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Wi-Fi Fine Time Measurement

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NKROW, Raphael Elikplim; SILVA, Bruno; HANCKE, Gerhard; ABU-MAHFOUZ, Adnan M.; SHU, Lei

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WiFi Fine Time Measurement: Is it a Viable Alternative to Ultra-Wideband for Ranging in Industrial Environments?

Nkrow Raphael Elikplim, *Student Member, IEEE*, Bruno Silva, *Member, IEEE*, Gerhard Hancke, *Fellow, IEEE*, Adnan M. Abu-Mahfouz, *Senior Member, IEEE*, and Lei Shu, *Senior Member, IEEE*

Abstract

Time-based ranging approaches have long been used for indoor positioning due to their reliability and accuracy. Two-Way-Ranging (TWR) with Ultra-Wideband (UWB) has often been utilised for Indoor Positioning Systems (IPS) in industrial settings due to the ranging accuracy offered by the temporal and spatial resolution of UWB even in challenging non-line-of-sight (NLOS) and reflective environments. With the adoption of the IEEE 802.11mc standard, WiFi now offers a Fine Time Measurement (FTM) capability that supports the WiFi Round Trip Time (RTT) protocol for time-of-flight ranging. This offers an improved ranging accuracy over previous non time-based WiFi ranging approaches, and is considered a potential alternative to UWB TWR. In this article, we introduce UWB TWR and WiFi FTM and discuss their use in real-time IPS. We include a quantitative comparison of ranging performance in line-of-sight (LOS) and NLOS ranging measurements to give an initial indication of accuracy in industrial settings. Recommendations for researchers and IPS designers on which technology type to deploy for LOS and NLOS conditions, as well as general guidelines for accurate ranging and localisation for both technologies, are also discussed.

I. INTRODUCTION

There is a strong demand for high-precision real-time locating systems, especially for indoor navigation and tracking. Over the years many radio- and non-radio-based approaches have been proposed for IPS. Radio-based approaches commonly use time-of-flight and received signal

strength estimation in conjunction with WiFi [1], Bluetooth [2] and UWB [3], while non-radio approaches include visible light [4], inertial measurement tracking [5] and geomagnetism [6]. Indoor positioning is challenging due to the inherent presence of obstacles causing signal obstruction, reflection and attenuation. These challenges are more pronounced in industrial settings, where we encounter a wider range of obstructions and more reflective surfaces [7]–[9], e.g. machines moving in a mining tunnel can obstruct line-of-sight between personnel and ranging beacons with tunnel rock walls also introducing strong multi-path effects due to reflection. Industrial applications also tend to be more safety and performance critical in nature, e.g. tracking equipment and personnel at a worksite to ensure safety [10], so even in complex environments with LOS and NLOS conditions the positioning needs to be reliable and accurate.

Among the numerous IPS options, UWB technology has emerged as a popular option due to its reliable and accurate ranging capabilities, which are attributed to its high spatial and temporal resolutions. Owing to these attributes, UWB has been a prominent technology used in industrial environments for real-time location systems [11], [12]. UWB is also emerging as a solution for ranging in consumer electronics, e.g. Apple iPhone 11 and newer models offer UWB. WiFi infrastructure is widely available [13]–[16] and coupled with the market penetration of WiFi-capable smartphones, this has inevitably led to a strong desire to develop IPS leveraging WiFi [17], [18]. With the adoption of the IEEE 802.11mc standard, WiFi makes provision for FTM without the need for clock synchronization. This time-of-flight measurement capability coupled with a maximum channel bandwidth of 160 MHz offers a better alternative for indoor positioning when compared to the previously used Received Signal Strength (RSS) approach to WiFi ranging [19]. The wider channel bandwidth of 160 MHz enables higher sampling rate compared to the 20 or 40 MHz channel bandwidth associated with previous 802.11 protocols, hence the receiver is able to sample enough signals to distinguish between the first signal arrival via direct path and multipath reception, for accurate range estimation [20]. FTM enables reliable estimation of distances between FTM-capable WiFi devices based on RTT and delivers sub-meter ranging accuracy, which is comparable to that of UWB [21], [22]. This raises the question whether WiFi FTM could offer a viable alternative for reliable ranging and positioning in industrial settings and offer an alternative to UWB.

In this article, we focus on the operation and performance of time-based UWB and WiFi ranging with the aim to compare the established solution (UWB) with a potentially emerging alternative (WiFi). We provide a brief introduction to time-based localisation and discuss the

use of UWB TWR and WiFi FTM in IPS. We then compare these two approaches in both LOS and NLOS conditions. Our work shows the ranging errors of the two approaches in the same environmental conditions, and aims to provide insights for IPS designers and researchers on which technology type is best suited for a particular environment. Guidelines for more accurate ranging regarding these two technologies, and time-based approaches in general, are also discussed. All abbreviations used in this article are listed in Table I for easy reference.

