small difference between the expected TOA and the measured value of the TOA. This difference is caused by the shift of the peak of the received waveform from the expected location after the signal arriving from other paths is added to the signal from the direct path. The shift in the location of the peak is mostly caused by the paths arriving close to the direct path arrival time. In UDP condition, shown in Fig. 1(b), the direct path is blocked by objects situated between the transmitter and the receiver and it cannot be detected at all. In TOA-based ranging, this condition causes significantly large ranging errors.

### B. Physical Scenarios for Multipath Condition

The physical environment around and between the transmitter and receiver determines the multipath condition. These multipath conditions affect the performance of TOA-based geolocation systems. The multipath conditions for indoor geolocation can be classified into four different physical scenarios: free space, line of sight (LOS), non-LOS (NLOS)-DDP and NLOS-UDP.

In free space, the receiver can easily detect the direct path and ranging accuracy is determined by the implementation of the device, including accuracy of the synchronization scheme, accuracy of the signal detection scheme, frequency of the timer used to record the transmit time and arrival time of the pulse.

In the LOS scenario for an indoor area there is no obstruction between the transmitter and the receiver and the direct path is always the strongest path. However, paths arriving in close vicinity of the direct path will shift the peak of the first path causing modest ranging errors [23]. The ranging accuracy is affected by the bandwidth of the pulse and the strength of the multipath components close to the direct path as well as the device implementation details. The ranging error in LOS scenarios is expected to be larger than ranging error in free space scenario.

In the NLOS-DDP scenario, the direct path between the transmitter and the receiver is obstructed by objects with low attenuation coefficients, such as wooden walls, sheetrock walls and furniture. In this scenario, usually, the direct path pulse is weakened, but still available in the received signal. This situ-
detection makes it more difficult to detect the TOA of the direct path pulse and to estimate the distance between the transmitter and the receiver. The ranging error in this scenario is expected to be larger than ranging error in the LOS scenario.

In the NLOS-UDP scenario, the direct path between the transmitter and the receiver is obstructed by objects with high attenuation coefficients that submerge the direct path pulse below the detection threshold. These situations are observed when large metallic objects such as elevators or concrete walls are situated between the transmitter and the receiver. In this scenario, the ranging error is expected to be much larger than the ranging error in the other scenarios.

III. A REAL-TIME TESTBED FOR ANALYSIS OF THE EFFECTS OF MULTIPATH

For a realistic performance measurement of TOA-based localization techniques it is desirable to use instrumentation to design a laboratory testbed capable of producing controlled and repeatable multipath conditions. The testbed allows comparative performance evaluation of alternative technologies in different multipath conditions and network infrastructure topologies prior to expensive large scale system deployments. In this section we introduce a testbed that uses Ray Tracing software to simulate different multipath conditions in indoor areas and maps the resulting impulse responses to a real-time hardware channel emulator to add the effects of fading to the multipath components and connect the actual commercial devices.

A. Overall Architecture of the Testbed

Fig. 2(a) illustrates the overall architecture of our testbed for performance evaluation of TOA-based localization systems. The central part of the testbed is an eight channel real-time emulator, PROPSIM C8 [20] designed by Elektrobit in Oulu Finland, which has the capability of simulating multipath condition for up to eight channels. A Target Node, several Reference Points and a Ray Tracing software simulator are connected to the PROPSIM.

The Ray-Tracing software is instrumented to simulate the site-specific impulse responses of the channel among the Reference Points and the Target Node. The hardware channel emulator uses the impulse responses produced by the Ray Tracing software to emulate the physical multipath conditions among the network components by adding the effects of fading to the multipath components in the real-time. The Target Node, Reference Nodes and the localization software construct the TOA-based geolocation system for performance evaluation, while the channel simulation hardware emulates the channel for different multipath conditions associated with different application environments and topologies. The Target Node reports the actual measurements of the TOAs to the Localization Software unit, which allows implementation of different localization algorithms. The statistical ranging and localization accuracy are determined after gathering the ranging and localization results. Fig. 2(b) shows the implementation layout of a four Reference Node testbed for the real-time performance evaluation of an IEEE 802.15.4a standard TOA-based geolocation system, the NanoLOC reported in[12], [21].

