Study and Mitigation of Platform Related UWB Ranging Errors

Nour Smaoui
University of Houston
nour@cs.uh.edu

Omprakash Gnawali
University of Houston
gnawali@cs.uh.edu

Kyungki Kim
University of Houston
kkim38@central.uh.edu

***Abstract*—Ultra Wideband technology has been presented as a precise and accurate solution for wireless ranging. However, the noise and errors created from the low-cost, off-the-shelf UWB devices have been a challenge. Therefore, a comprehensive characterization of these errors is required for these devices to work more efficiently in real applications. This paper will cover the characterization of errors in different environment and configurations, a zscore-based error estimation and correction method for LOS scenarios, and evaluation of its performance. The result shows errors with a maximum mean of 5cm after the proposed correction.**

***Index Terms*—UWB, error characterisation, range calibration**

I. INTRODUCTION

For the past few years, wireless range measurement has been the focus of many researchers due to its wide use in various types of sensing applications, and its non-intrusive characteristic. However; its granularity, precision, and accuracy of current wireless ranging systems depend on the used wireless technology, and their application field. Specifically, Ultra Wideband (UWB) ranging systems are claimed to provide centimeter level granularity ranging distances and being fit for many critical applications such as obstacle detection and indoor localization. We also noticed that off-the-shelf UWB systems such as Radino DW1000 [1] can display low, and various precisions and accuracies under different conditions. However, it is unclear on how the ranging errors in these systems are changing, and thus requires a comprehensive study of these systems.

Characterization of the ranging error variations is very important to identify the different factors involved in the ranging process. Additionally, it will also allow us to model the accuracy and precision of the used hardware covering as many factors as possible. We can then select the ones that intervene in the error modeling process and calibrate the ranging system.

However, covering the whole spectrum of error variation factors can be very challenging. Many variables internal to the hardware or related to the external environment can play a huge role in the modeling of the error. These variables failed the previous work from achieving a practical system that can reach accurate and precise ranging.

And although previous approaches took into consideration some of the scenarios, most of them are either using a custom hardware and/or software or are only considering a limited range of scenarios [2] [3]. For instance, Surepoint is using a custom development board that relies on 3 DW1000 chips to compensate for the localization error and only considered one environment for their evaluation while other systems combined the UWB measurements with accelerometers and gyroscopes measurements to improve the localization accuracy [4]. Also, some suggested solutions recommended calibration methods that rely on curve fitting. However, curve fitting based solutions can easily fall into overfitting if not studied comprehensively. In this work, we investigated different conditions these devices can be deployed, and based on that we extracted a set of factors that can affect the ranging error. We tried to extract them from real-life applications such as a worker localization in a construction site or a robot positioning in a building. We made sure that these conditions not only cover the environment where the devices are deployed but also the hardware and software configuration of the device such as the type of the device, the software implementation, the antenna height, and orientation. As for the environmental conditions, we analyzed the impacting factors in indoor and outdoor environments, and we extracted the major possible changes in this environment. We considered therefore different line-of-sight (LOS) and non line-of-sight (NLOS) situations and different environment occupancies. We then formulated a correction method based on the statistical characteristics of the ranging error that we extracted, and we comprehensively evaluated the proposed solution by comparing it to state-of-the-art calibration methods.

Our contributions are:

- A comparative study of the different factors that may affect the ranging errors.
- A statistics-based correction method to reduce the ranging errors
- A real-world evaluation of our calibration method compared to state-of-the-art calibration methods.

II. RELATED WORK

A. UWB ranging methods

In the literature, we find that there are various methods that can be used for UWB ranging or localization. Two of these methods are mostly used and discussed in previous work which are: the TDoA (time difference of arrival) and the TWR (two way ranging) methods.

TDoA is mainly a localization method. It requires presence of 3 or more anchors to be able to find the location of a tag. Systems using TDoA only require the tag to send a single message in broadcast that will be received by the anchors, then a time difference of arrival is calculated, hyperbolas are built using nonlinear regression and the location is found as the intersection of these hyperbolas. Details about this technique are elaborated further in [5]. However, this method requires the anchors to be synchronized to have a correct time difference of arrival. For UWB localization, we are interested in centimeter level accuracy. The synchronization between the anchors needs to be at least at nanosecond level since a 1 ns error is translated to 30 cm error.

As for the two-way ranging method; specifically, the asymmetric double-sided two-way ranging (ADS-TWR), it is a ranging method that can be extended to a localization method if associated with a multiliteration algorithm. This method allows the calculation of the time of flight of packets between a tag and an anchor using round trip and reply times [6]. Those time values are local to every anchor and tag and therefore a synchronization is not required. Although systems using the ADS-TWR support a lower number of tags, since the ranging operation require more than one message, they are easier to deploy and do not require synchronization between the system components. Thats why in this paper we are only interested in systems that utilize the ADS-TWR method for their range estimations.

