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A Cyber Physical Test-bed for Virtualization of RF Access Environment for Body Sensor Network

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Abstract— **Performance evaluation of wireless access and localization is important for body sensor networks, as any defects in the design not only cause wastage of resources but also threaten an individual's health and safety. However, the typical cyber methods, such as software simulation often fails to accurately simulate the influence of hardware implementation. The traditional physical methods, however, such as field testing, are not capable of creating repeatable and controllable channel condition. To combine cyber and physical factors as well as to address the issue, we present a cyber physical test-bed for environment virtualization to facilitate the performance evaluation of wireless access and localization in body sensor network. This test-bed creates a virtualized environment by emulating the wireless channel in a cybernetic way, using a real time channel emulator. The original devices or systems under testing can be physically connected to a channel emulator to evaluate the performance in the virtualization environment. Furthermore, the cyber physical test-bed supports various scenarios from in-body data transmission to time of arrival based indoor localization. To validate the cyber physical approach, emulated outputs are compared with the empirical data obtained from actual measurements. To overcome the bandwidth limitation of traditional digital channel emulators, we designed an analog channel emulator for UWB technologies. The preliminary verification of this analog emulator is introduced at the end of this paper.**

Index Terms— **Cyber physical test-bed; Performance evaluation; Body sensor network; Environment virtualization;**

I. INTRODUCTION

DUE to the rapid advancement in wireless technology, implantable medical devices and pervasive computing gave birth to a booming era of body sensor network (BSN). From the perspective of health care, body sensor networks can be defined as a network of wearable physiological sensors and implantable medical devices for both real-time health management and clinical treatment [1]. The wide variety of application for body sensor network includes physiological signal collecting for health monitoring [2, 3], implantable medical devices like pacemaker and implantable insulin pump[4, 5], clinical treatment methodologies such as wireless capsule endoscopies[6, 7] and so forth. Since personal physiological information usually communicates over wireless channels and awareness of localization of implantable devices enables medical treatment, the development of wireless access and localization becomes an essential element for the growth of BSNs

Performance evaluation guarantees the proper functioning of wireless access and localization system [5]. It is a very important step in the process of device or system development. Modern approaches for performance evaluation of wireless communication systems can be categorized into two classes: cyber and physical. Each of these classes suffers from their respective disadvantages. Software simulation is a typical cyber approach. It is often used to evaluate the performance of the algorithms in specific levels, including digital signal processing (DSP) algorithms for the physical layer, MAC or route protocols, and localization algorithms, based on corresponding channel models [5]. However, without taking into consideration the effect of the utilization of hardware, it is difficult to evaluate the performance of real world devices and systems solely with software simulation. In addition, software simulations cannot be used to evaluate the performance of most commercial devices and systems, due to the lack of details released by manufacturers [8]. Field testing, on the other hand, represents the physical approach of performance evaluation. It provides relatively reliable performance using actual devices and deployments. However, the wireless channel condition is invisible, uncontrollable and unrepeatable. Consequently, it is difficult to use field testing to evaluate the performance of BSN system in a specific channel condition as well as to analysis the causation of the defeat performance. Moreover, for implantable devices, such as the wireless capsule endoscopy and pacemaker, it is difficult to implement field testing due to the fact that taking measurement inside the human body is nearly impossible.

To improve the performance evaluation technique, a properly designed methodology is crucial. Such methodology must be capable of precisely mimicking radio signal propagation in a realistic scenario, whilst also being capable of evaluating with actual hardware. Based on the above mentioned requirements, the combination of cyber and physical approaches turns out to be a highly suitable solution and the cyber physical approach for performance evaluation should aim toward the tight coordination between computational element and physical environment.

In this paper, we present a cyber physical test-bed (CPT) for environments of wireless access and localization in BSNs, within which, the performance of wireless access and localization in different scenarios present in the BSN can be evaluated with actual devices. This test-bed creates an environment virtualization by emulating the wireless channel in a cybernetic way, using a real time channel emulator, PROPSim C8. The original devices or systems can be physically connected to a channel emulator to evaluate the performance in the environment virtualization. Specific cases have been studied to

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verify the design of the CPT and illustrate the applications in performance evaluation for wireless access and localization systems in various BSN scenarios. We compared the results of emulation with the existing results and field tested results to verify the availability of our approach.

The remainder of this paper is organized as follows. Section II describes the corresponding channel models for wireless access and localization in BSN. Section III presents the general architecture of the CPT in a component level and then talks about the hardware implementation. Section IV demonstrates how the CPT works in case studies, including in-body data transmission and TOA based localization. Section V, we presented the original design and result of the channel emulator for ultra-wide band (UWB) technology. Lastly, we conclude our work in Section VI and discuss future studies in this field.

II. BACKGROUND

Body sensor networks can be defined as networks for medical and non-medical devices that can be placed inside or on the surface of the human body [9]. Typically, wireless communication in BSN is used to transmit data among devices and track the positions of the devices mounted on or implanted inside the human body, such as wearable physiological sensors or wireless capsule endoscopies. The performance of wireless access and localization are both closely related to the influence of the environment, which is logically described as a channel model. In our CPT, the channel model is used as the input of the channel emulator that emulates the RF propagation among devices in the process of performance evaluation. The complexity of the human tissues structure and body shape make it difficult to drive a channel model for BSNs [1, 7, 10]. As the devices for BSN applications are placed on or inside the body, the BSNs channel model needs to take into consideration the influence of the body on the radio propagation. In the rest of this section, we will give a brief introduction of channel modeling for wireless access and localization for BSNs applications.

A. Path loss model for wireless access in BAN

The typical architecture of a BSN is shown in Fig. 1. The scenarios of wireless communications in BSNs can be defined as Implant to Implant (CM1), Implant to Body Surface (CM2), Body Surface to Body Surface (CM3) and Body Surface to Base Station (CM4).

For wireless access in BSNs, narrow band communication technologies are usually used and the wireless channel between transmitter and receiver can be described as a path loss model, which is given by:

$$PL(\mathrm{d}) = PL(d_0) + 10n\log_{10}(d/d_0) + S \qquad (1)$$

where $S \sim N(0,\sigma_s)$ and $PL(d_0)$ is the path loss measured at a specific distance d_0.

The path loss models of CM3 and CM4 can be developed based on the analysis of measurements. Several models of CM3 and CM4 have been presented in the draft of IEEE 802.15.6 based on physical measurements in candidate bands, such as 400MHz, 900MHz and 2.4GHz. However, since it is not feasible to conduct physical measurement and experimental inside human bodies [11], a 3D simulation and virtualization scheme was used by the National Institute of Standards and Technology (NIST) to study the propagation characteristics of Medical Implant Communication Services (MICS) band (402-405MHz) to develop the path loss models of CM1 and CM2 [11, 12], the parameters of that are shown in Table I and Table II. These two models were also adopted by IEEE 802.15.6 Standard.

