A Performance Comparison of Wi-Fi RTT and UWB for RF Ranging

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***Abstract*—This paper presents empirical Radio Frequency (RF) ranging performance results for two IEEE standards. IEEE 802.11mc is the underlying standard for Wi-Fi Round Trip Time (RTT) technology, and IEEE 802.15.4a is a standard for Wireless Personal Area Networks (WPANs) with RF ranging capability based on Ultra WideBand (UWB) technology. While UWB offers far more accurate range estimates than Wi-Fi RTT, its signal can penetrate a small number of obstacles due to typical UWB emission level restrictions. Consequently, one needs to deploy a large number of UWB radios in any moderately-sized or larger building to provide indoor localization capability. Wi-Fi RTT works over much longer distances and hence it has better coverage than UWB. As such and depending on the application, Wi-Fi RTT can be a viable alternative to UWB for RF ranging and indoor localization.**

***Index Terms*—Indoor localization, IEEE 802.11mc, IEEE 802.15.4a, Wi-Fi, round trip time (RTT), ultra wideband (UWB), two-way ranging (TWR), fine timing measurement (FTM)**

I. Introduction

Radio Frequency (RF) ranging is a technique through which two radios estimate the distance between them by exchanging a few messages. RF ranging can be used for localization, for example, through multilateration [1], [2]. RF ranging can in principle be done based on Received Signal Strength (RSS), if the strength of transmitted signal is known to allow the computation of path loss. However, the relationship between path loss and distance, for example through a power-law path loss model, is a weak one. Hence, the range estimate computed in this manner may be highly inaccurate. The preferred method for RF ranging is to use the Time of Arrival (TOA) of the RF signal. If the time at which the signal was transmitted is known and if the two radios are synchronized, then the Time of Flight (TOF) can be estimated. Given that the RF signal travels "mostly" at the speed of light c in free space, the distance between the two radios can be estimated as the product of TOF and c. We say mostly, because the speed at which the RF signal travels through any material other than free space is lower than c. However, it is reasonable to assume that the signal travels mostly through air, and hence multiplying TOF by c is a reasonable thing to do. Two-Way Ranging (TWR) relaxes the need for synchronization between the two radios [1]. TWR is similar to the Fine Timing Measurement (FTM) protocol that is described in the next section. Another popular technique for localization is Time Difference of Arrival (TDOA). There are at least two versions of TDOA. In one version, a radio at an unknown location computes the difference between arrival times of signals received from two anchor nodes that are time synchronized. In another version, two time synchronized anchor nodes compute the difference between arrival times of a signal transmitted by a radio at an unknown location [1].

The basic capability that enables localization based on TOA or TDOA is the ability to estimate the arrival time of an RF signal at a receiving radio. The TOA can be estimated precisely when there exists a Line of Sight (LOS) propagation path between the two radios and the transmitted signal has a large bandwidth. For example, the signal can be a pulse of a very short time duration as in impulse radio Ultra WideBand (UWB) communications and ranging [3]. The large bandwidth makes it possible to resolve the multipath components. This results in a much more accurate estimate of the range than through the use of RSS. When there is a Non-LOS (NLOS) propagation path between the two radios, the range estimate would still be accurate if the multipath component corresponding to the direct path between the two radios can be detected.

This paper compares the performance of two TOA-based RF ranging technologies. One is UWB using TWR based on the IEEE 802.15.4a standard. UWB is the most commonly used technology for estimating TOA in indoor environments. The other technology is Wi-Fi Round Trip Time (RTT) based on the IEEE 802.11mc standard. The IEEE 802.11mc signal does not have as large a bandwidth as a UWB signal, and hence it is not expected to do as accurate RF ranging as UWB. However, it has the advantage that it provides Wi-Fi connectivity, thereby relaxing the need for installing UWB nodes in the environment.

A comprehensive evaluation of ranging performance of Wi-Fi RTT in LOS testing scenarios is presented in [4]. [5] compares the ranging performance of three UWB localization products in a large room representing an industrial environment. This paper evaluates IEEE Wi-Fi RTT and UWB standards outdoors, in an office building, and in a single-family house according to many LOS and NLOS testing scenarios.

The rest of the paper is organized as follows. Section II provides a qualitative comparison of IEEE 802.11mc and IEEE 802.15.4a standards. Section III goes over the system configuration and performance metrics used in our tests. Section IV presents the test scenarios. RF ranging performance results are presented and analyzed in Section V. Concluding remarks and

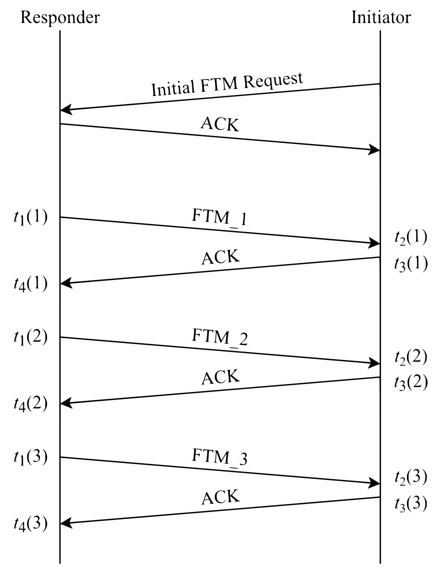


Fig. 1: An example of the FTM protocol

insights obtained in this study are presented in Section VI.