TABLE I: Abbreviations used in this paper and their definitions

| Abbreviation | Definition | Abbreviation | Definition |
|--------------|---------------------------------------------------|--------------|------------------------------|
| AP | Access Point | NLOS | Non-Line-Of-Sight |
| API | Application Program Interface | PRF | Pulse Repetition Frequency |
| DS-TWR | Double-Sided Two-Way Ranging | RSS | Received Signal Strength |
| FTM | Fine Time Measurement | RTT | Round Trip Time |
| IEEE | Institute of Electrical and Electronics Engineers | SFD | Start Frame Delimeter |
| IoT | Internet of Things | SS-TWR | Single-Sided Two-Way Ranging |
| IPS | Indoor Positioning System | STA | STAtion |
| LOS | Line-Of-Sight | TDoA | Time Difference of Arrival |
| MAE | Mean Average Error | ToA | Time of Arrival |
| MSE | Mean Squared Error | TWR | Two-Way Ranging |
| | | UWB | Ultra-WideBand |

II. TIME-BASED APPROACHES FOR LOCALISATION

Time-based positioning methods aim to estimate the distance between transmitters and receivers based on the signal time-of-flight (ToF), i.e. difference between the received time and transmitted time of radio signals. Classical time-based approaches include Time of Arrival (ToA) and Time Difference of Arrival (TDoA). ToA localisation estimates distance based on the propagation time between a sender and receiver who share a synchronised clock, i.e. compares the sent time embedded in the message with the received time [23]–[25]. TDoA exploits the difference in signal propagation times from multiple transmitters, as measured by the receiver. In contrast to ToA, there is no need for clock synchronization between all the nodes in TDoA localisation [26], [27].

The main hurdle for time-based localisation is the different paths potentially traversed by the signals. Multi-path transmission leads to multiple signal components arriving at different times at the receiver, which could cause inaccurate ranging if the arrival time is based on an incorrect path, e.g. the main path component might be attenuated and the receiver chooses another path component that is stronger but delayed due to longer path traveled. Even though this problem exists, most time-based ranging algorithms still assume the ideal case that there is LOS communication with an easily distinguished main path component [7]. As a result, NLOS and multi-path components caused by reflections from obstacles and machinery result in positive biases (overestimation) of the estimated distances, especially in industrial localisation systems where NLOS is more common. A typical illustration of this scenario is depicted in Fig. 1(a) where signals are reflected by machinery, walls and other obstacles. If not taken into consideration, this affects the ToA estimation of the signal by the device being localized (STATION and tag in this scenario) and would affect localisation accuracy. Any time-based approach to ranging in industrial settings would therefore have to be resilient in both LOS and NLOS environments.