B. Impulse response model for localization in BAN

In medical and non-medical applications, positions of devices are critical to some specific applications. The wireless localization systems can locate the target based on the distance or angle related features of the received signal radiated from the device. There are four commonly used technologies for this purpose: Receive Signal Strength (RSS), Time of Arrival (TOA), Time Difference of Arrival (TDOA) and Angle of Arrival (AOA). For RSS based localization, the distance between transmitter and receiver is calculated based on the measured path loss and the statistical path loss model, which is identical to the channel model for wireless access. For the other three technologies, the distances or angles among devices are calculated based on the measurement of propagation time or the difference of propagation time of the transmitted signals. For these three technologies, the performances are closely related to the multipath condition, which can be described as an impulse response channel model, given by:

$$h(t,\tau) = \sum_{i=1}^{N} \beta_i e^{j\phi_i} \delta(t-\tau_i) \qquad (2)$$

where β_i and ϕ_i represent the amplitude and phase of the i^{th} path arriving at delay τ_i. The parameter N is the number

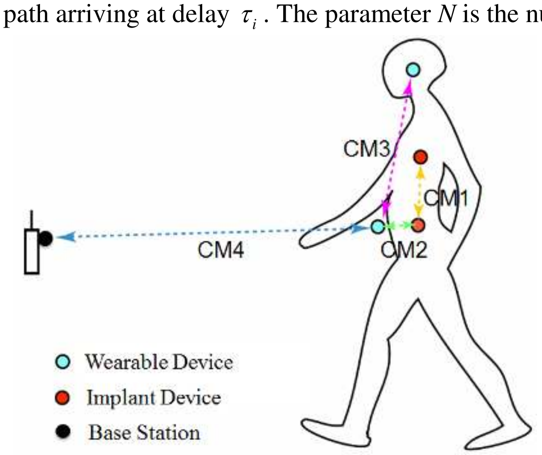

Fig. 1 Scenarios of wireless communication in BSN

TABLE I PARAMETERS OF PATH LOSS MODEL OF CM1

Implant to Implant (CM1)	$PL(d_0)(db)$, where $d_0 = 50mm$	n	$\sigma_s(db)$
Deep Tissue	35.04	6.26	8.18
Near Surface	40.94	4.99	9.05

TABLE II PARAMETERS OF PATH LOSS MODEL OF CM2

Implant to Body Surface (CM2)	$PL(d_0)(db)$, where $d_0 = 50mm$	n	$\sigma_s(db)$
Deep Tissue	47.14	4.26	7.85
Near Surface	49.81	4.22	6.81

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of paths between the transmitter and the receiver. If we use $x(t)$ and $y(t)$ to represent the transmitted and received waveform, we have:

$$y(t) = x(t) \otimes h(t) = \sum_{i=1}^{N} \beta_i e^{j\phi_i} x\left(t - \tau_i\right) \quad (3)$$

Typical wireless channels for localization applications in BSNs can be partitioned into two categories: Implant to Body Surface (CM2) and Body Surface to Base Station (CM4). In both categories, TOA based localization is frequently used due to its practical and high accuracy features.

One of the well-known applications for the Implant to Body Surface scenario is the wireless capsule endoscopy for which the awareness of the capsule location gives raise to specific medical treatments. Since the electromagnetic wave propagation in dispersive biological tissues is frequency dependent on permittivity and conductivity and the propagation velocity of a homogeneous medium, the TOA of waveforms can therefore be calculated by accumulating the waveform propagation in different organs and tissues [26]. The above mentioned propagation velocity is given as:

$$\mathrm{v}(\omega) = \frac{c}{\sqrt{\varepsilon_r(\omega)}} \quad (4)$$

where c is the velocity of light in the free space and $\varepsilon_r(\omega)$ is the relative permittivity of a human tissue and the frequency dependency of permittivity of human organs and tissues can be found in the Cole-Cole model [27]. Currently there is no standard impulse response model of CM2 that can be found, however using relatively mature EM field software simulation methods such as FDTD makes the in-body TOA localization increasingly promising.

The representative application of the Body Surface to Base Station scenario is the indoor human tracking for which the human is localized by measuring the distance or angle among the target node (wearable devices on the surface of the human) and the reference nodes (external base stations). In the literature, most of the works relative to indoor human tracking applications are based on the standard channel model. Such applications suffered from huge localization errors because the standard impulse response model failed to take the effect of the human body into consideration. A few recent works [13, 14] showed that the TOA ranging error is significantly affected by the geometric relationship among the positions of the transmitter, receiver and human body, and the TOA ranging error e_{TOA} is given by:

$$e_{TOA} = \varepsilon_M + \delta(P_{NLOS}(\theta) - 1) \times \varepsilon_{NLOS} \quad (5)$$

where ε_M represents the ranging error caused by the multipath phenomenon in the typical indoor environment, which is included in the standard impulse response model. ε_{NLOS} is the ranging error coming from the none-line-of-sight scenario caused by the human body, which is dominating the overall ranging error when the human body is blocking the direct line between the transmitter and receiver.

$\delta(x)$ is the impulse function, given by:

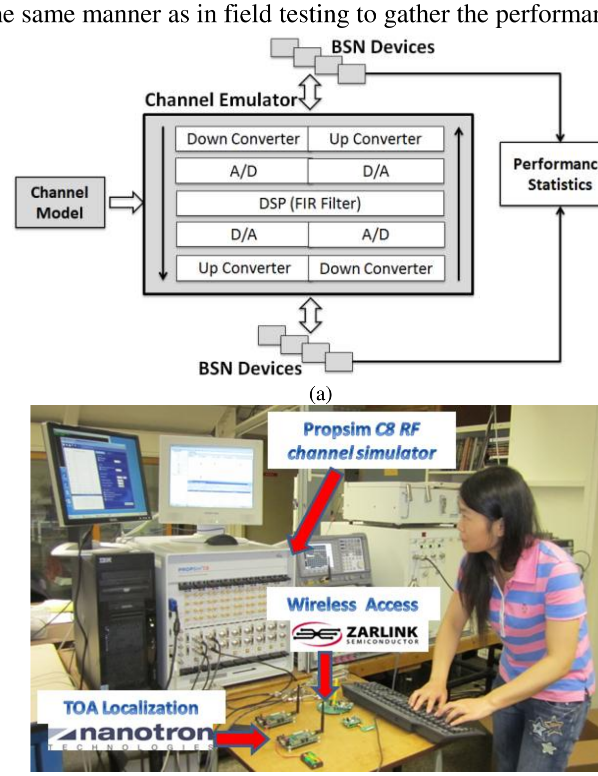
$$\delta(x) = \begin{cases} 1 & x = 0 \\ 0 & x \neq 0 \end{cases} \quad (6)$$

P_{NLOS} is the possibility of the NLOS condition, which is affected by the human body. P_{NLOS} is 1 while NLOS occurs; otherwise P_{NLOS} is 0.