B. Real-Time Channel Emulator

The real-time channel emulator used in the testbed is the PROPSIM C8, originally designed for modeling of channels for wireless communication systems using multi-input-multi-output (MIMO) antennas [20]. This channel emulator utilizes the impulse response method to emulate the radio propagation among up to eight transmitters and eight receivers. All the parameters of the impulse response of the channel model, including center frequency, number of paths as well as delay, phase, attenuation and fading of each path are programed through the graphical user interface of the hardware platform. The RF input signal is down-converted to analog complex baseband signals. These signals are filtered and converted to digital format by analog to digital (A/D) converters. A finite impulse response (FIR) filter structure is used to simulate the sum of multiple delayed versions of the input signal according to the impulse response model of each channel. The resulting signal is digital to analog (D/A) converted and up-converted to the original RF frequency. By combining different fading characteristics to the impulse response, such as Rayleigh, Rician or Lognormal, the channel emulator can construct the propagation environment for a wide variety of application environments for urban and indoor wireless networks. The bandwidth of each channel of the PROPSim C8 is 70 MHz, which accommodates popular cellular and wireless local and personal area networking applications such as IEEE 802.15.4 wireless personal area networks which is used as the example in this paper. The details of the implementation of PROPSim C8 are available at Ref. [20].
C. Ray-Tracing for Simulation of Multipath

Ray-Tracing is the most popular site-specific wideband radio waveform propagation modeling technique for indoor environments [26]. It has been used extensively for simulation of multipath condition for performance evaluation of wireless communication [27], [29] and indoor geolocation systems [28]. Using the specific floor plan of a building, the reflection and transmission coefficients of each wall and the positions of the specific transmitter and receiver, the Ray-Tracing software constructs the complex impulse response of the channel by providing the time of arrival, amplitude and the phase of each multipath component between the transmitter and the receiver [26]. Once the channel impulse response is determined by the software, the real-time hardware platform can add different fading conditions to each path to reflect the effects of objects such as tables or cabinets, and human bodies moving in the area of measurement. The Ray-tracing software used in this paper, PlaceTool (as shown in Fig. 3) is a measurement calibrated proprietary software developed by Center of Wireless Information Network Studies (CWINS), Worcester Polytechnic Institute. Description of this software is available in reference [26].

IV. RESULTS OF PERFORMANCE MEASUREMENTS

In this section we use the testbed described in section III for the performance evaluation of a TOA-based geolocation system developed based on an IEEE 802.15.4a recommended TOA device in a typical office building at the Atwater Kent Laboratories, Worcester Polytechnic Institute. The results of performance evaluation from the testbed and actual field testing, including statistics of ranging error and localization error, are compared to show the correspondence of the results of these two approaches and demonstrate the feasibility of this approach for performance measurement of indoor geolocation systems in different multipath conditions. The statistics of ranging error and localization error obtained from the field test are used as the reference to justify the relevance of the results from the testbed to a real situation. We first define physical scenarios for different multipath conditions representing a variety of multipath conditions and the details of the algorithms used in the TOA-based geolocation device under examination. Then, we show the results of ranging error measurements in different multipath conditions, and finally we provide an example for an actual localization application in a specific indoor scenario.

A. Performance Evaluation Scenarios

As we described in Section II, we consider four classes of multipath conditions: free space, LOS, NLOS-DDP and NLOS-UDP, for performance evaluation of TOA-based localization devices in different multipath conditions. These classes of multipath conditions result in widely diversified performances for TOA-based indoor geolocation systems. In this section, we define four physical scenarios at the Atwater Kent Laboratory building, Worcester Polytechnic Institute, which are creating these classes of multipath conditions.

For performance measurements in the free space we conducted test for ranging error between the Target Node and a Reference Node with separation of 2.34m inside the anechoic chamber with RF absorbing walls. Since the walls absorb the RF signal, we have no reflected paths and the only path for transmission of the signal is the direct path between the transmitter and the receiver. This environment resembles free-space propagation, where direct path is the only path for signal transmission.