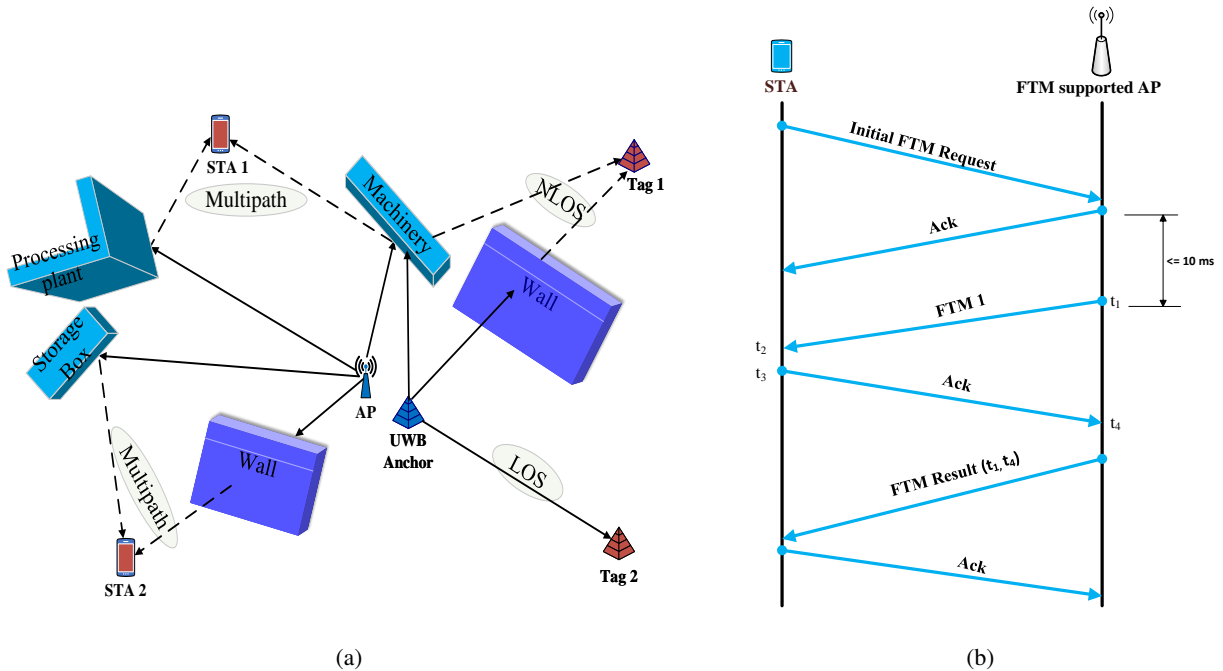


Fig. 1: (a) A typical illustration of LOS, NLOS and multi-path components in an industrial setting. (b) FTM session for RTT extraction in WiFi networks.

A. Ultra-Wideband Ranging and Localisation

UWB has been used for positioning in most industrial settings for decades and its propagation attributes in LOS and NLOS conditions have been studied in detail [7], [28]. It offers high temporal and spatial resolution with better multi-path fading immunity compared to other narrow-bandwidth and wideband carrier-based communication technologies. Due to these attributes, ranging accuracy up to 30 *cm* is achievable, making it viable for most industrial settings [11], [29]. Ranging in UWB is based on an RTT approach known as TWR, where a tag sends a ranging request to the anchor with every packet timestamped at both ends. The timestamped packets eliminate the local clock differences in the ToF calculation as it indicates the total time it takes for the tag to send a packet to the anchor and receive a response. As radio waves travel at approximately the speed of light, we can calculate the distance between the tag and anchor using the recorded ToF. It is however worth mentioning that clock stability, together with frequency synchronization and correction, is required to reduce the influence of local clock variability and efficient determination of the frame timestamp, as each nanosecond of error in ToF can translate 30 *cm* of error in the range estimate [28], [30]–[32].

B. WiFi Ranging and Localisation

Traditionally, WiFi signals has extensively been used for localisation with RSS approaches, with reported localisation accuracy ranging from 2 *m* to 5 *m* [23]. Existing RSS-based systems for industrial applications are either geometric-based [33] or fingerprint-based [34], with the fingerprint-based approach being prominent and pragmatic, as it does not assume line-of-sight propagation and does not require geometric parameters. The main hurdle with the utilization of RSS is the high dependence on prior environment-dependent signal characterization. System accuracy will suffer if the environment changes, e.g. obstacles are added or moved, or if signal variability caused by the dynamic and unpredictable nature of radio channel causes shadowing, channel fading and multi-path propagation. This makes measurements less stable, which in turn affects the final localisation estimates [1], [35]–[37]. The advent of the 802.11mc standard (to provide gigabit speeds per second in WiFi networks), brought an FTM protocol known as WiFi-RTT that has been harnessed for sub-meter localisation accuracy [17], [38]–[41]. The FTM protocol allows mobile devices to compute their distances to the nearest FTM supported access point (AP), without necessarily connecting to the AP. The FTM protocol evaluates the ToF of the signal at the AP, as well as the ToA at the STA. The difference between the ToA and ToF

is used to estimate the distance between the AP and STA. The RTT process is depicted in Fig. 1(b) for one burst, where a mobile STA initiates a session to compute its distance to the AP. The STA sends an initial message (FTM Request) to the FTM-supported AP. An acknowledgement message is sent back to the STA. A packet is then sent from the AP to the STA, and the sending time is logged as t_1 by the AP. The receive time is logged as t_2 by the STA. The STA sends an acknowledgement packet at time t_3 to the AP and the reception time is logged as t_4 by the AP. A report is then sent to the STA, which includes the timestamps t_1 and t_4 . The RTT is calculated as $(t_4 - t_1) - (t_3 - t_2)$. RTT helps to solve the time synchronization hurdles associated with ToA and TDoA [23], [26], however a good clock stability with frequency synchronization helps to obtain better ranging results. We compare the WiFi FTM and UWB TWR approaches for different sight conditions in the next section.

III. EXPERIMENTAL RANGING COMPARISON BETWEEN WiFi AND UWB

UWB uses a channel bandwidth of more than 500 MHz coupled with TWR to estimate distances, while the WiFi FTM protocol operates with maximum channel bandwidth of 160 MHz. We compare the ranging accuracy of these technologies in LOS and NLOS scenarios in two different environments to see if the WiFi FTM can provide promising ranging accuracy, even though it has narrower bandwidth compared to UWB. In this work, UWB TWR and WiFi RTT with FTM, are explored and compared in two different environments for both LOS and NLOS conditions. Both TWR and RTT approaches allow for ranging without time synchronization between the two participating devices.