Such examples show that even in the Body Surface to Base Station scenario, the human body itself is an essential influence to the performance of localization. Therefore, the influence of human body on multipath is necessary to be considered for the performance evaluation of wireless access and localization in body sensor networks. However, the channel model showing the influence of human body on multipath conditions is still unavailable.

III. CPT for Environment Virtualization of Wireless Access and Localization in BSN

Taking the advantages of both the cybernetic approach and physical approach, we designed and implemented a cyber physical test-bed for environment virtualization of Wireless access and localization in BSNs. Fig. 2 (a) illustrated the overall architecture of the CPT. In this CPT, a real time channel emulator is used to emulate the influence of the environment according to the input channel model, which is generated based on the scenario of communication, including the environment surrounding the devices and the positions of the devices. The BSN devices under evaluation are connected to the virtualized environment emulated by the channel emulator and executed in the same manner as in field testing to gather the performance.



(a)

(b)

Fig. 2 Architecture and implementation of cyber physical test-bed for environment virtualization of BSN. (a) Architecture of CPT (b) Implementation of CPT

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Fig. 2 (b) shows the implementation our CPT using PROPSim C8, a real time multi-channel channel emulator, which is commercially available by Elektrobit. The bandwidth of each channel of the PROPSim C8 is 70 MHz with the frequency range between 30~2700MHz, which accommodates popular cellular and wireless local and personal area networking applications such as IEEE 802.15.4, IEEE802.15.6 and Wifi. The details of the implementation of PROPSim C8 are available at Ref. [15].

A. Real-Time Channel Emulator

Generally, the channel emulator utilizes the impulse response method to emulate the radio propagation. The parameters of the impulse response in 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) convertors. 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 Gaussian, Rayleigh, Rician or Lognormal, the channel emulator can construct the propagation environment for a wide variety of application environments form urban and indoor wireless networks to body sensor networks.

B. Channel Model Generation

In order to evaluate the performance using this CPT, the corresponding channel models, which represent the influence of environment on wireless channel in real world application, should be loaded into the channel emulator to create the environment virtualization. In our CPT, the specific path loss model and impulse response model are generated and emulated as following:

1) Path loss model

The path loss channel model is used to evaluate the performance of wireless access and RSS based localization. We transform the Path-loss model into a one-tap impulse response model and combine it with Gaussian fading to form the input of PROPSIM C8. The parameters of the path loss model are provided by standards such as IEEE 802.15.6. For the scenarios outside human body, the distance of the path loss mode can be calculated according to the positions of transmitter and receiver in the application field or in the map. For the scenarios inside the human body, a 3-D body mesh, as shown in Fig.3 (a) is used to provide the coordinates of wearable and implanted devices.

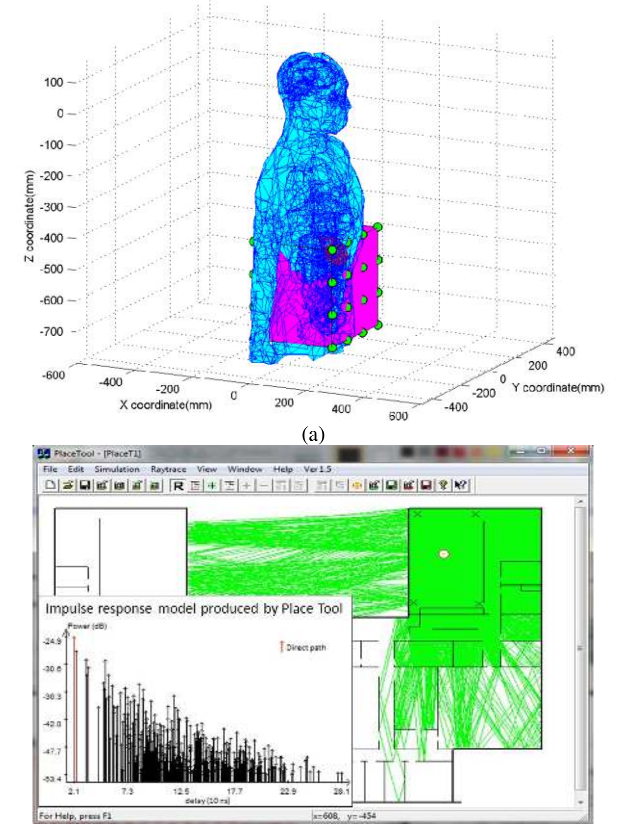
2) Impulse response model

We use Ray-Tracing software to produce a site-specific impulse response channel model for the multipath environment in the CM4 scenarios. Ray-Tracing is the most popular site-specific radio waveform propagation modeling technique used for simulation of multipath condition for performance evaluation of wireless communication [16, 17] and localization systems [18]. 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 [19]. For example, in the surface to external BSN application scenario, we can use the environment of the application and calculate the multipath reflection and coefficients of each wall, objects and human body from the transmitter to receiver. Ray-tracing software will add fading, power loss and time of arrival on each path and construct channel profiles. The Ray-tracing software used in this paper, PlaceTool (as shown in Fig. 5) is a measurement calibrated proprietary software developed by the Center of Wireless Information Network Studies (CWINS), Worcester Polytechnic Institute. A description of this software is available in reference [20].

To achieve 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:

$$f(x)=\begin{cases}\frac{x}{\sigma^2}\exp\left(-\frac{x^2}{2\sigma^2}\right), & x\geq 0\\ 0, & x<0\end{cases} \tag{7}$$

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



(a) (b)

Fig. 3 3-D body mesh and Ray-tracing software used for generate the channel model for emulation. (a) 3-D body mesh. (b) 5 Ray-tracing software

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Because there is no available channel model that describes the influence of the human body on multipath conditions in the literature, we could not implement the influence of the human body into the ray-tracing software. However, the validity of ray-tracing algorithm in simulating the multipath condition has been verified by many studies [18, 21]. We believe that if the influence of the human body can be added to ray-tracing software, the CPT can evaluate the performance of human tracking precisely.