II. Brief Overview of Underlying Standards

In this section, we briefly introduce the standards that support the Wi-Fi RTT and UWB ranging technologies we tested.

IEEE 802.11mc standardized the Fine Timing Measurement (FTM) procedure, which is currently consolidated into IEEE 802.11-2016 [6, Sec. 11.24.6]. The FTM procedure allows a Wi-Fi station to determine its distance from another Wi-Fi station. The Wi-Fi station can be an access point (AP) or a mobile phone. An example of the FTM protocol operation is shown in Figure 1. First, the initiator, which can be a cell phone, sends an initial FTM request to a responder, which can be a Wi-Fi AP. After the responder agrees and sends an acknowledgment (ACK), it starts to send FTM messages. The RTT is calculated as

$$\mathrm{RTT} = \frac{1}{n}\sum_{i=1}^{n}\left[\left(t_4\left(i\right) - t_1\left(i\right)\right) - \left(t_3\left(i\right) - t_2\left(i\right)\right)\right]. \qquad (1)$$

Note that the responder can send multiple FTM messages so the RTT can be averaged to improve its accuracy. The bandwidth that can be used by FTM frames in an FTM session can be 5, 10, 20, 40, 80, or 160 MHz, which supports non-HT (high-throughput), HT, VHT (very high-throughput) formats [6, Table 9-258]. Moreover, the FTM protocol allows the mobile device to exchange FTM packets with a Wi-Fi AP that the mobile device is not associated with and simultaneously exchange data and FTM packets with the AP it is associated with.

UWB technology was standardized in IEEE 802.15.4a [7] in 2007, which was consolidated into the IEEE 802.15.4-2015 [8] standard. IEEE 802.15.4a introduced High Rate Pulse (HRP) repetition frequency UWB physical layer (PHY), which supports fine ranging. IEEE 802.15.4-2015 introduced Low Rate Pulse (LRP) repetition frequency UWB PHY, while providing full backwards compatibility with the original 802.15.4a standard. Table I summarizes high-level characteristics of HRP UWB PHY in IEEE 802.15.4-2015. HRP UWB can use different bandwidths, starting as low as 499.2 MHz. Specifically, Channels {0:3, 5:6, 8:10, 12:14}, Channels {4, 11}, Channel 7 and Channel 15, use bandwidths of 499.2 MHz, 1,331.2 MHz, 1,081.6 MHz, and 1,354.97 MHz, respectively. Note that the ranging feature of HRP UWB PHY is primarily based on TWR between ranging-capable devices.

TABLE I: Summary of IEEE 802.15.4-2015 HRP UWB PHY

HRP UWB PHY	Frequency Band (MHz)	Channel Numbering	Modulation
Sub-gigahertz	250 - 750	0	BPM-BPSK*
Low band	3244 - 4742	1 - 4	
High band	5944 - 10234	5 - 15	

*BPM: burst position modulation; BPSK: binary phase-shift keying

III. System Configuration and Performance Metrics

The information presented in Section II suggests that, by employing a signal with far greater bandwidth, UWB can provide more accurate ranging than Wi-Fi RTT. The actual improvement depends on building construction material, floor plans, and other factors. One has to deploy and test these technologies in preferably more than one building to quantify the improvement. We picked three systems to test.

One system, called Wi-Fi RTT hereafter, is a development kit and an implementation of the IEEE 802.11mc FTM procedure. The system uses a dual-band 2.4 GHz / 5 GHz 2x2 MIMO 802.11n/11ac radio designed to support IEEE 802.11mc. We let one radio to be an FTM responder and the other an FTM initiator.

The other two systems, called UWB-A and UWB-B hereafter, are based on the IEEE 802.15.4a standard. Both systems use Channel 2, which has a center frequency of 3,993.6 MHz and a bandwidth of 499.2 MHz. The difference between the two systems is in their transmit powers, for which there are no worldwide regulations. UWB-A uses a higher transmit power than UWB-B. In principle, this should make it possible for the UWB-A signal to penetrate a larger number of walls than the UWB-B signal. Each radio in the UWB-B system, which is once again a development kit, is programmable and can be set as either an anchor or a tag. The transmit frequency and bandwidth can also be configured. We used two radios in our tests, and set one as an anchor and the other as a tag. Similarly, we used two UWB-A radios in our tests, one set as an anchor and the other set as a tag. It is shown in Section V that these two systems perform differently.

