Toward Standard Non-line-of-sight Benchmarking of Ultra-wideband Radio-based Localization

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***Abstract*—Performance of Ultra-wideband (UWB) radios in non-line-of-sight (NLoS) environments has been a topic of interest among researchers, especially when it comes to indoor localization applications. It is known that NLoS propagation of electromagnetic waves can severely affect the localization accuracy. Despite the interest in indoor localization performance, it is still difficult to compare results from different studies without proper evaluation standards. Understanding the types of materials used in a testing environment could be a proper technique for benchmarking different localization solutions in different scenarios. We provide a systematic study to investigate effects of signal refraction and attenuation on UWB signals in different construction materials by examining the Channel Impulse Response (CIR) and ranging accuracy. Further, we present failure scenarios for common NLoS identification and mitigation techniques.**

***Index Terms*—Ultra-wideband, UWB, UWB Indoor Localization, Non-Line-of-Sight, NLoS, Benchmarking**

I. INTRODUCTION

Ultra-wideband (UWB) radios have received a lot of attention in the past few years after development of affordable commercial chips like DW1000 [1] by decaWave [2]. UWB radios facilitated precise indoor localization due to the capability of estimating time of arrival (ToA) of wireless packets in sub-nanosecond level, hence it drew attention of researchers and even made it's way to industrial solutions. While researchers proved that UWB-based localization techniques are viable solutions, yet there is no benchmarking standard to fully understand the localization performance in different scenarios. It is difficult to make a systematic comparison between proposed solutions without a proper performance evaluation standard; furthermore, the evaluation scenarios cannot be fully aligned to real-world deployment environments.

Researchers developing new UWB-based, including decaWave-based, localization systems, evaluate their new approaches typically in Line-of-Sight (LoS) scenarios, and in more serious and recent work also in non-Line-of-Sight (NLoS) scenarios. The reason to include these scenarios in their evaluation is they want to mimic realistic environments, which consists of a mix of LoS and NLoS scenarios. LoS scenarios are well-defined and generally mean no visual obstruction between the tags and the anchors used in UWB localization experiments. Unfortunately, we have found no consistent definition of NLoS scenarios. It appears that the researchers are using walls or other types of obstruction as NLoS, i.e., visual NLoS scenario. While the intention of the researchers in incorporating NLoS experiments is commendable and is in the right direction for the field, without understanding UWB propagation properties of UWB through those obstructions, it is difficult to not only compare results from different publications but also to know if we are truly evaluating UWB-based localization where the tags and the anchors may have "difficult" obstructions in-between: a thin paper may create visually NLoS scenario but will not have much impact in localization performance. Thus, NLoS is loosely defined; hence it is interpreted differently in various contexts.

From technical standpoint there is a clear difference between LoS and NLoS scenarios. A radio signal, when LoS is obstructed, can be attenuated, refracted, reflected, or diffracted. The receiver always receives a combination of the above mentioned signals with different proportions. Although visual NLoS blocks LoS between transceivers, a large proportion of radio signals may still be able to penetrate the obstructing material. Refracted signals are delayed compared to LoS signal; hence they add a positive bias to time-of-arrival (ToA) observed by the receiver, which translates to ranging bias in distance estimation and localization applications. With prior knowledge of the environment, including possible sources of reflection, and obstructions' shape and material, we may be able to correct the positive bias caused by the delayed signals. The localization techniques developed by researchers routinely use these properties of UWB propagation through obstacles. If NLoS is interpreted inconsistently, a technique that claims to work well in NLoS scenario may not work well in NLoS scenario replicated by another researcher. In fact, this has been one of the challenges in the field of UWB-localization because researchers have found it difficult to replicate the results reported by others despite a large number of researchers using the same decaWave chips.

It can be extremely difficult to identify what truly happens to radio signals especially in real-world dynamic NLoS scenarios. With the lack of a proper benchmarking standard, research studies created their own test scenarios to evaluate their proposed localization solutions. Since it is hardly possible to create exactly the same customized test environments from one study in another one, it is impossible to correctly compare their results. Furthermore, physical properties of the obstructing material, even if the exact same material is used, affect the behavior of radio signals: (1) Thickness and substance affect attenuation and refraction. (2) Smoothness of the surface affects reflection. (3) Shape and thickness of edges affect diffraction. The two latter cases are harder to characterize when we try to understand NLoS scenarios in a typical test environment.