For the localization of implanted devices, the accuracy deviates within several centimeters. Only the localization system developed based on Ultra-Wideband (UWB) has a resolution that can meet this requirement. However, due to the bandwidth limitation of the PROPSim C8, the CPT introduce above is not capable of evaluating the performance of UWB systems, whose bandwidth is larger than 500MHz. To address this problem, we designed a UWB channel emulator. Details of the UWB channel emulator and preliminary results will be introduced in Section V.

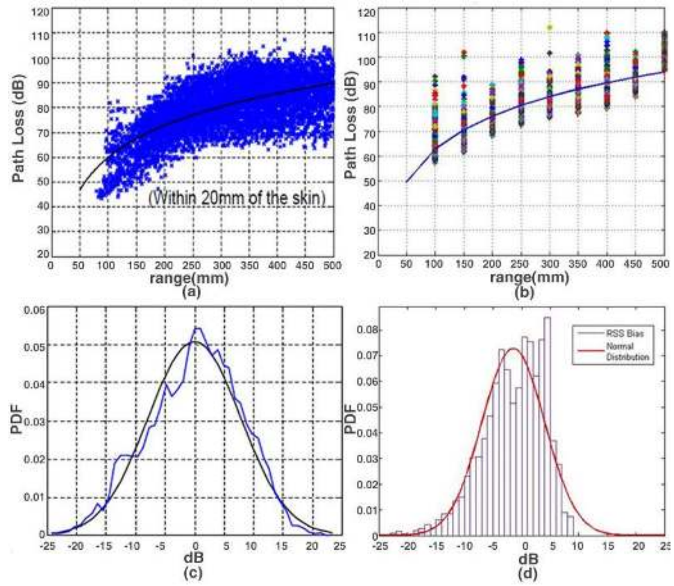

Fig. 4 Comparison of standard path loss model and emulated path loss model

IV. Case Studies

In this section, we use the CPT introduced in Section III for the performance evaluation of data transmission inside the human body and TOA-based indoor localization to verify our approach and to showcase the application of the CPT. In the case of data transmission inside the human body, we first compared the path loss channel model emulated by the CPT with the standard channel model to verify the accuracy of the channel emulation and then examine the influence of modulation and demodulation of the transceiver on the performance of data transmission inside the human body.

In the case of TOA-based indoor localization, proper impulse models for CM4 have not yet been brought about in the literature. The current version of ray-tracing software is unable to simulate the influence of the human body. Therefore, the effect of the human body to the multipath channel is not considered in the experiment. The ranging accuracy and localization accuracy of a commercial system developed based on IEEE 802.15.4A Standard is evaluated in a typical office building. The results measured using this CPT are compared with the field tested results to verify the functionality of the CPT in emulating multipath channel conditions.

A. Performance evaluation of data transmission inside human body

Zarlink ZL70101 Application Development Kit, which is developed based on a MICS band transceiver [22], is selected to be the BSN devices for performance evaluation of in-body data transmission. The development kit includes two development boards of body sensor nodes. To emulate the RF propagation inside the human body, the path loss models of CM1 and CM2 presented in the draft of IEEE 802.15.6 are used and the parameters are shown in Table I and Table II.

1) Accuracy of Emulated Path Loss Model

In this experiment, the path loss model with the distance from 100 mm to 500 mm is emulated by the channel emulator, PROPSim C8. The body sensor nodes transmit data through the emulated in-body wireless channel and the received signal strength (RSS) are corrected to figure out the curve fitting of path loss and the fading. Fig. 4(a) shows the curve fitting of path loss of the standard model, which is also presented in Ref. [11]. Fig. 4(b) shows the curve fitting of path loss measured by the devices through the emulated channel. Close agreement can be found between the standard channel model and the measurement result, thus emulation accuracy can be proved. Fig. 4(c) shows the fitting of the fading in the standard model, which is a typical Gaussian distribution. Fig. 4(d) shows the fitting of the fading measured by the devices, which is also Gaussian distribution with similar parameters to the standard fading. The results again prove that our CPT can accurately emulate the path loss model.

1) The Influence of Modulation on Data Transmission

The performance of data transmission is affected by the settings of the device, such as the modulation scheme and transmitting power. Therefore, the devices settings should be selected properly to ensure the performance of the communication system. Traditionally, field testing is used to evaluate the performance of the system under different setups before real application. However, due to the difficulty of deployment inside the human body, field testing is not feasible. In this experiment, we use the CPT to emulate the virtualized environment inside the human body and study the influence of modulation of the transceiver on the success rate of data transmission. There are three selections of modulation schemes provided by the transceiver [22]: 2FSK high sensitivity, 2FSK high rate and 4FSK. The performances of these modulation schemes are evaluated based on the statistical results of the emulation. The setups of measurement include the modulation scheme, channel conditions and distances between the transmitter and receiver. The channel conditions used in this experiment include CM1 (near surface to near surface), CM1 (deep tissue to deep tissue), CM2 (near surface to body surface) and CM2 (deep tissue to body surface) and the distances between transmitter and receiver include 50 mm, 100 mm, 150 mm, 200 mm and 250 mm. For each measurement, 20000 packets are transmitted by the transmitter. Number of received

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packets is used to calculate the success rate of data transmission, which is defined as following:

$$P_{SRDT} = \frac{N_{RX}}{N_{TX}} \quad (8)$$

where P_{SRDT} is the success rate of data transmission, N_{RX} is the number of successfully received packets and N_{TX} is the number of transmitted packets.

Fig.5(a) shows the performance of CM2 (near surface to body surface) and Fig.5(b) shows the performance of CM2 (deep tissue to body surface). In these two scenarios, 2FSK high sensitivity modulation always achieves the best performance. The 2FSK high rate modulation has poorer link quality compared to 2FSK high sensitivity, while 4FSK is the worst of the three modulations. When the distance between the transmitter and receiver is larger than 100 mm, the connectivity can hardly be maintained using 4FSK. Fig.5 (c) shows the performance of CM1 (near surface to near surface) and Fig.5 (d) shows the performance of CM1 (deep tissue to deep tissue). Similar results are shown in these two scenarios and we can easily judge that 2FSK high sensitivity modulation always outperforms the other two. In these two scenarios, not only dose the 2FSK high sensitivity achieve a high success rate, but 2FSK high rate and 4 FSK also attain good performance. These results are important to the developers of BSN systems. For example, according to the results, we know that the 4FSK scheme of this device should not be selected, except when the transmitter and receiver are both located inside human body and the distance between them is less than 50 mm.