The test field for performance evaluation in the LOS conditions is in a classroom on the second floor of the Atwater Kent Laboratory, Worcester Polytechnic Institute, shown in Fig. 4(a). We installed four Reference Points in the corners of the room and moved the Target Node among 25 locations inside the room on a grid shown by dots in the figure. We used the data based collected in these locations for the analysis of the ranging and localization accuracies.

The physical scenarios for the NLOS-DDP and NLOS-UDP cases were at the third floor of the Atwater Kent Laboratory, shown in Fig. 4(b). In these scenarios we focus
on the ranging error caused by obstructions between the transmitter and receiver. In the NLOS- DDP scenario, shown in the lower part of the Fig. 4(b), there is a typical office wall between the Target Node and the Reference Node. This wall is composed of metallic studs covered with plaster sheetrock. A Reference Node is deployed inside the room and the ranging error for 14 positions for the Target Node in the hallway is evaluated. The NLOS-UDP scenario is shown in the middle part of the Fig. 4(b), the Target Node and the Reference Point are separated by a metallic chamber and two office walls. The Reference Point is located behind the chamber and ranging accuracy is evaluated for 12 target positions at the other side of the chamber. The metallic chamber blocks the direct path between the transmitter and receiver creating an UDP scenario for multipath arrivals.

In all three scenarios outside the chamber, the multipath conditions of the channel are obtained from the Ray Tracing software but they do not include the details of furniture and movements of human bodies in the area. The indoor RF multipath channel is also heavily rich with diffuse scattering RF propagation phenomena. Rayleigh fading is commonly used in the literature to model these effects when there are many objects in the environment that scatter the radio signal [26]. To achieve a realistic statistics for the ranging and localization performance, we applied Rayleigh fading to each path of the channel multipath profile obtained from Ray Tracing simulation software. Implementation of this fading behavior is embedded in the PROPSIM C8 channel emulation hardware. The probability density function of Rayleigh fading is given by:

$$f(x) = \begin{cases} \frac{x}{\sigma^2} \exp\left(-\frac{x^2}{2\sigma^2}\right), & x \geq 0 \\ 0, & x < 0 \end{cases}$$

(5)

where $f(x)$ is the probability density, $x$ is the random variable representing the amplitude variations of the impulses and $\sigma^2$ is known as the fading envelope of the Rayleigh distribution. The value of $\sigma^2$ of the Rayleigh fading for each path in the PROPSIM C8 is adjusted to 0.5 times the power of that multipath component.

B. Devices and Algorithms Used for Performance Evaluation

The device used for performance evaluation, NanoLOC, is an RF chip with the capability of TOA measurement, designed based on the IEEE 802.15.4a Standard and it is commercially available through Nanotron Inc. The hardware of the NanoLOC development board and the way it connects to the testbed is shown in Fig. 2(b). We have used five NanoLOC development boards and the localization software developed by Micro Architecture and IC design Laboratory (MICL), University of Science and Technology, Beijing, to implement the scenarios for performance evaluation that were described in Section IV(A). The focus of the performance evaluation in all four scenarios is the measurement of the ranging errors in different multipath conditions, but in the LOS scenario we also provide an example of localization results as well. Therefore, we have used both ranging and localization algorithms to produce the results of our performance analysis.

1) Ranging Algorithm

NanoLOC uses a two-way TOA ranging algorithm, shown in Fig. 5, which avoids the need for high precision synchronization between the transmitter and the receiver [11], [14]. The system calculates the flight time from the transmitter to the receiver and returning to the transmitter to determine the estimate distance between two nodes. This estimated distance is given by:

$$\hat{d} = t_r \times c = \frac{t_{\text{round}} - t_{\text{echo}}}{2} \times c = \frac{(T_4 - T_1) - (T_3 - T_2)}{2} \times c$$

(6)
is the propagation time, and \( c \) is the speed of radio propagation in free space. The \( T_1 \) denotes the time that Node A sends the ‘Ranging data’ pulse, \( T_s \) is the time Node B receives ‘Ranging data’ pulse, \( T_3 \) is the time Node B sends ‘Acknowledgement (ACK)’ pulse, and \( T_4 \) is the time Node A receives ‘ACK’ pulse. \( T_1, T_2, T_3 \) and \( T_4 \) are all measured by the local timer in NanoLOC. The ranging statistics in all four scenarios are derived based on this distance calculation algorithm.