B. *Wireless ranging calibration methods*

Both methods discussed earlier are prone to errors. For this reason, many works were tried to mitigate these errors using calibration methods. In the case of TDoA, the main correction at the level of the anchors concerned was the clock offsets. The calibration was done either by collecting the errors in ToA (time of arrival) data on the premise in known locations [7] [8] or by using a maximum likelihood estimator of the clock drift at the level of every anchor. Also, systems based on Decawave DW1000 chipsets are recommended to perform an antenna calibration for both systems using TWR and TDoA. Although the reported results of ranging after calibration presents only around 4.5 cm error, they are only applicable to specific conditions [9]. Some other correction techniques of ranging error based on polynomial curve fitting were presented in [10]. However, the reported range errors are reaching up to 60 cm which is an error rate that we intend to beat. In more recent work, an evaluation of state-of-the-art calibration methods was presented [11]. Two methods were applied: linear regression and natural neighbor interpolation. The latter method showed a calibration error of a mean of 9 cm with a standard deviation of 9 cm. However, in the first case the delay is considered as a constant independant from environmental conditions and the second one requires more packet exchanges to find the correct delay of every device. As mentioned earlier, wireless ranging is not limited to UWB. Like in UWB, ranging systems based on TWR exist for 802.15.4. To mitigate the ranging errors, new TWR approaches were introduced such as TWR-MM [12]. The idea is to increase the number of exchanged packets to estimate the time-of-flight and average the result to reduce errors. The system was evaluated with 100 packets exchanged which is not practical since ranging applications can be critical and require the reported range in short delays. Other works estimated the range between devices based on RSSI. Such systems also required calibration of the RSSI values. In [13] [14], the authors considered a set of curve fitting models like exponential and polynomial fitting to map the signal strength levels to ranges. Other works formulated a logarithmic relation between the distance and the signal strength and calibrated it by proposing a propagation model of the 802.15.4 radio waves [15], used RSSI fingerprinting [16] or combined both [17] to reduce the ranging errors. However, these methods are not applicable in our case since they depend on the environment where they are deployed which is not the intention of this paper. Therefore, to have calibration that is applicable to all deployments, a study of the behavior of the error is necessary. The challenge here is to find all possible settings in the environment where the system is deployed. Previous work investigated some of these parameters effect on the radio waves communication barrier with Wi-Fi in vehicles. The loss of wireless signals path was studied under different conditions including the antenna height, the distance of the transmitter from a barrier, and the barrier material type [18].

III. EXPERIMENTAL STUDY

To be able to generate a formulation of the ranging error, we designed a set of experiments to find the factors that can affect the behavior of the ranging error. We started by investigating the errors at the level of the platform and we extended it to cover environmental conditions. For this purpose, we provide a comparative study taking into consideration six factors: the received power level, the ranging distance, the antenna orientation, the height of the device above ground level, the visible line-of-sight and non line-of-sight and the deployment environment (indoor environment vs outdoor environment). For all the conditions, we measured the range reported by the UWB tag at fixed distances ranging from 1m up to 50m with a step of 1m.

A. *Two way ranging and the sources of error*

The asymmetric double sided two way ranging method in UWB depends on two major factors: the round time and the reply time. Decawave DW1000 manual introduces two sources of error when this method is used. The first is related to the propagation delay detection and the second is related to inaccuracies in the clock frequencies between the communicating devices A and B [6]. An expression of latter error is presented by formula 1.

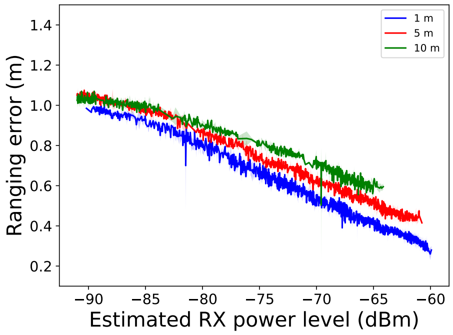

Fig. 1: Received power level effect on the ranging error for 1, 5 and 10 m

$$error = \hat{T}_{prop} \times (1 - \frac{K_a + K_b}{2}) \quad (1)$$

Where $\hat{T}_{prop}$ is the propagation time, K_a and K_b are the number of times the clock runs at the desired frequency in device A and B respectively. And knowing that the DW1000 chips run crystals with a range of 20 ppm, clock A and B can have a maximum combined error of 40 ppm. Therefore, even at large distances like 100 m, the error introduced by the clock can result in a maximum of 6.7 picoseconds error translated to 2.2 mm. We conclude then, that the clock inaccuracies do not impact the time of flight considerably to be a substantial source of error and we can give more importance to the propagation delay detection errors.