A. Experimental Environments

We perform our ranging experiments in two LOS and two NLOS environments to establish practical insight as well as environmental diversity. We carefully chose these environments to be representative of possible structures found in industrial settings. In an industrial setting one would often have obstacles, causing NLOS ranging, and reflective surfaces. Our experimental environments incorporate thick, re-enforced concrete walls, reflective metal walls and some more permeable barriers such as plasterboard. As a starting point, this gives a good representation of different LOS and NLOS links and the impact of these environments on positioning accuracy for UWB and WiFi ToF ranging. These environments and their floor plans are shown in Fig. 2 and Fig. 3 for LOS and NLOS cases respectively.

1) *LOS Environments*: We consider two LOS environments. Environment 1 is a corridor with mostly permeable plasterboard walls with reduced reflectivity. In Environment 2 is also a corridor but the sides are predominantly metal that exhibits high reflectivity. The anchor to tag distance in Environment 1 and 2 is up to 22 *m* and 16 *m* respectively. Figs. 2(a) and (b) show the selected environments for environment 1 and 2 respectively. Also, Figs. 2(c) and (d) show the respective floor plans for environment 1 and 2.

2) *NLOS Environments*: We consider two types of NLOS conditions. Environment 1 represents a hard NLOS condition, where the direct path signal is attenuated and a reflected path is considered the ToF path. The obstacle is a 24.7 *cm* thick steel-enforced concrete wall, with anchor tag distance up to 12 *m*. Environment 2 represents a so called soft NLOS, or through-the-wall (TTW) condition, where the direct path signal passes through an obstacle and is delayed but still recognized as the ToF path. The obstacle is a 15 *cm* thick plasterboard wall, with anchor-tag distance up to 16 *m*. Figs. 3(a) and (b) show the selected environments for environment 1 and 2 respectively. Also, Figs. 3(c) and (d) show the respective floor plans for environments 1 and 2.

B. Experimental Setup and Configurations

1) *UWB Module Configuration*: Two Decawave 1001 UWB modules were configured as the main UWB modules for this experiment. One of the modules is configured as an anchor, and the other as a tag with the Single-Sided Two-Way Ranging (SS-TWR) option. In this case, the anchor is responsible for calculating the distance estimates. The tag sends UWB ranging frames compliant with the IEEE 802.15.4 standard data frame encoding, initiating a trigger for range request to the anchor. For LOS and NLOS ranging in both environments, the anchor and tag modules were placed 1 *m* apart and ranging data was then logged on a computer connected to the anchor. The tag was then moved an additional 1 *m* away from the anchor (anchor position is fixed) after logging 100 ranging samples for each distance. We configured both anchor and tag to channel 5 with a bandwidth range of 6240-6739.2 MHz with center frequency of 6489.6 MHz. We set the Pulse Repetition Frequency (PRF) to 64 MHz. PRF defines the time interval between sending two consecutive pulses by the UWB module. The inter-ranging delay, which defines the time delay to send successive ranging requests, is set at 200 *ms*. We place the anchor and tag on a tripod (1.5 *m* in height) for measurement stability.

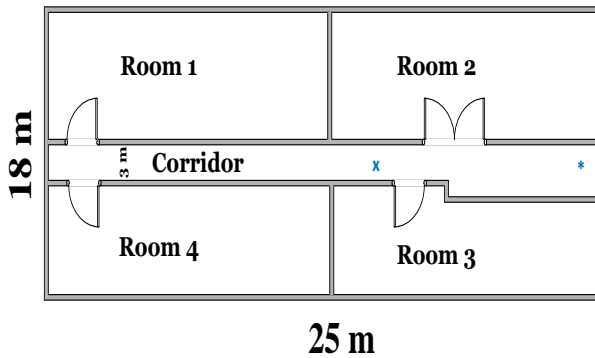
2) *WiFi Module Configuration*: The WiFi FTM/RTT protocol has been been commercially integrated into several Google devices and supported within the Android operating system. For



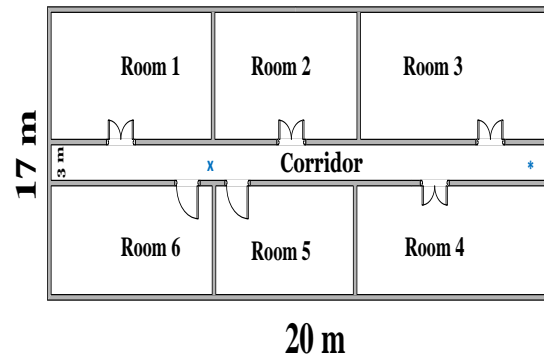
(a) LOS ranging Environment 1. The distance between the anchor and tag is 9 m in this picture.