2) Localization Algorithm

To demonstrate the validity of the testbed for performance evaluation of localization algorithms in a specific deployment scenario we implemented the Trilateral-Centroid algorithm for our LOS localization deployment scenario shown in Fig. 4(a). The general concept behind the algorithm used in this experiment is shown in Fig. 6. In this figure \( L \) is the area used for testing the localization algorithm; \( RN_i \) is the \( i^{th} \) Reference Point; \( r_i \) is the estimated distance between Target Node and \( RN_i \); \( R_i \) is a circle centered at the location of \( RN_i \) and \( r_i \) is the radius of that circle. Assuming the Target Node is located among four Reference Nodes, the algorithm finds the coordinates of the Target Node from:

\[
(\hat{x}, \hat{y}) = \text{Centroid of } \{L \cap R_1 \cap R_2 \cap ... \cap R_n\}
\]

As shown in Fig. 6, the location of the Target Node, \( T \), is calculated by determining the centroid of the intersect of all circles \( C_i = (x_i, y_i) \) in the area \( L \). In other words

\[
(\hat{x}, \hat{y}) = \frac{1}{N} \sum_{i=1}^{N} (x_i, y_i) \tag{7}
\]

C. Testbed Results versus Empirical Measurements

Performance evaluation of indoor localization systems depends on the multipath fading characteristics of the channel, which is a function of uncontrolled elements such as movements of the people or objects close to the transmitters and the receivers. As a result, statistical channel modeling and statistical performance evaluation is commonly used in the localization literature for comparative performance evaluations [26]. The cumulative distribution function (CDF) of the results of statistical performance evaluations is one of the most popular presentations used to compare the results of statistical behaviors [5,7,16,23].

To demonstrate the validity of our testbed for statistical performance evaluations, we compare the results of measurements from the testbed with the results obtained in an actual physical medium. The CDF of the results of ranging or localization error as well as their mean and standard deviation are used to compare the performance of our example system described in Section IV(B) using the testbed emulations and measurement with actual deployments in the four scenarios described in Section IV(A). The correlation between two CDFs is calculated to evaluate the goodness of the fit of the two CDFs. These results correspond to four scenarios for ranging under different multipath conditions and an example with localization algorithms and a typical deployment scenario.

1) Ranging Accuracy

Ranging error \( e_x \) is defined as:

\[
e_x = \hat{d} - d \tag{8}
\]

where \( \hat{d} \) is the ranging result obtained from the device using Eq. (6) and \( d \) is the actual distance between the two nodes.

Fig. 7 (a) through (d) show the typical impulse response and corresponding channel profile in each scenario and compares the CDF of ranging error of the NanoLOC device obtained from the testbed emulation and the actual measurement made in the field test. The number of tests for building each CDF and the correlations between CDFs for each scenario are shown in Table I. Fig. 7(a) corresponds to measurements of 2000 samples for the transmitter and the receiver placed 2.34m apart inside the chamber representing the free space scenario. The second column of the Table II shows the mean and variance of the ranging error for the free space experience. In this scenario the system introduces errors of up to 2m both in the laboratory testbed and the actual
measurements inside the chamber. These errors are caused by inaccuracies in the implementation of the hardware. The CDF and the mean and variance of the errors obtained from the emulations of the testbed show very close agreement with the empirical results of the field test.