We take the first steps toward standard NLoS benchmarking to understand how attenuation and refraction affect radio signals. We are not trying to provide a new solution for indoor localization nor NLoS detection. Our contributions are:

- We present a methodology to observe effects of attenuation and refraction on UWB radio signals by minimizing reflection and diffraction.
- We explore true effect of attenuation and refraction on UWB radio signals when the signal propagates in different construction materials.
- We present scenarios where NLoS ranging performance of UWB radios are severely affected by NLoS, but it is impossible to identify and mitigate without use of fingerprinting and proper amount of learning data.

II. RELATED WORK

Propagation of radio frequency signals through different materials has been studied before. The main focus in literature work is analyzing the impact of building walls and objects on propagation model and degradation in reliability of RF communication. The type of investigated materials in those benchmarking works has been summarized in Table I.

The lack of common standard in other RF benchmarking works is obvious from Table I.

III. BACKGROUND

In this section we talk about how RF signals propagate in presence of obstacles, and specifics of UWB signals and common techniques in UWB-based localization.

A. Propagation of RF Signals

Propagation of radio waves in various mediums have different behaviors. NLoS is transmission of radio signals where LoS is obstructed. As shown in Fig. 1a, when a radio wave hits an obstacle, it may be impacted in one of the following ways:

1) Attenuation: Amplitude or signal strength may decrease due to absorption of the signal.

2) Refraction: Waves may change direction when it goes from a medium to another medium with different density due to change in the propagation speed.

3) Reflection: Waves may bounce from a smooth object larger than it's wavelength.

4) Diffraction: Waves may bend and change direction around an object, especially sharp edges, by maintaining their original speed and become a secondary source of waves.

B. UWB Radio

DW1000 by decaWave is an Impulse-based UWB radio that operates in 3.5 GHz to 6.5 GHz center frequency with bandwidth choices of 500 MHz and 900 MHz. The radio chip is able to estimate and report Channel Impulse Response (CIR) with received packets along with RX quality information.

C. Anechoic Chamber

An anechoic chamber is a room designed to isolate transceivers from outside noise. The room is covered by highly absorbent materials to absorb signals and prevent reflections. We did our experiments in an anechoic chamber to minimize signal reflections and diffractions.

D. Two-way Ranging

To estimate the range between transceivers, an asymmetrical double-sided two-way ranging method can be used, which is one of most common and practical UWB ranging techniques in indoor localization. Since DW1000 is capable of reporting ToA of packets with sub-nanosecond resolution, it enables us to calculate the time-of-flight (ToF) with decimeter-level precision. Fig. 2 shows the message exchange protocol. Using the reported timestamps we can calculate ToF with Eq. 1 [9].

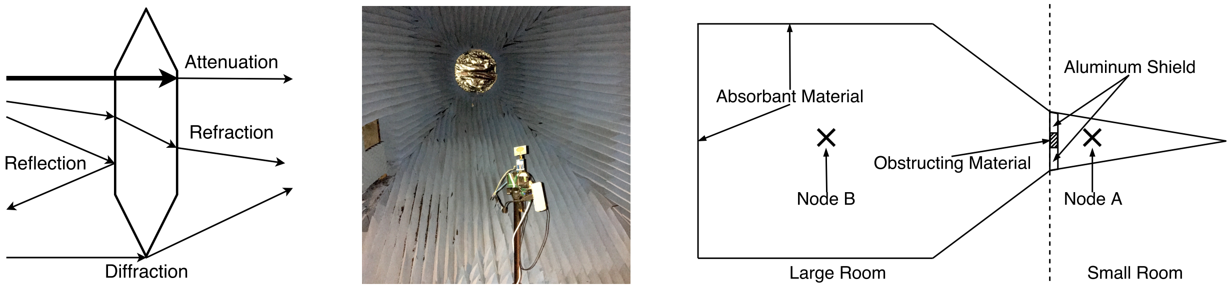
$$ToF = \frac{T_{round1} \times T_{round2} - T_{reply1} \times T_{reply2}}{T_{round1} + T_{round2} + T_{reply1} + T_{reply2}} \qquad (1)$$