(b) LOS ranging Environment 2. The distance between the anchor and tag is 14 m in this picture.



(c) Floor plan for LOS environment 1. Ranging experiments were conducted on the corridor with mostly permeable plasterboard walls. Anchor (*) and tag (x) positions are indicated in blue.



(d) Floor plan for LOS environment 2. Ranging experiments were conducted on the corridor, with the sides of the corridor predominantly metal. Anchor (*) and tag (x) positions are indicated in blue.

Fig. 2: Experimental setup and floor plans for the selected LOS environments

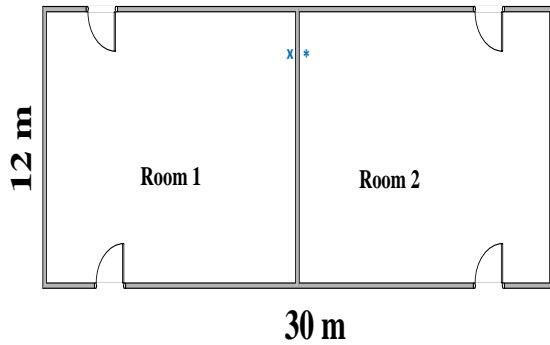
the collection of ranging information, we use one Google WiFi router as AP and a Google Pixel 2 mobile phone running Android version 11 as the STA. Open source Android apps like the "WifiRttScan" application can be used to collect and log the ranging data, however we developed a custom application using the "WifiRttManager" Application Program Interface (API) available in Android 9.0 and above, to log both the ranging and RSS data simultaneously (100 samples per location) in a report format. For fair comparison with UWB, we set the inter-ranging delay to be the same as what was set for UWB, i.e 200 ms. Also, the Google AP was placed at the same height as the UWB anchor, and the phone is attached to the tripod at the same height as shown in Fig. 2 (b). The AP (router) and STA (phone) is placed 1 m apart and then the STA is moved 1



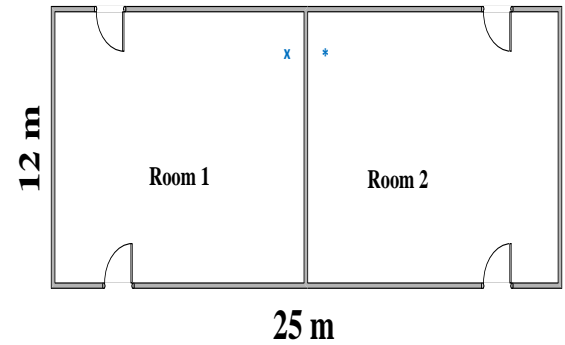
(a) NLOS ranging Environment 1. This picture shows the opposite sides of the 24.7 cm thick concrete wall with an anchor-tag distance of 1 m.



(b) NLOS ranging Environment 2. The picture shows the opposite sides of the 15 cm thick plaster board wall, with an anchor-tag distance of 3 m in this scenario.



(c) Floor plan for NLOS ranging environment 1. Ranging experiments were conducted at opposite sides of the room partition (24.7 cm thick steel-enforced concrete wall). Anchor ('*') and tag ('x') positions are indicated in blue.



(d) Floor plan for NLOS ranging environment 2. Ranging experiments were conducted at opposite sides of the room partition (15 cm thick plasterboard wall). Anchor ('*') and tag ('x') positions are indicated in blue.

Fig. 3: Experimental setup and floor plan for the selected NLOS environments.

m further after each measurement, with ranging and RSS information collected simultaneously. The operating frequency of the Google AP is set to 5 GHz. The maximum channel bandwidth of the AP is 160 MHz with the IEEE 802.11mc standard.

C. Performance Comparison and Evaluation Between WiFi and UWB

1) *Ranging Accuracy Comparison for Different Environments:* The ranging accuracy of WiFi and UWB are compared for Environments 1 and 2 under both LOS and NLOS conditions. The

results are presented in Table II. A laser distance meter (LDM-100 from CEM instruments) with a precision of $\pm 1.5 \text{ mm}$ was used to measure the distances (ground truth) between the two ranging devices. Ranging accuracy is the difference between the reported distance by WiFi RTT and UWB TWR, and the ground truth measurement. We sample 10, 50 and 100 measurements each for the reported distances for both WiFi and UWB, and provide the Mean Squared Error (MSE) and the Mean Absolute Error (MAE) for the sample measurements. Also, the comparative LOS and NLOS ranging results with errors (ground truth - 10 averaged ranging samples) for WiFi and UWB are presented in Fig. 4. We sample 10 measurements to plot Fig. 4 because we want to simulate and mimic a real-time localisation scenario, where the sample size for localisation is limited.