B. Performance evaluation of TOA based indoor localization

The localization system used in the evaluation, NanoLOC development kit, is developed based on NanoLOC, which is a RF chip with the capability of TOA measurement. NanoLOC is designed to support IEEE 802.15.4a Standard and it is commercially available through Nanotron Inc. The two-way TOA ranging algorithm adopted in NanoLOC is introduced in Ref. [24] and the principle of Trilateral-centroid localization algorithm used in NanoLOC development kit can be found in Ref. [25].

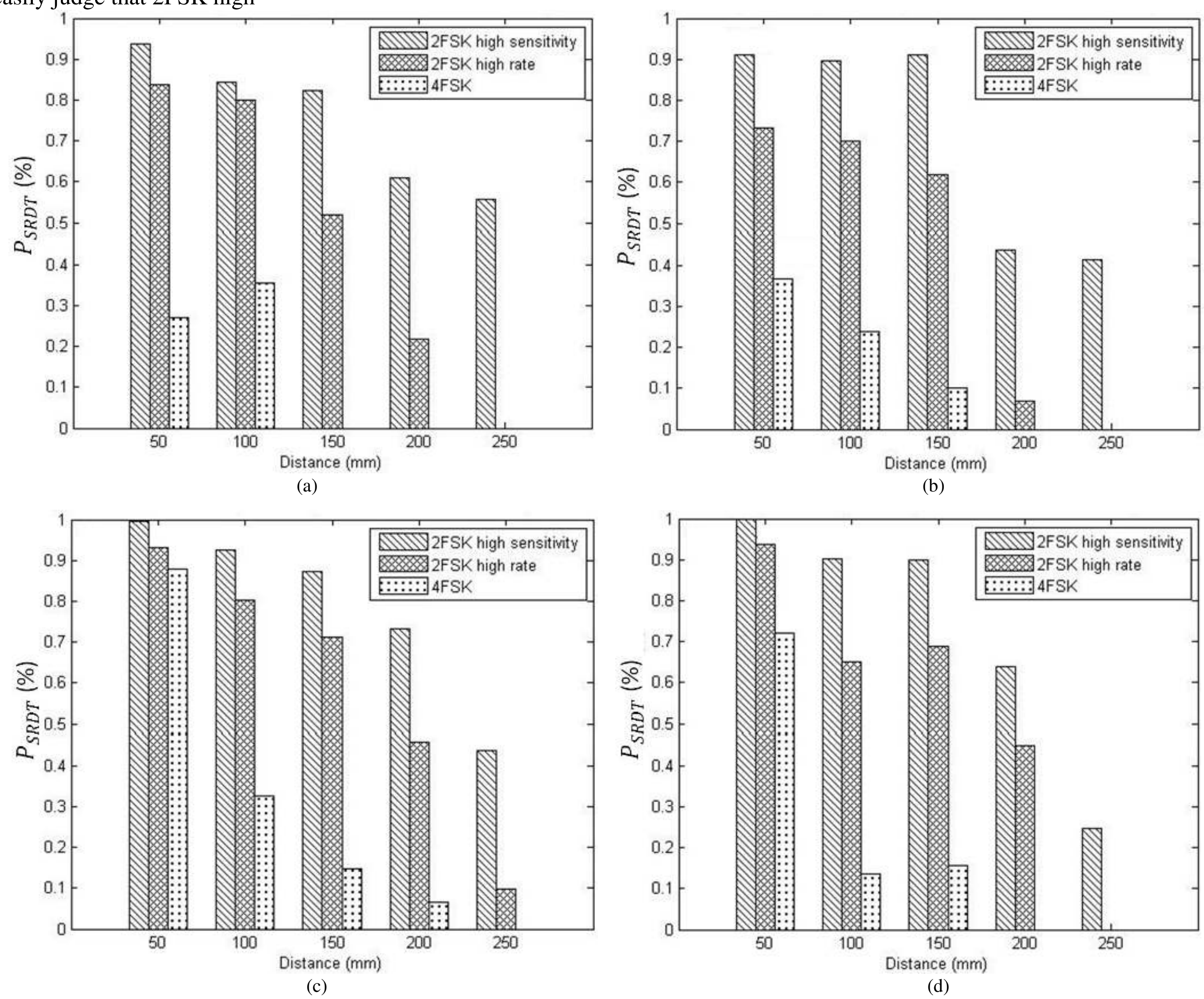

Fig.5 The influence of modulation on the performance of data transmission inside human body. (a) Implant to body surface, near surface model. (b) Implant to body surface, deep tissue model. (c) Implant to implant, near surface model. (d) Implant to implant, deep tissue model.

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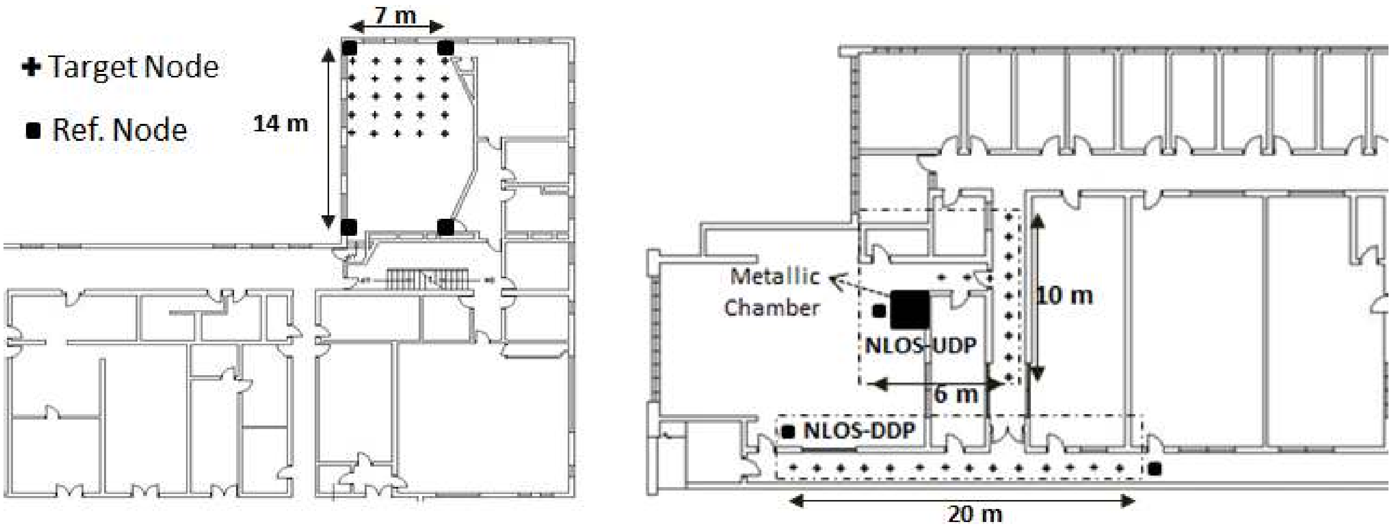