IV. HOW DO WE EVALUATE NLOS UWB TODAY?

Features like large bandwidth, low duty cycle and high penetration rates enabled UWB indoor localization systems to achieve accuracies around 10 cm [18]. Three most popular techniques used in UWB indoor localizations are Time of Arrival(ToA) estimation [19], Time Difference of Arrival(TDoA) [20] and Angle of Arrival (AoA) estimation [21]. In all the techniques, line of sight (LoS) signal is used to estimate the location of the target. In all the mentioned approaches handling non line of sight signals (NLoS) is a real challenge. Literature work in this area can be categorized into two sections: Avoiding NLoS signals [11], [22] and Utilizing NLoS signals [10]. In utilizing NLoS techniques, NLoS signals are added to LoS to improve the robustness of indoor localization system. These approaches do not try to distinguish between NLoS and LOS signals. In avoiding NLoS approaches, the focus is on increasing the chance of receiving the LOS signal either by using more antennas and links or detecting NLoS signals and discarding them. Despite the advancements in both categories (Avoiding/Utilizing NLoS), the lack of common standard to evaluate these works is obvious. In Table II, we summarized experiment set ups used by literature work in UWB localization area for performance evaluation of their system. As shown in Table II, there is no common ground to compare the proposed work. Since in most of the related work, the authors did not precisely specify the type of materials in their test environment, we had to guess the material based on the experiment's environment. It is essential to mention that competitions like Microsoft Indoor Localization provide a common environment to evaluate indoor localization systems but they require all the competitors to bring and set up their system in the specific location. The focus of our work is providing guidelines toward standard benchmarking of indoor localization systems. Researchers at TU Berlin also started some work toward standardization of indoor localization systems [23]. They proposed a framework to collect location

TABLE I: NLoS RF Propagation Studies

Ref	Frequency Band	Environment	Type of Material
[3]	500-2000 MHz and 3,000-8,000 MHz	Lab	Brick, Brick-faced Concrete, Brick-faced Masonry Drywall, Uncoated Glass and Dry Lumber
[4]	200MHz3 GHz	Academic Building	Cinder blocks
[5]	900MHz	Lab	Brick, Concrete
[6]	0.5 to 2 GHz and 3 to 8 GHz.	Lab	Concrete
[7]	800 MHz to 6 GHz	Lab	Windows with Transparent Conductors
[8]	700 MHz-5 GHz.	Residential House	Not Reported



(a) Propagation of radio when interacting with an obstacle of a different medium. Signals can be attenuated, refracted, reflected, or diffracted.

(b) Complete NLoS created by aluminum-covered signal shield. No communication is possible.

(c) Experiment setup in an anechoic chamber, showing the receiver node and aluminum-covered signal shield, allowing signals to go through only the obstructing material.

Fig. 1: RF signal propagation and anechoic chamber

TABLE II: UWB Localization State of the Art - Experiment Set up

Ref	Test Environment	Type of Material	Most Probable Material
[10]	Room in a commercial building	Not Reported	Wooden Walls
[11]	$20m \times 20m$ in academic building	Not Reported	Concrete and Wooden Wall
[12]	Office space	Not Reported	Wooden Walls
[13]	The hole of a building	Not Reported	Concrete Walls
[14]	A residential apartment	Not Reported	Wooden and Brick Walls
[15]	Heavy Machines Laboratory	Metallic surface and motors	Metal
[16]	A lecture room, a cluttered laboratory and a corridor	Not Reported	Wooden and Concrete Walls
[17]	Several offices, hallways, one laboratory, and a large lobby	Not Reported	Wooden and Concrete Walls

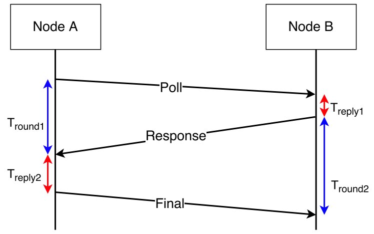


Fig. 2: Asymmetric double-sided two-way ranging. First, Node A sends a ranging poll message, then Node B sends a response, and finally Node A sends a final message including T_{round1} and T_{reply2}, so the receiver can calculate time-of-flight.

estimations and ground truth information and also calculate statistical information about the accuracy of indoor localization systems which is being tested.