Fig. 7 (b) and third column of the Table II are associated with the statistics of the LOS scenario. This scenario introduces errors up to 15m that are caused by multipath components arriving in close proximity to the direct path. As discussed earlier, these multipath components shift the peak of the transmitted pulse from its expected value and that shift causes the additional error [23]. The statistical results of ranging error from the testbed emulation are again very close to the actual measurements in the classroom depicted in Fig. 4(a).

Fig. 7(c) shows the CDF and the third column of the Table II the mean and variance of the ranging error obtained from the testbed emulations and the empirical measurements in the NLOS-DDP scenario. This case introduces errors up to more than 20m caused by obstruction of the direct path by the wall between the transmitter and receiver, shown in the lower part of Fig. 4(b). Results of the experiment on the laboratory testbed and the field test again show close agreement. The wall has increased the mean of the ranging error close to two times.

Fig. 7(d) and the fourth column of Table II illustrate the statistics of the performance in the fourth scenario, the NLOS-UDP, where the direct path is blocked by a large metallic object introducing errors up to 30 meters for the test device. Results of the testbed emulation and the empirical measurements again show close agreement. The mean of localization error is close to two times more than the third scenario.

As shown in Fig. 7 and Table II, the first and second order statistics of the ranging error observed with the testbed are very close to results obtained by empirical measurements in test field. All the correlations of the first three scenarios are larger than 0.995 and the correlation of the NLOS-UDP scenario is larger than 0.975. These results clearly indicate the validity of the testbed to replace field tests in different multipath conditions. The statistical results of our measurements did not show any influence of operating in the vicinity of the walls or windows.

TABLE I. RANGING PERFORMANCE COMPARISON

<table>
<thead>
<tr>
<th>Channel Condition</th>
<th>Free space</th>
<th>LOS</th>
<th>NLOS-DDP</th>
<th>NLOS-UDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of measures</td>
<td>2 × 10³</td>
<td>2 × 10³</td>
<td>2.8 × 10⁵</td>
<td>2.4 × 10⁶</td>
</tr>
<tr>
<td>Correlation</td>
<td>0.9972</td>
<td>0.9954</td>
<td>0.9974</td>
<td>0.9751</td>
</tr>
</tbody>
</table>

TABLE II. RANGING PERFORMANCE COMPARISON

<table>
<thead>
<tr>
<th>Channel Condition</th>
<th>Free space</th>
<th>LOS</th>
<th>NLOS-DDP</th>
<th>NLOS-UDP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field test Mean(m)</td>
<td>1.13</td>
<td>3.70</td>
<td>7.22</td>
<td>15.25</td>
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<tr>
<td>Standard deviation (m)</td>
<td>0.65</td>
<td>2.58</td>
<td>3.97</td>
<td>4.96</td>
</tr>
<tr>
<td>Testbed Mean(m)</td>
<td>1.08</td>
<td>3.32</td>
<td>7.22</td>
<td>14.66</td>
</tr>
<tr>
<td>Standard deviation (m)</td>
<td>0.62</td>
<td>2.50</td>
<td>3.35</td>
<td>7.75</td>
</tr>
</tbody>
</table>
2) Localization Accuracy

Analysis of the localization performance allows understanding of the influence of the deployment scenario and the localization algorithm. Here we use the deployment in the second scenario with four Reference Nodes, a Target Node, and 25 target locations, shown in Fig. 4(a), and the Trilateral-Centroid algorithm, described in Section IV(B), to discover the validity of the testbed for localization performance analysis. The localization error is defined as:

$$e_L = \sqrt{(x-x)^2 + (y-y)^2}$$  \hspace{1cm} (9)

where $e_L$ is the localization error, $\hat{(x,y)}$ is the Target node’s calculated location coordinate and $(x,y)$ is the actual Target Node’s location coordinate.

Fig. 8 compares the CDF of localization error in the scenario defined in Fig. 4(a), using the algorithm depicted in Fig. 6, obtained from the testbed emulator and the empirical results in the field test. In this experiment, 2000 localization errors are collected for building each CDF and the correlation between the CDFs is 0.9944. Table III compares the mean and standard deviation of the error obtained from the testbed emulator and the field test. Again, the first and second order statistics of the results from the emulation testbed and the field tests show close agreement confirming the validity of the testbed for performance evaluation using an actual deployment and a localization algorithm.