For each system tested, we placed two devices on two tripods at the height of 1.55 m. Note that Wi-Fi RTT can operate in both 2.4 and 5 GHz Industrial, Scientific, and Medical (ISM) radio bands. To avoid interference from other Wi-Fi signals, we turned off all the Wi-Fi signal transmitters (APs, wireless printers, screen share devices, etc.) in the buildings we used for testing. Occasionally, there was spurious

Fig. 2: Single-family house used in our tests

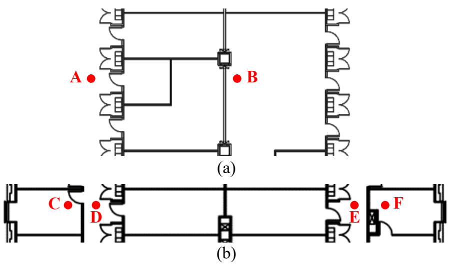


Fig. 3: Different number of walls between the radios

Wi-Fi interference from nearby buildings, but those signals were quite weak due to long distances and signal attenuation.

All three systems can generate range estimates at the rate of at least 10 Hz. We obtained multiple range estimates for each choice of transmitter and receiver locations. We use two performance metrics in this paper. One is the average error (AE) $\overline{e_d}$, defined by

$$\overline{e_d} = \frac{1}{N}\sum_{n=1}^{N}\left(d - \hat{d}_n\right), \tag{2}$$

where d is the true distance between the transmitter and receiver locations and $\hat{d}_1, \hat{d}_2, \ldots, \hat{d}_N$ are the range estimates logged. A useful feature of $\overline{e_d}$ is that it can indicate presence of systemic biases in estimating the range. If $\overline{e_d}$ is positive (negative) over many choices of transmitter and receiver locations, this is an indication that the system is underestimating (overestimating) the range. However, there is a downside to reporting $\overline{e_d}$ only. If $d - \hat{d}_n$ is positive for some values of n and negative for the others, then the error terms may cancel each other out. In the most extreme case, one may have $\overline{e_d} = 0$ while the system is making large errors. For that reason, we also report the mean absolute error (MAE) $\overline{|e_d|}$ given by

$$\overline{|e_d|} = \frac{1}{N}\sum_{n=1}^{N} d - \hat{d}_n \ . \tag{3}$$

IV. Test Scenarios

We evaluated the performance of the systems in LOS and NLOS situations separately. In an LOS test, there are no obstacles between the radios, and the received signal on the direct path should be stronger than the signals received on reflected paths. We designed two LOS test scenarios. One test was done in an outdoor parking lot over a weekend when there were no cars in the lot. The other one was done in a long corridor inside a building at the National Institute of Standards and Technology (NIST). At each venue, we placed one radio at a fixed location while we placed the other one at different distances, ranging from 1 to 100 m, from the first radio. We used a laser meter to measure the distance between the two radios. Aside from the signal received on the direct path in the parking lot, the only other strong signal was the reflection off the ground. In the corridor, on the other hand, there were hundreds of reflected paths off the walls, the floor, the ceiling, the walls at either end of the corridor, etc.

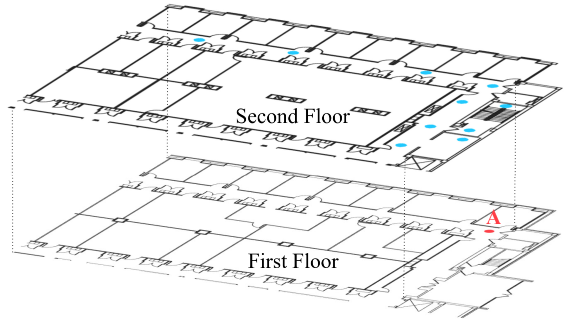


Fig. 4: Radios placed on different floors

The NLOS tests were carried out in two NIST buildings. One was a large, multi-story office and laboratory building with brick exterior walls and a combination of drywalls and metal walls inside. The other was a typical U.S. single-family house with two floors, a basement, and a detached garage, shown in Figure 2. The house is mainly made of wood on the exterior and drywalls inside. The nearest building is 80 m away, which means the possibility of Wi-Fi interference from other buildings was remote. The office building and the single-family house are instrumented with, respectively, 300 and 60 test points laid on the floors and professionally surveyed. Therefore, it is straightforward to compute the ground truth distance between any pair of test points even in NLOS situations. We designed five scenarios for our NLOS tests:

- Different Number of Walls Between the Radios: This test was carried out in the office building. We placed the radios at pairs of locations separated by 1-5 walls. Figure 3 shows examples of this scenario. We placed one radio at Location A and another at Location B to get a 2-wall test. Likewise, we used Locations C and F for a 4-wall test. Altogether, we had two 1-wall cases, two 2-wall cases, three 3-wall cases, three 4-wall cases, and two 5-wall cases. The true distances between the radios in these cases are shown in Table II. Note that all the walls between the radios are drywalls.
- Radios Placed on Different Floors: In this scenario, one radio was placed on the first floor (at Location A in Figure 4) of the office building. The other radio was placed on the second floor, on the third floor, or in the stairwell, to test how far apart the radios can be and