The lack of evaluation standard is more serious in NLoS identification techniques since the main idea in such works is utilizing differences between LOS and NLoS signals. Recently in [24] authors pointed out visual NLOS challenge in which the LOS signal is obstructed by walls and objects but the received signal still is very similar to LOS signal. This phenomena seriously degrades the performance of previous work in NLoS identification/mitigation area [24]. The decaWave company (Manufacturer of DW1000 chips) also studied the problem of visual NLoS signals through several application notes [25], [26]. Our results also indicate the similarity of LOS signal with visual NLOS signals. We also show that the real time approach proposed by [24] which compares the received signal's power with first path power is not reliable in the cases that there are not enough multipath reflections in the received signals.

V. EXPERIMENTS

Fig. 1b and 1c show the experiment setup in an anechoic chamber. We divided the chamber into a small room and a large room by placing an aluminum shielded object between the rooms. We placed the transmitter node inside the small room and the receiver node inside the large room. Despite using an RF-opaque shield, communication is still possible through diffracted signals. We confirmed that the transceivers cannot communicate when we removed diffraction effect by completely covering edges of the signal shield with signal absorbent walls. Although the signal shield is covered by multiple layers of aluminum, we verified that one layer of aluminum with thickness of 0.024 mm is sufficient to completely block signals and no communication would be possible. Further, we cut a 158 mm × 158 mm hole in the shield to allow signals reach the receiver node. Then we covered the hole with different construction materials listed in Table III, which are purchased from Home Depot, so the signals can go through only the obstructing material. This method enables us to observe the pure effect of signal attenuation and refraction caused by different materials. We used two radinoL4 DW1000 as our transceivers and implemented an application to collect ranging data, implemented as asymmetrical double-sided two-way ranging, along with CIR and RX quality information. Transceivers were placed in approximately 3.86 m apart from each other, operating in UWB channel 2 (4 GHz center frequency and 500 MHz of bandwidth), with preamble length of 2048, and data rate of 110 kbps.

A. Single Materials

1) CIR Analysis: Due to the very large bandwidth of UWB signals (500 MHz) high resolution (1 ns) estimate of Channel Impulse Response (CIR) is possible in UWB communication. CIR represents UWB channel as in many studies CIR has been utilized to find differences in LoS and NLoS signals. In our experiments, received packets are only NLoS signals which traveled through the obstacle. We compare the estimated CIR of received signal to study the impact of different materials on channel characteristics. Fig. 3 illustrates CIR information after changing the obstructing material between sender and receiver. As shown in Fig. 3, despite the changes in amplitude values, the overall pattern of CIR remains the same and very similar to original LoS (not obstructed) signal. Fig. 3 clearly shows the similarity between LoS and obstructed signals.

2) RX Power Level Analysis: When signals travel through an obstacle, they get attenuated and lose energy. We observe this effect in Fig. 4, showing the amount of received signal strength as an indicator of the impact of different materials. Concrete has the highest impact on power and drywall has the lowest impact.

3) Ranging Bias: NLoS propagation of UWB signals through different materials cause the signal to be attenuated and refracted. Refraction changes the propagation speed of signals and adds a delay which translates to ranging bias. Ideally, attenuation and decrease in received signal strength should not impact ranging accuracy, but previous studies [27] show that ranging has a bias varying with received signal level. Fig. 5 shows ranging bias caused by different materials, with paver brick having the largest bias.

B. Composite Materials

We conducted a few experiment to analyze the impact of composite materials on UWB signals. In each experiment two layers of different materials are obstructing LoS signal.

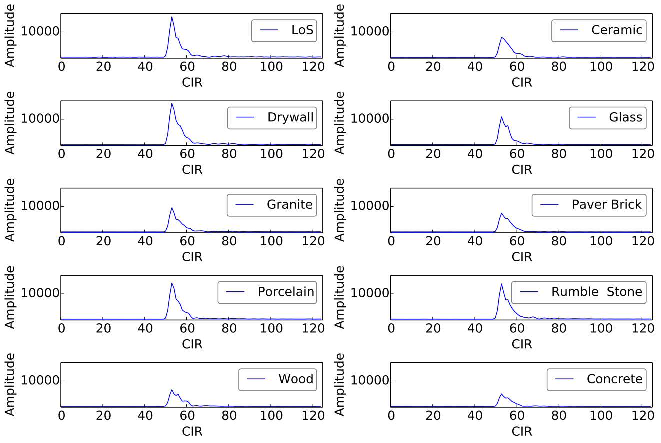


Fig. 3: CIR Impacted by different materials, obstructing LoS. Signals get attenuated and amplitude of CIR is decreased.