B. *Effect of received power level*

UWB is a communication technology based on impulse radio. The centimeter level granularity that it offers comes from its capability to detect the first path with high accuracy from the Channel Impulse Response (CIR) data. DW1000 documentation confirms that the first path detection accuracy can be affected by the received power level [19] [20]. The reported error introduced by the received power level is between 5 cm and -10 cm for power levels between -95 dBm and -50 dBm. To confirm this claim, we ran an experiment where we collected ranging data at different transmission power boost values ranging from 0 to 33.5 dBm. We collected for each power level 100 ranging data samples (distance estimation and received power level) at different distances ranging from 1 to 10 m. Figure 1, shows the error mean as a function of the received power level for 1, 5 and 10 m. The first observation is that for all distances the ranging error decreases when the received power level increases which confirms the error trend mentioned by Decawave. However, the errors mentioned in Decawave documentation do not match the errors reported by our experiment which confirms the exsitance of another source of errors. Therefore, we kept investigating other possible sources.

C. *Effect of ranging distance*

The objective of our UWB system is to test ranging performance over a multitude of distances. So the first step would be to verify if the ranging error changes along with the distance between the nodes in our system. We designed an experiment where we collect ranging data from our system at various distances ranging between 1 m and 50 m with a step of 1 m and we measured the ranging error for every distance. For all distances, we made sure that the transmission power at the level of both nodes is constant. To investigate the behavior of the error we analyzed it first at every distance separately as shown in figures 2,3 and 4. We selected as an example the distance of 1 m, 5m, and 8m to show that the ranging error at any distance changes following a Gaussian distribution with different means and standard deviations. We also confirmed that the ranging error means varies when we increase the distance as figure 6 shows. The mean of ranging error follows a trend where it increases from around 17 cm at 1 m distance to 50 cm at 8 m distance then it drops to -1.05 m at 51 m.

A correlation can be found between the ranging distance and the received power level. As figure 5 shows, since we are using a constant transmission power level, the received power level decreases when the distance increases. However, we notice that the ranging error at different distances does not follow the same behavior described by the DW1000 documentation which proves that another factor is introducing more errors.

D. *Effect of environmental conditions*

UWB ranging and localization system can be used inside buildings but also in outdoor environments (parks, parking lots, construction sites ...). These two environments exhibit different morphologies. In fact, buildings, for instance, are typically formed by a multitude of walls forming rooms, corridors, and hallways increasing, therefore, the multipath components of the radio waves.

In the UWB ranging application, objects/individuals are often in motion and can have different degrees of freedom including rotations. And since different antenna orientations can change the radio waves propagation model, we investigated the effect of antenna orientation by running the ranging system under two setups: a 0 degrees orientation means that the antennas are facing each other and have the same orientation and a 90 degrees orientation means that the antennas of the nodes are orthogonal to each other.

Also, one major application of UWB ranging is UWB localization (i.e worker localization in a construction site). In this specific case, we found that the tags on the workers can be held either at the level of the waist or at the level of the chest. Based on the previous ascertainment, we compared the error variation when the anchor and tag are at a distance of 1 meter above the ground and when they are at 1.5 meters above the ground.

We collected ranging data at a multitude of distances while keeping a constant transmission power level.