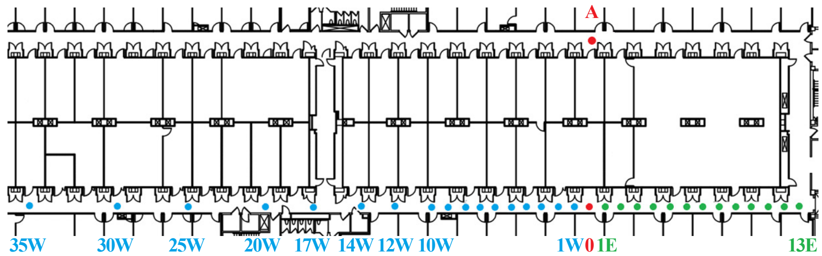


Fig. 5: Office environment coverage test

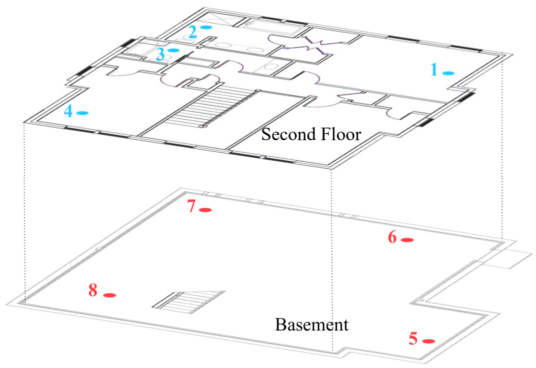


Fig. 6: Radio locations in single-family house extreme tests

TABLE II: True distances of the radios with different numbers of walls between them

Case	True Distance (m)	Case	True Distance (m)
1-Wall (1)	3.00	3-Wall (3)	20.82
1-Wall (2)	3.00	4-Wall (1)	23.22
2-Wall (1)	10.65	4-Wall (2)	20.62
2-Wall (2)	18.32	4-Wall (3)	20.82
3-Wall (1)	18.31	5-Wall (1)	25.02
3-Wall (2)	18.32	5-Wall (2)	23.12

still be able to communicate and provide range estimates. Each floor is 3.55 m high and it is constructed of concrete. There are also piping and wiring in the ceilings/floors.

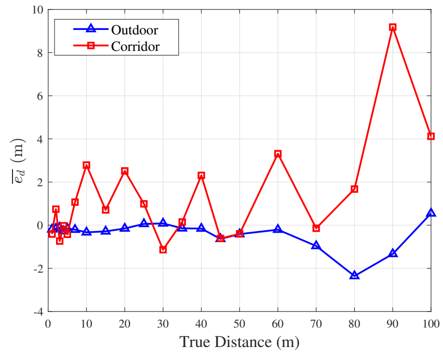
- Office Environment Coverage Test: In this scenario, we placed the radios in two parallel corridors shown in Figure 5. One radio was kept fixed at Location A and the other one was placed at Locations 0, 1W, 2W, . . . , 35W, 1E, 2E, . . . , and 13E in the other corridor. Note that Location A was exactly across from Location 0 and 17.71 m away from it. Moreover, the distances between Locations 0 and 1W, 1W and 2W, 0 and 1E, etc., were 1.81 m. There are offices and laboratories between the corridors with metal walls separating them and drywalls along the corridors. These spaces house computer servers, metal shelves/cabinets, and various office and laboratory equipment. The purpose of this scenario was to evaluate system coverage in an environment with office and IT equipment.
- Single-Family House Coverage Test: In this scenario, one radio was placed at a test point at the center of the main part of the house on the first floor while the other one was placed at each of the other 59 test points fairly uniformly covering the main house (first floor, second floor, and basement) and the detached garage.
- Single-Family House Extreme Tests: In the previous scenario, one radio was placed at the center of the house. Therefore, the two radios could not be as far apart as possible. To push the systems further, in this scenario we placed one radio at one corner of the basement (i.e., Location 5, 6, 7 or 8 in Figure 6) and the other radio at a corner on the second floor (i.e., Locations 1, 2 or 4 in Figure 6). We did not have access to the fourth corner on the second floor. Instead, we used Location 3 in a bathroom with poor radio reception. Altogether, with four points to choose from in the basement and four on the second floor, there were 16 pairs to examine.

V. Performance Results

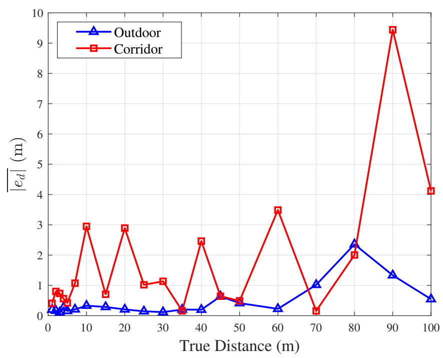
In this section, we present the ranging performance of the three systems in the scenarios described in Subsection IV. The performance results for LOS and NLOS scenarios are presented in Subsections V-A and V-B, respectively. Overall performance results are presented in Subsection V-C.