TABLE II: Measurement errors between WiFi and UWB for the different environments

| Technology | Condition | Environment | Error Metric | Number of Ranging Samples | | |
|------------|-----------|-------------|---------------|---------------------------|------------|-------------|
| | | | | 10 Samples | 50 Samples | 100 Samples |
| WiFi | LOS | 1 | MSE (m^2) | 0.611 | 0.470 | 0.403 |
| | | | MAE (m) | 0.708 | 0.619 | 0.569 |
| | | 2 | MSE (m^2) | 0.442 | 0.432 | 0.397 |
| | | | MAE (m) | 0.396 | 0.320 | 0.274 |
| | NLOS | 1 | MSE (m^2) | 2.435 | 2.084 | 2.154 |
| | | | MAE (m) | 1.347 | 1.267 | 1.307 |
| | | 2 | MSE (m^2) | 0.488 | 0.675 | 0.497 |
| | | | MAE (m) | 0.530 | 0.560 | 0.494 |
| UWB | LOS | 1 | MSE (m^2) | 0.197 | 0.200 | 0.199 |
| | | | MAE (m) | 0.423 | 0.424 | 0.422 |
| | | 2 | MSE (m^2) | 0.296 | 0.190 | 0.175 |
| | | | MAE (m) | 0.527 | 0.427 | 0.410 |
| | NLOS | 1 | MSE (m^2) | 4.666 | 4.061 | 4.000 |
| | | | MAE (m) | 1.967 | 1.812 | 1.793 |
| | | 2 | MSE (m^2) | 0.858 | 0.848 | 0.843 |
| | | | MAE (m) | 0.893 | 0.883 | 0.879 |

It is observed that better accuracy is obtained with UWB for LOS conditions in both Environment 1 and 2. The above observation can be confirmed from Table II with the MSE for UWB and WiFi being 0.197 m^2 and 0.611 m^2 respectively for LOS Environment 1 and 0.296 m^2 and 0.442 m^2 respectively for LOS Environment 2. This could be attributed to the fine range resolution of UWB, as well as the higher channel bandwidth attributes. This indicates that for a

typical LOS environment, whether in a low or high reflective environment, UWB appears to be the better option for indoor positioning.

For the NLOS environments, WiFi performed better than UWB. In Environment 1, exhibiting hard NLOS, the MSE for UWB and WiFi are $4.66 m^2$ and $2.44 m^2$ respectively. This is due to the thick concrete wall reflecting or absorbing most of the UWB signals. For Environment 2, exhibiting soft NLOS, the MSE for UWB and WiFi are $0.858 m^2$ and $0.488 m^2$ respectively. The MAE also follows the same patterns as the MSE for both LOS and NLOS for each environment. WiFi performs better in terms of ranging for soft and hard NLOS than UWB. This is possibly due to WiFi signals having better penetration capability than UWB signals even when operating at 5 GHz and is therefore better suited to ranging in soft and hard NLOS conditions than UWB.

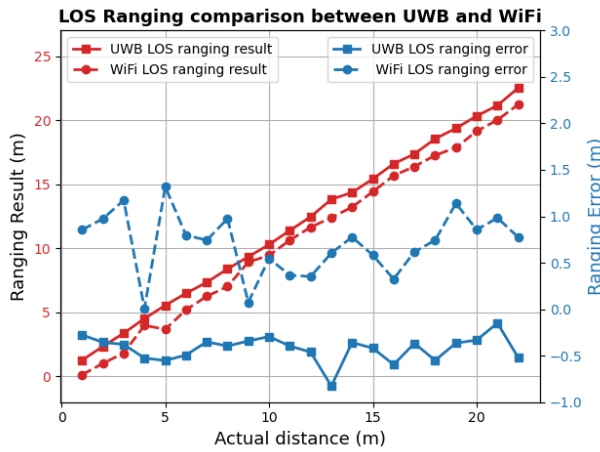
From the above discussed results, it is better for IPS designers to deploy UWB-based IPSs in a typical LOS environment and WiFi-based IPSs in NLOS environments to maximise positioning accuracy. Also, it is observed from Table II that averaging more samples yields smaller errors in most cases, and this can be considered when real-time positioning is not a priority.