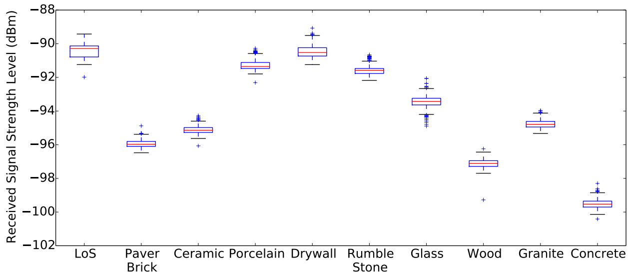


Fig. 4: RX signal strength values with different obstructing materials. Signals get attenuated and the signal power is decreased.

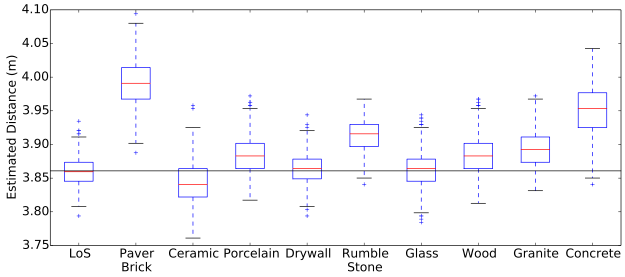


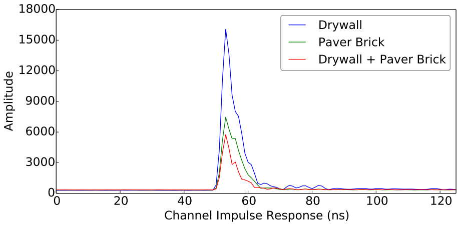
Fig. 5: Reported range in different materials. Horizontal solid line represents the true distance of 3.86 m. Combined effect of attenuation and refraction of signals add ranging bias.

1) CIR Analysis: Fig. 6 illustrates estimated CIR values after obstructing LoS with two layers of materials. Fig. 6a and 6b show impact of single materials on UWB signals separately and once they are put together to obstruct signals. Multiple layers of different materials, decrease the amplitude of signals more, but the shape still is the same as LoS signal.

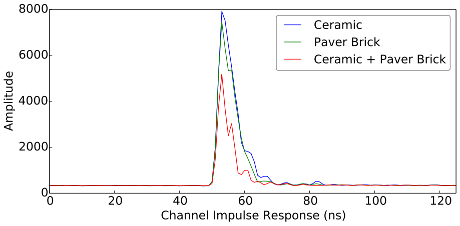
2) RX Power Level Analysis: Fig. 7 shows the effect of composites on RSS level. The impact is higher compared to single materials.

TABLE III: Construction Materials Used in Our Experiments

Material	Paver Brick	Ceramic	Porcelain	Drywall	Rumble Stone	Glass	Wood	Granite	Concrete
Thickness (mm)	59	5	5	10	43	2.4	20	10	58



(a) Drywall and Paver



(b) Ceramic and Paver

Fig. 6: Multiple layers of obstruction. CIR peak amplitude decreases, but the shape remains the same.

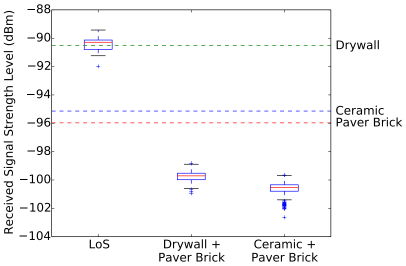


Fig. 7: Rx power values with different composite obstructing materials. Horizontal dashed lines are median RSS for single materials. Signals get attenuated more than single materials.

3) Ranging Bias: Fig. 8 shows the effect of composites on range estimate accuracy. The impact is higher compared to single materials.