V. SUMMARY AND CONCLUSION

Performance evaluation is an essential step in the design and deployment of a localization system because it is needed to verify that a system meets the application requirements. Due to difficulties in simulating the influence of design of the device and implementation of the system on the performance of localization systems, it is very difficult to accurately measure the performance of localization systems using software simulations. To address this problem, we have designed a controllable and repeatable real-time testbed for TOA-based localization systems operating in multipath rich indoor areas. This testbed used Ray-Tracing software to simulate different multipath conditions and these multipath conditions were used for simulation of the channel using a hardware emulation system, PROPSIM. The testbed was then used for performance evaluation of IEEE 802.15.4a devices in different multipath scenarios. It was shown that the results of performance evaluation obtained from the testbed closely follow the empirical measurements in the field tests in a typical office building.

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 IEEE 802.15.4a devices validated the testbed. From the test results, we can clearly see the localization performance achievable in different scenarios. Comparisons made between the testbed results and field test results show close agreement.

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TABLE III. LOCALIZATION PERFORMANCE COMPARISON

<table>
<thead>
<tr>
<th>Method</th>
<th>Mean (m)</th>
<th>Standard deviation (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field test</td>
<td>1.50</td>
<td>0.78</td>
</tr>
<tr>
<td>Testbed</td>
<td>1.69</td>
<td>0.71</td>
</tr>
</tbody>
</table>

Figure 8. Comparison of localization error CDFs from the testbed and the empirical measurements

REFERENCES


**Jie He** (S’11) received the B.E. degree from USTB in 2005. He got his PhD degree from University of Science and Technology Beijing (USTB), China in 2012. He began to work in the field of wireless indoor location system in 2007. From 2011 to 2012, he was a visiting student, working in the field of Body Area Network in Center for Wireless Information Network Studies, Department of Electrical and Computer Engineering, Worcester Polytechnic Institute (WPI). His current research interests include indoor location system, wireless sensor networks and body area network.

**Kaveh Pahlavan** (M’79–SM’88–F’96) is a professor of electrical and computer engineering, a professor of computer science, and director of the Center for Wireless Information Network Studies, Worcester Polytechnic Institute, Worcester, Massachusetts and the chief technical advisor of Skyhook Wireless, Boston, Massachusetts. His current area of research is opportunistic localization for body area networks and robotics applications. He is the principal author of *Wireless Information Networks* (with Allen Levesque), John Wiley and Sons, 1995, 2ed Ed. 2005; *Principles of Wireless Networks – A Unified Approach* (with P. Krishnamurthy), Prentice Hall, 2002; and *Networking Fundamentals: Wide, Local, and Personal Communications* (with P. Krishnamurthy), Wiley 2009. He is the founder and editor-in-chief of the International Journal on Wireless Information Networks and founder and chairman of a number of IEEE conferences in wireless access and localization. He was awarded Westin Hadden Professor of ECE at WPI during 1993-1996, elected as a fellow of IEEE in 1996, awarded a Nokia fellowship in 1999, and the first Fulbright-Nokia scholar at University of Oulu, Finland, 2000.

**Shen Li** (S’12) received her B.E. degree from University of Electronic Science and Technology of China in 2010. She is currently working toward the M.S. degree in electrical and computer engineering with the Center for Wireless Information Network Studies, Department of Electrical and Computer Engineering, WPI. She began to work on indoor geolocation from 2010. Her current research interests include body area network and indoor geolocation system.

**Qin Wang** is a professor in School of Computer and Communication Engineering, University of Science and Technology Beijing (USTB), China and the director of Micro-architecture and IC Lab of USTB. She got the PhD degree from USTB in 1998. From 2005 to 2007, she had been a visiting scholar in Harvard University. She is also a voting member of IEEE802.15.4 and SPI00. Her research interests include wireless sensor networks, micro-architecture, VLSI and embedded system.