2) *Ranging Stability Comparison between WiFi and UWB for Different Sight Conditions:* In this section, we analyze and compare the ranging stability between WiFi and UWB in LOS and NLOS scenarios. A discussion of ranging stability is necessary because, ranging results vary even for a given anchor-tag distance. This is likely to affect positioning in real-time scenarios. The distance between the anchor/AP and tag/STA is successively incremented by $1 m$ as discussed in sections III-B1 and III-B2. We use the standard deviations of ranging values for this analysis, 10 values each are sampled to depict a real-time localisation scenario.

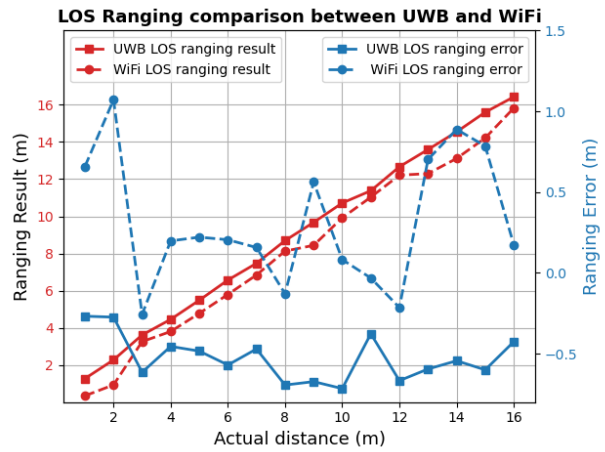
The standard deviation for the ranging values for UWB and WiFi are $0.140 m$ and $0.330 m$ respectively for LOS Environment 1. For LOS Environment 2, the standard deviation for UWB and WiFi are $0.136 m$ and $0.400 m$ respectively. These results again show the superiority of UWB ranging in LOS cases. There is a more interesting outcome in the NLOS environments. For NLOS Environment 1, the standard deviations for UWB and WiFi are $0.893 m$ and $0.788 m$ respectively. This again appears to indicate that ranging stability in UWB is better and hence more accurate than WiFi in LOS scenarios, but performs worse than WiFi in NLOS situations. These observations are verifiable from the ranging error plot in Figs 4 (a) and (c) as less perturbations are observed in the ranging error plot for UWB in Fig. 4(a) but the same cannot be said for Fig. 4(c). However, in Environment 2 the standard deviation for UWB and WiFi are $0.245 m$ and $0.619 m$ respectively. This scenario is a deviation from what was observed for Environment

1. These observations are verifiable from the ranging error plot in Figs. 4 (b) and (d), as less perturbations are observed in the ranging error plot for UWB in both Fig. 4(b) and Fig. 4(d).

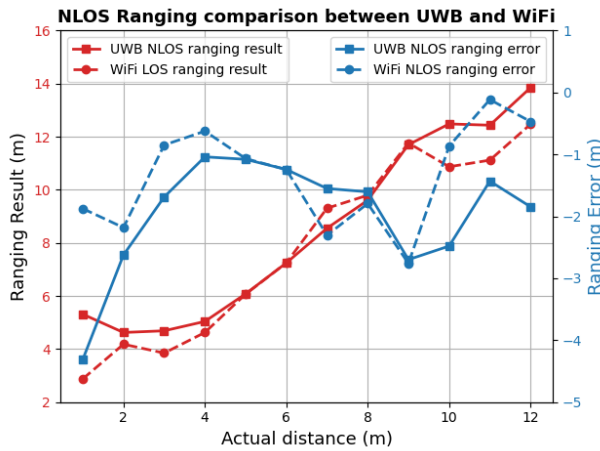
In summary, better ranging stability is observed for WiFi in a NLOS environments in comparison to UWB if the obstacle is significant like the concrete wall in Environment 1. UWB performs better in Environment 2 in terms of ranging stability as the plasterboard wall has lower permittivity than the concrete wall and UWB gets better penetration result in Environment 2. These results indicate that the relative permittivity of obstacles in the environment should be considered when deploying IPSs in industrial settings, with WiFi being preferable in NLOS environments containing obstacles with high permittivity.