(a) (b)

Fig. 6 LOS and NLOS scenarios. (a) LOS scenario. (b) NLOS scenario

1) Scenarios

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

The field testing for the free space scenario is conducted in an anechoic chamber inside CWINS lab, Worcester Polytechnic Institute (WPI), MA, with the Reference nodes located 2.34m from the target nodes. Both LOS and NLOS scenarios are also conducted inside Atwater Kent (AK) building, WPI. Fig. 8(a) shows the room AK233 in which the field testing for LOS scenario was accomplished. Four base stations are located at the corners of the classroom and the Target node appears at different locations. The NLOS scenario is conducted on the third floor of AK building and it's partitioned into two different sub-scenarios, NLOS-DDP and NLOS-UDP. In NLOS-DDP, the target node and the base station are separated by a wooden wall in which the direct path still survives after the penetration. In NLOS-UDP, the target nodes are separated from the base station by a metal-walled chamber, which totally cuts off the direct path and causes undetectable direct path (UDP) condition.

2) Results

To evaluate the performance of a localization system, the most frequently used metrics are ranging errors and localization errors. The ranging error e_R is defined as the difference between actual distance and distance estimation of each reference point- target node pair in equation (9):

$$e_R = \hat{d} - d \tag{9}$$

where $\hat{d}$ is the ranging result obtained from the measurement and d is the actual distance between the two nodes.

Fig. 7(a) through (d) compares the CDF of ranging error obtained from the evaluation experiment with cyber physical test-bed approach and actual measurement in field test. From the comparisons, one can see that the ranging error distributions observed in the CPT emulation results are very similar to those observed in the field test. Table III shows the mean and standard deviation observed in each of these approaches. From Table III one can see that the means and stand deviations found in the CPT emulation results are also similar to those found in the field test.

Both the results of CPT approach and field testing clearly indicate the ranging accuracy variation observed in different test scenarios, as the multipath condition changes. From the result of the free space case, we can see that the best performance of the indoor tracking system in the 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 the ranging error of free space. We can also see the influence of the wooden wall and the metallic chamber to the ranging accuracy by comparing the ranging error of NLOS-DDP and NLOS-UDP with free space and LOS scenarios.

The localization error is defined as the Euclidean distance between the actual location of target node and the location estimation of the target node in equation (10):

$$e_L = \sqrt{(\hat{x}-x)^2 + (\hat{y}-y)^2} \tag{10}$$

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

Fig. 8 compares the CDF of localization error observed in the cyber physical emulation and field test results. Table IV compares the mean error, stand deviation between the CPT approach and field testing approach. The distribution of localization error obtained from the CPT shows a close agreement with the results of the field tests, proving that the CPT described in this paper is also well capable for emulate the complicated multipath condition and performance evaluation of TOA based indoor localization.

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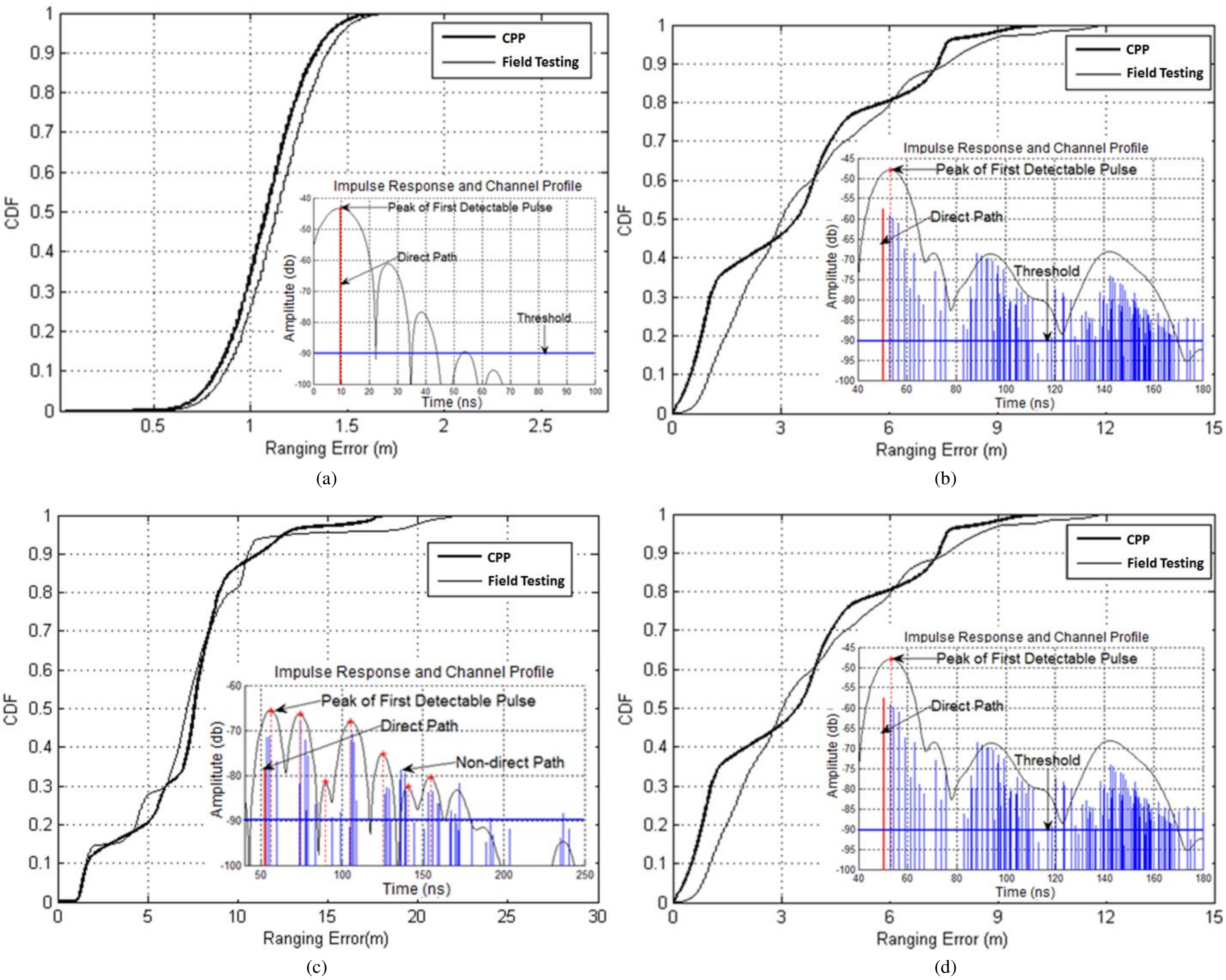