A. Performance in LOS Scenarios

The true distance from a fixed radio to a movable radio was varied from 1 to 100 m in LOS tests in both the outdoor parking lot and the office building corridor. All three systems provided range estimates at all test locations. However, we noticed that the Wi-Fi RTT system could not generate estimates larger than 99.99 m. This may have been due to hard coded algorithmic and memory settings made by the manufacturer. Figure 7a shows that the average error of the Wi-Fi RTT system in the outdoor LOS test was between 0 and -2 m, and the system mostly overestimated the range. The average error was much worse in the indoor corridor and could be as large as 9 m. In addition, the system mostly underestimated the range in the corridor. Figure 7b shows that the mean absolute error in the parking lot was much better than that in the corridor, which is a rich multipath environment. The performance of the UWB-A system is depicted in Figure 8. As shown in Figure 8a, sometimes the system overestimated the range in the parking lot and sometimes it underestimated it, but it almost always overestimated the range in the corridor. Figure 8b shows that

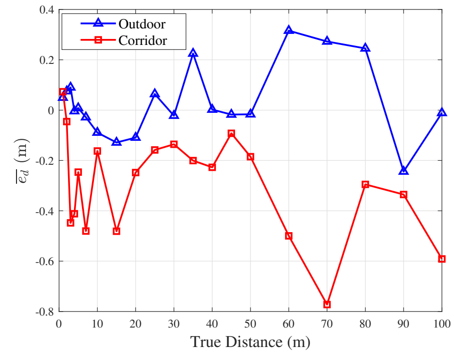


(a) Average error

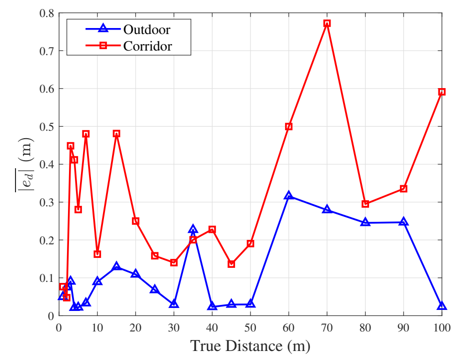


(b) Mean absolute error

Fig. 7: Performance of Wi-Fi RTT in LOS tests



(a) Average error



(b) Mean absolute error

Fig. 8: Performance of UWB-A in LOS tests

UWB-A had a better ranging performance in the parking lot than in the corridor, just like Wi-Fi RTT.

The performance of the UWB-B system is shown in Figure 9. We have plotted the outdoor performance and the corridor performance in different subfigures, because they had vastly different dynamic ranges. Our first observation is that the system overestimated the range in the parking lot and underestimated it in the corridor. As for mean absolute error, UWB-B's performance in the parking lot was similar to UWB-A's. Our second, and more important, observation is that UWB-B's average error in the corridor increased rapidly when the true distance exceeded 30 m. To be specific, the reported distances became much smaller than the true distances. To understand the reason, we examined the Channel Impulse Response (CIR) data made available by UWB-B. Figure 10 shows two sample sequences of CIR data when the true distance is 30 m. In each subfigure, three clusters of signal arrivals can be seen, and the hollow red circle depict UWB-B's decision as to where the first arrival is. The true first arrival happens at roughly time index 750. Therefore, UWB-B's range estimate for the second sequence of CIR data, which is based on its wrong decision that the first arrival happened around time index 260, would have a large error. The two clusters to the left are due to reflections off distant objects and are most likely symptoms of "wrap around" effects in the accumulator of the digital signal processing chain. Interestingly, the range estimate generated by UWB-B is occasionally negative. Given

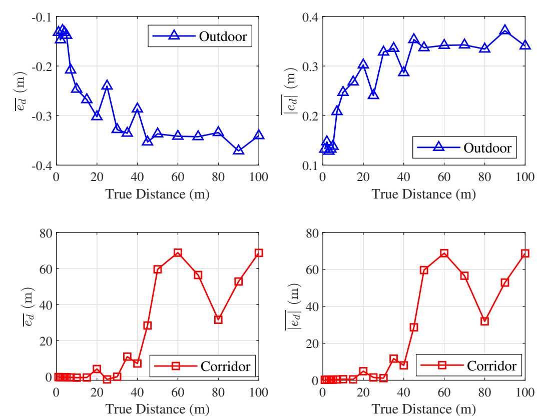


Fig. 9: Performance of the UWB-B system in LOS tests

that we did not see such a phenomenon in other tests, we conclude that the long corridor is a special case for UWB-B. With plenty of multipath, the system may still receive non-negligible reflections off distant objects. It appears that UWB-A does not have this problem, because it never generated three different values for the range in the corridor scenario that UWB-B did frequently.