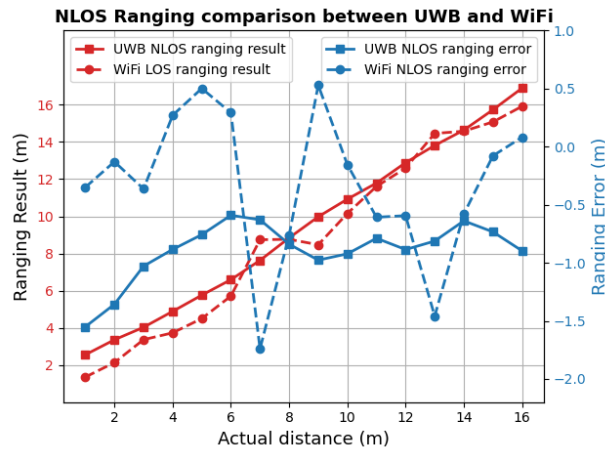
(a) LOS Ranging results with errors for Environment 1



(b) LOS Ranging results with errors for Environment 2



(c) NLOS Ranging results with errors for Environment 1



(d) NLOS Ranging results with errors for Environment 2

Fig. 4: Ranging accuracies and error comparison between WiFi and UWB in different LOS and NLOS Environments

IV. COMMENTS ON ACCURATE RANGING AND LOCALISATION WITH WiFi AND UWB

A. Module Placement During Deployment of IPS

An important aspect of IPS deployment is module placement to ensure area of interest coverage. Module placement is a critical factor to consider for IPS accuracy, as module positioning affects localisation results. From our experiments, lower accuracy was observed when both the WiFi and UWB modules were positioned close to the wall. In Figs. 4 (c) and (d), it is observed that the ranging accuracy was poor for both WiFi and UWB, when placed too close to the wall, i.e, in the case for 1 to 2 m ranging. In this experiment for NLOS in Environment 1, both modules were placed approximately 0.5 m from the wall for 1 m ranging. As a result of direct reflection of the signals, the distances were over estimated. Once moved at least 1 m from the wall for the subsequent ranging experiments, better estimates were observed.

B. Selection of Ranging mode

For UWB, Double-Sided Two-Way Ranging (DS-TWR) is preferable over SS-TWR, if both options are available and energy consumption is not a hurdle. In DS-TWR, both nodes estimate distances to each other, with the results averaged (better precision) as compared to a single node estimating the distance in SS-TWR. However, the energy requirement of DS-TWR is higher compared to SS-TWR, making it less favorable and less pragmatic for IoT applications. This idea is also extensible to WiFi, where Two-sided RTT or one-sided RTT can be opted for (both supported by "WifiRttManager" API).

C. Frequency Selection and Channel Configuration

For hard NLOS scenarios with obstacles of high permittivity, performing WiFi ranging with the 2.4 GHz channel is preferable over the 5 GHz channel. The 2.4 GHz channel exhibits less attenuation than the 5 GHz channel and delivers more accurate ranging results. The Decawave module used for the experimentation supports 6 channels with center frequencies 3494.4, 3993.6, 4492.8, 3993.6, 6489.6, 6489.6 MHz. Similarly to WiFi, better ranging accuracy and stability are observed for typical NLOS conditions when lower frequency channels are selected. Unless signal interference is a concern, it is recommended that lower frequencies are used for ranging channels to obtain more accurate and reliable results with less deviations.

D. Data Rate and Preamble length

The IEEE 802.15.4 protocol defines three data rates, i.e 110 Kbps, 850 Kbps and 6.8 Mbps for data communication. Selection of any of the data rates does not have a noticeable effect on the ranging accuracy, however higher data rates will significantly decrease air utilization, by reducing frame duration in the air. The synchronization header in UWB contains the preamble and Start of Frame Delimiter (SFD), which is a frame flag indicating the start of a frame. When the receiver receives a message from the transmitter, it searches the channel to observe the preamble and looks for the SFD symbols. The first SFD is timestamped as ToA for the message [42]. There is a significant increase in accuracy when the length of the SFD symbol is changed from 128 symbols to 1024 symbols.

V. CONCLUSION

In this article, we introduced and compared UWB TWR and WiFi FTM for use as time-based localisation technologies in real-time IPS. We analyze and compare the ranging capabilities, accuracy and stability for WiFi RTT and UWB TWR in two distinct environments representing LOS and NLOS conditions representative of industrial settings. We show that UWB TWR performs better for LOS conditions in terms of ranging accuracy and ranging stability, when compared to the WiFi FTM protocol. However, the performance of UWB degrades in terms of accuracy in NLOS environments, especially in hard NLOS conditions with obstacles of high permittivity. In this latter situation, WiFi becomes a viable alternative offering better accuracy and stability. Therefore, the relative permittivity of materials used for industrial buildings, as well as the line-of-sight conditions in the environment must be considered during the selection of UWB TWR and WiFi FTM for IPSs. For future work, we will consider transfer learning mechanisms to transfer domain knowledge from a UWB ToF localisation network to a WiFi ToF localisation network, and vice versa, to explore redundancy in localisation systems. For this work, we will also consider typical industrial settings with soft and hard NLOS links.

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