C. Diffraction

In another experiment, we explored effect of diffracted signals on ranging accuracy. We blocked LoS between transceivers with an aluminum shield but this time we allowed signals to be diffracted, so the communication is possible. The experiment setup is shown in Fig. 9. The true distance between transceivers were 407 cm, but the estimated distance has a median of 405.18 cm. As shown Fig. 9, we can calculate the total distance that signals traveled as $d_1 + d_2 = 405.87$ cm.

VI. IMPLICATIONS

There are three main implications from results of our work.

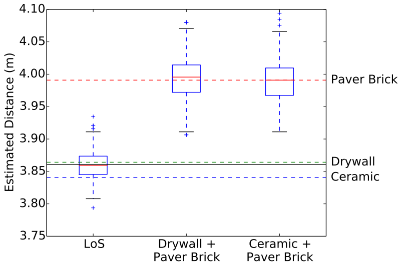


Fig. 8: Reported range in different composite materials. Horizontal solid line represents the true distance of 3.86 m. Horizontal dashed lines are median distance for single materials. Signals get attenuated and refracted more than single materials which adds more ranging bias.

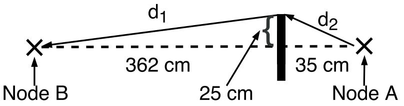


Fig. 9: Diffracted signal takes a longer path than LoS, hence the estimated distance should be larger than LoS.

A. Careful Configuration of Anechoic Chamber Experiments

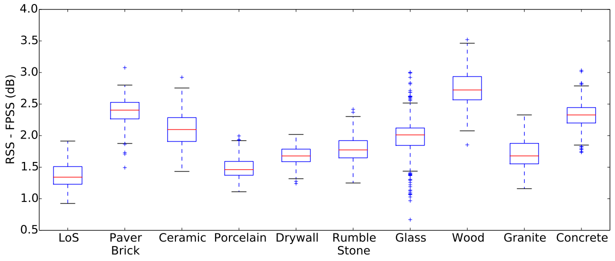
Despite being common knowledge, separate impacting factors of NLoS RF propagation is not investigated in UWB-based indoor localization studies. Observing only the combined impact of attenuation and refraction requires removing reflection and diffraction by shielding the transmitter in an anechoic chamber and allowing signals to only go through obstruction materials. Observing only the impact of diffraction requires using a RF-opaque shield in an anechoic chamber.

B. Limitation of Existing NLoS Identification Approaches

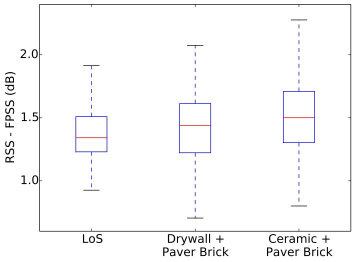
NLoS identification approaches mainly rely on the differences between LoS and NLoS signals to accurately detect NLoS signals. Our results show that in absence of multipath reflections, LoS and visual NLoS signals are very similar to each other which makes them hardly distinguishable. A recent work [24] on NLoS identification is to determine if the difference between total RX power and first path power is larger than 6 dB. Fig. 10 shows the difference in total RX power level and first path power level in our experiments which is less than 3 dB; hence it is not easily distinguishable from LoS.

C. Benchmarking

We showed that different materials have different impact on UWB-based localization performance, which means any benchmarking effort should specifically identify and report



(a) Single layer obstruction



(b) Multiple layers of obstruction

Fig. 10: Difference between total RX power level and first path power level is less than 3 dB. Small difference makes LoS and NLoS hardly distinguishable.

types of materials used in the testing environment. Furthermore, by identifying the materials in the test environment, researchers might be able to model the ranging bias more accurately.

VII. CONCLUSIONS

We identified an important problem in the domain of UWB communications and indoor localization applications. Lack of proper standard in benchmarking and neglecting the difference between visual NLoS and RF NLoS makes the results of different studies non-comparable. We are the first to systematically propose methods for evaluating UWB-based systems in NLoS scenarios. Separately observing each impacting factor in NLoS RF propagation (reflection, attenuation, refraction, and diffraction), helps understanding these impacts better in more complicated scenarios. We verified reproducibility of results in time, by redoing the measurements after 40 days in the same anechoic chamber.

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