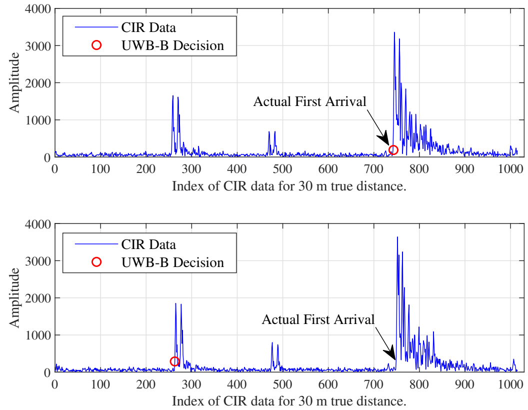
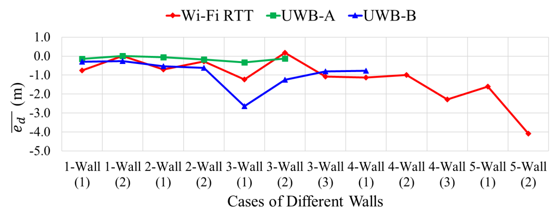
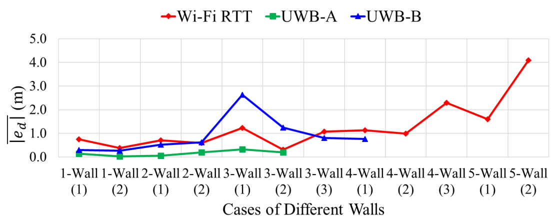


Fig. 10: Two sample UWB-B's CIR sequences



(a) Average error



(b) Mean absolute error

Fig. 11: Performance in the different number of walls test

B. Performance in NLOS Scenarios

The performance of the three systems as a function of the number of walls between the two radios in NLOS scenarios is shown in Figure 11. First, we examine wall penetration by these systems. UWB-A did not provide any range estimates when there were four or five walls between the radios, and it generated estimates in only two out of three 3-wall cases. UWB-B was slightly better than UWB-A, as it managed to generate estimates in all 3-wall cases and one of the three 4-wall cases. Wi-Fi RTT, however, provided estimates in all cases, even when there were five walls between the two radios. This suggests that the IEEE 802.11mc signal is more capable of penetrating walls than the IEEE 802.15.4a UWB signal. Second, when it did generate a range estimate, UWB-A provided more accurate estimates than the other two systems. In addition, UWB-B had similar performance to Wi-Fi RTT whenever both generated range estimates. Lastly, as the number of walls increased, so did the mean absolute error for both the UWB-A and Wi-Fi RTT systems. This was more pronounced for Wi-Fi RTT than for UWB-A.

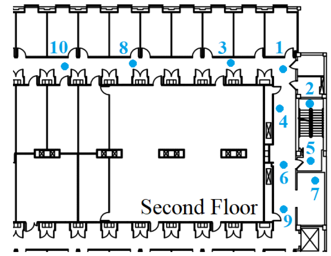
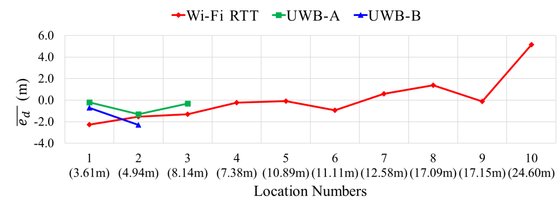
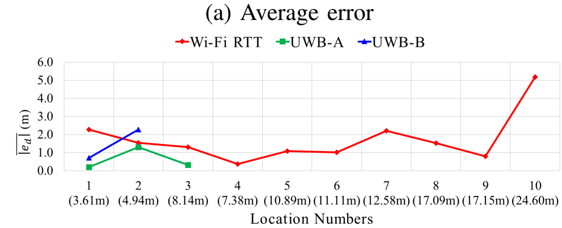


Fig. 12: Locations tested on the second floor and stairwell



(a) Average error



(b) Mean absolute error

Fig. 13: Performance in the different floors test

Next, we evaluated how these systems performed when the two nodes were on different floors of a building to determine whether it was harder for signals to penetrate floors/ceilings than walls. We placed the first radio on the first floor of the office building. We found out that none of the systems could generate range estimates when the second radio was on the third floor. Figure 12 shows the locations of the second radio on the second floor and in the stairwell where we tested. Note that the location of the first radio on the first floor was just beneath Location 1 on the second floor. Location 2 was on the half floor in the stairwell between the first and second floors. Locations 3-10 were on the second floor. Wi-Fi RTT generated range estimates at all 10 locations, while UWB-A generated estimates at Location 1, 2 and 3 only and UWB-B at Location 1 and 2 only. Figure 13 shows the performance of all three systems as a function of the true distance between the two radios. Once again, UWB-A had the best accuracy when it worked, and UWB-B was not far behind. The mean absolute error of Wi-Fi RTT was less than 2.27 m in all cases, except at Location 10.