Fig. 7 Comparison of ranging accuracy. (a) Free space. (b) LOS scenario. (c) NLOS-DDP scenario. (d) NLOS-UDP scenario

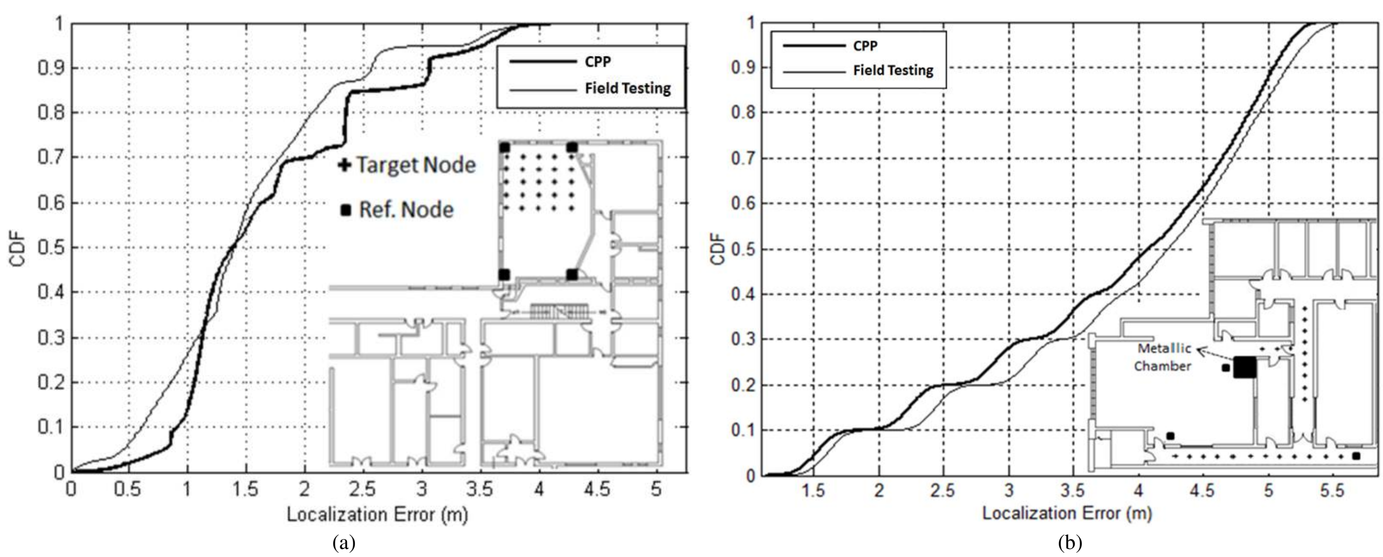

Fig. 8 Comparison of loclaization accuracy (a) LOS scenario and (B) NLOS scenario

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TABLE III RANGING PERFORMANCE COMPARISON

Channel Condition		Free space	LOS	NLOS -DDP	NLOS -UDP
Field testing	Mean(m)	1.13	3.70	7.22	15.25
	Standard deviation(m)	0.65	2.58	3.97	4.96
CPT	Mean(m)	1.08	3.32	7.22	14.66
	Standard deviation(m)	0.62	2.50	3.35	7.75

TABLE IV LOCALIZATION PERFORMANCE COMPARISON

	LOS		NLOS	
	Mean (m)	Standard deviation (m)	Mean (m)	Standard deviation (m)
Field testing	1.50	0.78	3.91	1.14
CPT	1.69	0.71	3.77	1.16

I. UWB CHANNEL EMULATOR

Traditionally, channel emulators are developed based on DSP processors or field-programmable gate arrays (FPGA). The bandwidth of the channel emulator is limited by the speed of the DSP processor or the FPGA. The maximum bandwidth of the commercial available channel emulator in the market is 125MHz. For most of the narrow band and wide band communication cases such as Wi-Fi, WPAN and so forth, such bandwidth is already adequate. For UWB systems, however, the bandwidth is still far from enough. In this section, we designed a channel emulator for UWB using analog devices to overcome the bandwidth limitation of the digital solution.

1) *UWB Channel Emulator*

Fig. 9 shows the architecture of the UWB channel emulator and the process of emulating an impulse response channel model using this emulator. The frequency of these devices should cover part of or the whole of the UWB band and the bandwidth is larger than 500 MHz. The overall architecture of the UWB channel emulator includes a pair of impulse splitter/combiners, delay controllers, path loss controllers and phase controllers. We use the power splitter (Mini Circuit ZN4PD1-63W) to split the original input RF signal to multipath signals and also combine the multipath signals to form an output RF signal. The RF signals travel in cables at a constant speed so that given a tunable cable length and the speed of RF signal in the cable, the travel time of RF signal can be dynamically controlled. Different lengths of RF cables have been employed to control the tap delay of the impulse channel model as the delay controller. MCU driven controllable attenuators (Hittite HMC624LP4 with a MCU, ATMega 128) have been selected to create the path loss. The phase of each tap can be managed by controllable phase shifter. At current stage, this UWB channel emulator is designed for high accuracy TOA based localization so that the phase controller can be temporarily omitted. When an impulse comes in, the splitter creates replicas and each replica goes through different lengths of wire to obtain different tap delays and then get attenuated to specific value by the path loss controller. After that, all the taps are gathered together to form the specific channel model.

2) *Validation*

To validate the UWB channel emulator, a network analyzer has been connected to the emulator and impulses have been sent from the input port. Typical output of single attenuator and tap delay line recorded in Fig. 10. As can be seen from Fig. 10(a), every single attenuator is able to create Gaussian random variables with a 31.5dB span, where the picture on the top left corner shows the measurement platform. Since a single attenuator has 0-6GHz bandwidth and 0.5dB LSB steps up to 31.5dB, we can cascade two attenuators in each fading control unit in order to get enough attenuation for in-body cases. Fig. 10(b) shows the measurement results of tap delay line. The origin wire lengths are 26cm, 52cm and 153cm, if we take 2.1×10^8m/s as the rough propagation velocity inside the cable, the measured wire lengths are 23.43cm, 49.69cm and 134.99cm. Such results can be regarded as acceptable due to the fact the error occurred at the connectors and distributors are not taken into consideration and the velocity inside wire is not accurate enough.