If we use an upper limit of 6 or even 4 m for localization error to say a ranging system has coverage at a given location, then we can say that Wi-Fi RTT is superior to the other two systems in the office environment coverage test. It worked up to Location 25W to the west and Location 13E (which was at the end of the corridor) to the east. Meanwhile, both UWB-A

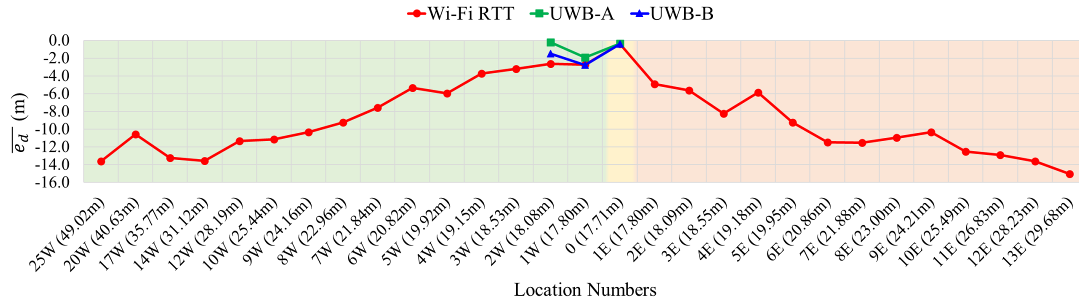


Fig. 14: Average error in the office environment coverage test

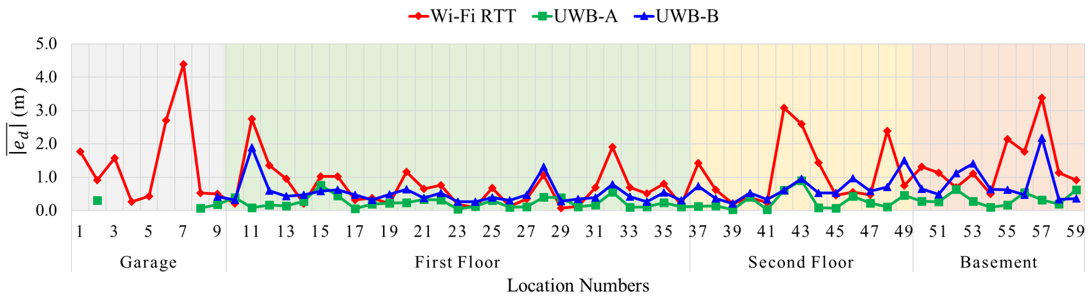


Fig. 15: Mean absolute error in the single-family house coverage test

TABLE III: Performance comparison of the three systems

Metric	System	LOS		Office Building			Single-Family House		Overall
		Corridor	Outdoor	Different # Walls	Different Floors	Coverage	Coverage	Extreme	
AE	Wi-Fi RTT	1.91	-0.38	-1.16	-1.33	-8.65	-0.93	-1.29	-2.43
	UWB-A	-0.32	0.02	-0.07	-0.80	-0.84	-0.23	-0.14	-0.24
	UWB-B	25.23	-0.28	-0.96	-2.86	-1.34	-0.62	-0.61	1.30
MAE	Wi-Fi RTT	2.35	0.45	1.26	2.34	8.66	1.02	1.32	3.04
	UWB-A	0.33	0.08	0.08	0.80	0.84	0.25	0.21	0.27
	UWB-B	25.80	0.28	0.96	2.86	1.34	0.62	0.61	2.58
RMS	Wi-Fi RTT	3.93	0.77	1.65	3.07	9.56	1.40	1.58	4.96
	UWB-A	0.41	0.12	0.14	1.01	1.16	0.34	0.28	0.41
	UWB-B	42.00	0.29	1.25	2.97	1.65	0.75	0.65	11.61
STD	Wi-Fi RTT	3.44	0.67	1.18	2.77	4.07	1.05	0.91	3.90
	UWB-A	0.25	0.12	0.12	0.61	0.79	0.25	0.24	0.33
	UWB-B	33.59	0.09	0.80	0.81	0.97	0.42	0.22	11.54

and UWB-B worked at Location 0, 1W and 2W only. The average errors of all three systems as a function of the true distance between the two radios are shown in Figure 14. As it can be seen, (i) all three systems overestimated the range, (ii) all systems had similar average errors at Location 0 (-0.3 m for UWB-A and -0.4 m for the other two systems), (iii) UWB-A had better accuracy than the other two systems when it worked, and (iv) Wi-Fi RTT's range estimate error increased when the true distance got larger.