Further time domain validation has been conducted by comparing the output of UWB channel emulator with PROPSim C8. In this case, wires with multiple different lengths have been used to obtain more tap delay readings and the curve fitting result has been plotted. As can be seen from Fig. 13, our emulator has a very similar time domain property compared with PROPSim C8. To make the UWB channel emulator real time and become capable to multiple scenarios, our future work will be implementing a delay control unit by using MCUs, RF switches and wire combinations to dynamically control the tap delay. We believe that based on the delay control unit, our emulator will be competitive to all of the existing wireless channel emulators and at the same time become remarkable for the ultra-wide bandwidth.

II. CONCLUSION

Performance evaluation is rather important for BSNs because any defects in the design not only lead to a huge waste of resources but also threatening the health and safety of a human being. Due to difficulties in simulating the influence of design of the device and implementation of the system on the performance of communication and localization, it is very difficult to accurately measure the performance using software simulations. To address this problem, we have designed a cyber physical test-bed for environment virtualization of wireless access and localization in BSNs. The platform was then used for performance evaluation of commercial wireless access and localization system in typical scenarios. It was shown that the

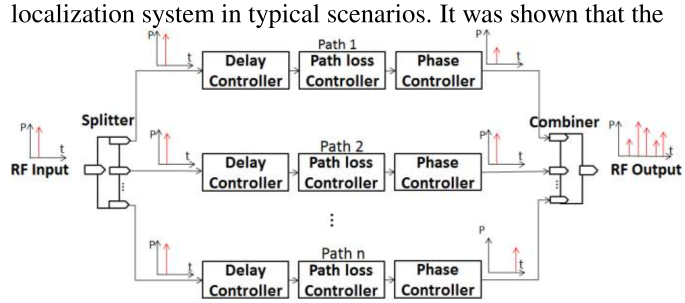

Fig. 9 Analog test-bed for ultra-wideband channel emulation

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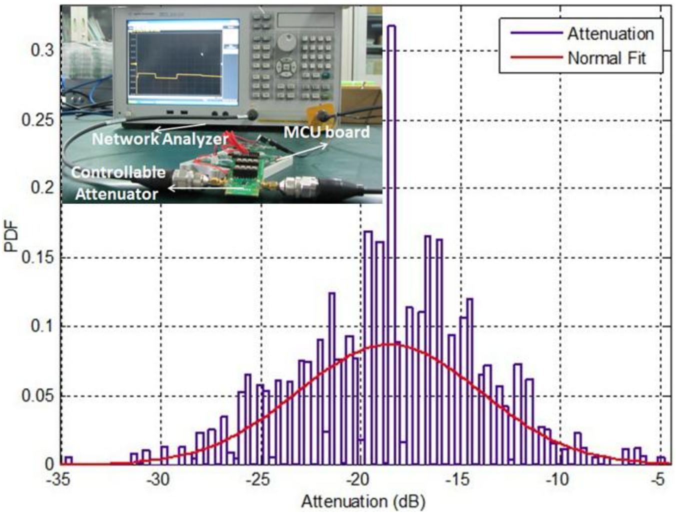
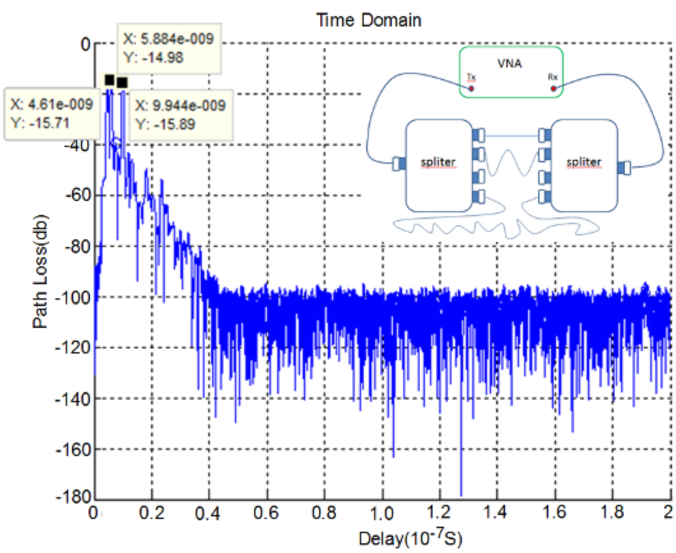


(a)



(b)

Fig. 10 Validation result for the self-defined UWB emulator. (a) Validation result for path loss controller. (b) Validation result for delay control controller.

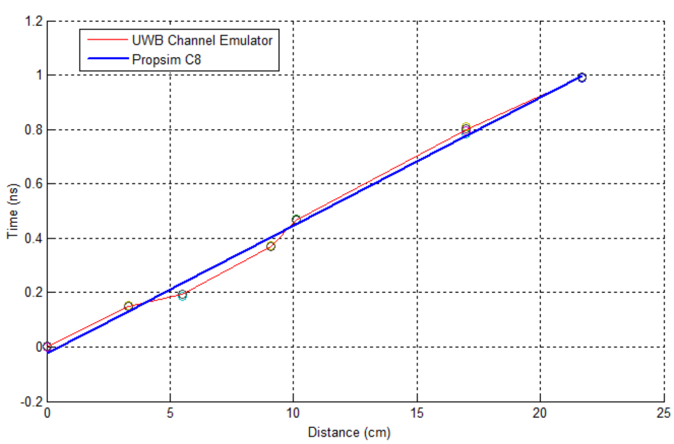


Fig. 11 Comparison of TOA distance meausrments between UWB channel emualtor and Propsim C8

results of the performance evaluation obtained from the cyber physical test-bed closely follow the empirical measurements in the field tests. At the end of this paper, we presented a channel emulator for UWB developed based on an analog solution to overcome the bandwidth limitation of the digital solution. The preliminary experiment result verified this analog approach.

The channel models considering the effects of the human body, especially the multipath models for TOA based localization, are critical to the implementation of CPT. However, there are no available multipath models in the literature. For the next step, we will work on modeling effects of the human body on multipath propagation for the localization of on-body sensors and modeling the multipath propagation for the localization of in-body sensors and add the effect into the process of performance evaluation. Another future work is to implement the delay controller of the UWB channel emulator and the UWB channel emulator.

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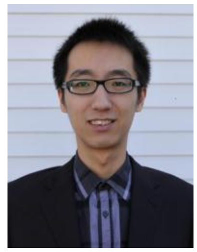

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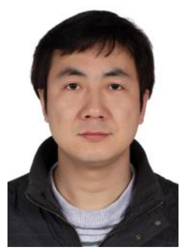

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