Figure 15 presents the results for the single-family house coverage test. As mentioned in Section IV, we placed one radio roughly at the center of the house on the first floor and the other radio at different locations throughout the house. We tested at nine locations in the detached garage. Only the Wi-Fi RTT system was able to generate range estimates at all these nine locations. UWB-A and UWB-B worked, respectively, at three and one locations only. All three systems worked at all locations inside the main structure, including the first and second floors and the basement. In general, Figure 15 shows that the performance of all three systems was worse in the garage, second floor, and basement than on the first floor. In addition, the figure shows that (i) most of the time Wi-Fi RTT had the largest and UWB-A the smallest mean absolute error among the three systems, (ii) the mean absolute error of Wi-Fi RTT was less than 3 m at 56 out of 59 locations, and (iii) UWB-A's mean absolute error was less than 1 m at 53 locations where range estimates were provided.

In the single-family house extreme tests, we learned that Wi-Fi RTT worked at all 16 pairs of locations for the two radios, while UWB-A and UWB-B worked at only six location pairs.

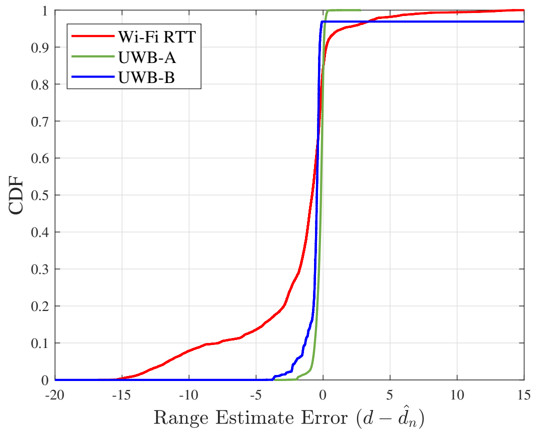


Fig. 16: CDF of range estimate error over all tests

The largest mean absolute error for Wi-Fi RTT was 2.78 m, which was observed when the radios were at Locations 1 and 8 that are 12.12 m apart. The largest mean absolute errors for the UWB-A and UWB-B came from location pair (3,7), where the nodes are 6.66 m apart. The errors were 0.50 m for UWB-A and 0.92 m for UWB-B.

C. Overall Results

In this subsection, we present the results obtained in all tests (LOS or NLOS) in summary form. Table III presents numerical values for not just average error (AE) and mean absolute error (MAE) for all three systems, but also the root mean square (RMS) and standard deviation (STD) of the error. Performance figures have been provided for various tests and overall. The corridor and overall performance for the UWB-B system was adversely affected by its poor performance in the LOS scenario in the long corridor in the office building discussed in Subsections V-A. The UWB-A system had the best performance among the three systems tested, regardless of which performance metric we look at.

Figure 16 shows the Cumulative Distribution Function (CDF) of range estimation error for all three systems over all tests. The sharp rise of the CDF curves for UWB-A and UWB-B systems just before zero value for error indicates again that UWB ranging systems are more accurate than Wi-Fi RTT. Wi-Fi RTT's absolute error was less than 3 m with roughly 80% probability. Finally, aside from the long corridor LOS behavior which resulted in some positive errors, all other errors for UWB-B were negative. This indicates that UWB-B generally overestimates the range. Note that neither Table III nor Figure 16 shows the main advantage of Wi-Fi RTT, namely, its better coverage than the two UWB systems.

VI. Conclusions

Our tests suggest that UWB can provide accurate indoor localization for wooden structure single-family houses with drywalls equipped with about a dozen UWB anchor nodes. However, for larger buildings made of heavier construction materials and having a large number of rooms, Wi-Fi RTT can be a more viable solution. It provides not only Wi-Fi connectivity but also indoor localization, even though it is not as accurate as UWB. A purely UWB-based localization solution may be impractical in such buildings due to UWB's limited communication range and obstacle penetration capability, which implies that a large number of UWB anchor nodes would have to be installed in the building. Using UWB along with other sensors, such as Inertial Measurement Unit (IMU), magnetometer, and altimeter, may be a more promising path to explore. One should also take advantage of any other RF signals available, such as Wi-Fi and Bluetooth Low Energy (BLE). Development of such hybrid localization solutions is an active area of R&D, but it is beyond the scope of this paper.

It has been suggested that a system based on Wi-Fi RTT, GPS, Wi-Fi, and sensors available on the smartphone can provide 1 m localization accuracy [9]. At the first glance, this claim may appear to be inconsistent with Figure 16 that suggests Wi-Fi RTT's ranging error is between $\pm$ 4 m with 80% probability. However, the differences are in (i) "localization accuracy" vs. "ranging error", (ii) use of additional sensors and technologies vs. using Wi-Fi RTT only, and (iii) performance evaluation in different environments. Last but not the least, the IEEE 802.11az standard, under development by the IEEE Next Generation Positioning Group (NGP) Task Group (TG) [10], is expected to be available in 2021. For the same channel bandwidth, 802.11az will have the same accuracy as 802.11mc, but it offers new capabilities, such as (i) scalable location for large populations of users and (ii) encryption and location integrity.

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