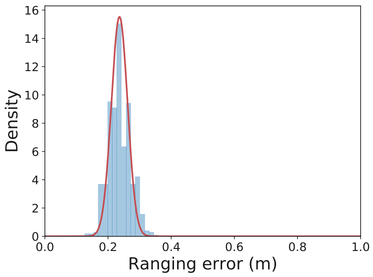

Fig. 2: Ranging error distribution at 1 m range

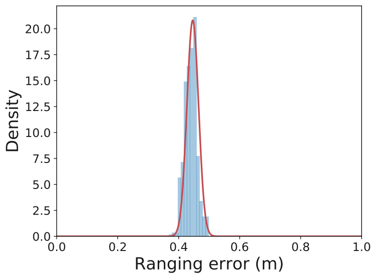

Fig. 3: Ranging error distribution at 5 m range

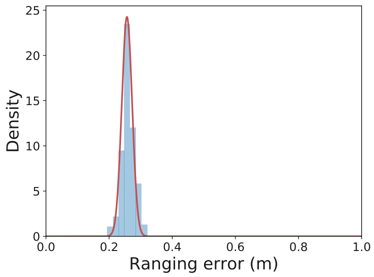

Fig. 4: Ranging error distribution at 8 m range

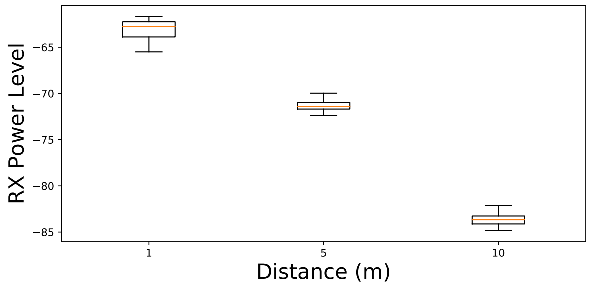

Fig. 5: Power level distribution for different distances

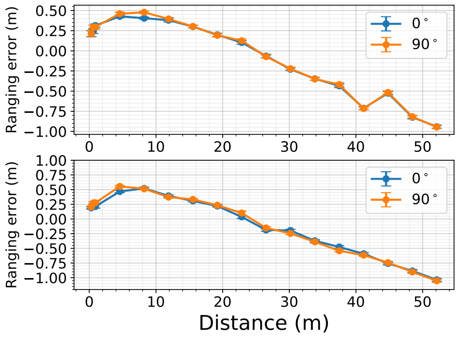

Fig. 6: Antenna orientation effect on the ranging error in an indoor (top) and outdoor (bottom) environment

Figures 6 and 7 show the ranging error pattern for different antenna orientations and antenna heights in an indoor and outdoor environment (respectively).

We observed that the ranging error is not affected neither the antenna orientation nor by the antenna height in both environments, except for distance above 42m where the ranging errors present a large offset in indoor environments at a height of 1.5m and no communication in outdoor environments at the same height.

We can, therefore, consider that the environmental factor can be removed from the error model that we intend to build.

E. Effect of line-of-sight vs non line-of-sight

UWB ranging is a very useful solution for environments with complex topologies and multiple obstacles. However, if obstacles exist between the transmitter and receiver, the wireless signals are prone to attenuation, and only reflected and/or refracted signals can reach their destination which can affect the measured range by the UWB devices. To be able to simulate such harsh environments, we arranged the anchor and tag location in visual non line-of-sight. We considered for NLOS experiments; two environments (indoor and outdoor). For the indoor experiment, we used a wall as an obstacle and for the outdoor experiment, we used three types of obstacles: a human, a car with a metallic structure, and a wall made of concrete.

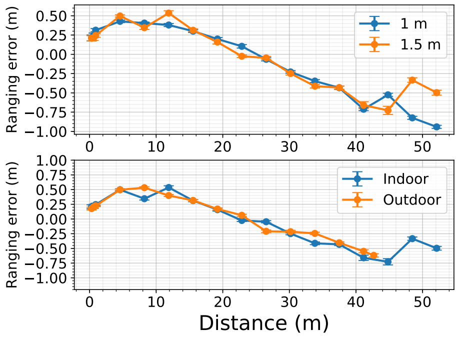

Fig. 7: Ranging error comparison at 1 m and 1.5 m height (Top) and at 1.5 m height in an indoor vs outdoor environment (bottom)

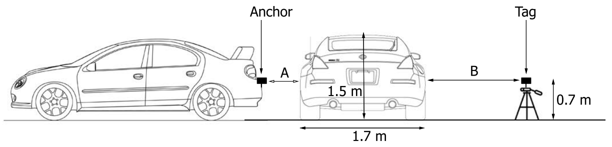

Fig. 8: Non line-of-sight experimental setup in an outdoor environment with a car as an obstacle

We first studied the effect of NLOS in an indoor environment with a wall as an obstacle between the tag and the anchor. The ranging was performed at distances reaching up to 12m. Figure 9 shows that in NLOS, the ranging stops after 10m with ranging errors between 0.8m and 2.5m with relatively high standard deviation at distances higher than 8 meters.

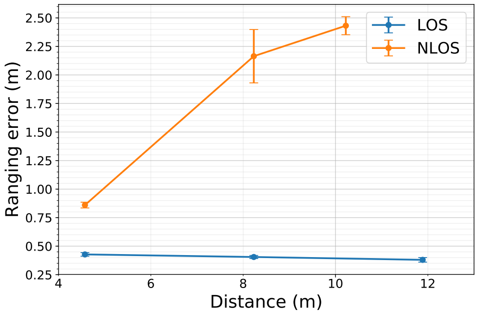

Fig. 9: NLOS effect on the ranging error in an indoor environment

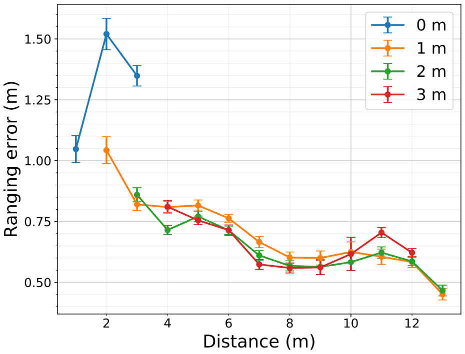

Fig. 10: NLOS effect on the ranging error in an outdoor environment with a human obstacle

This shows that not only the ranging is inaccurate but also imprecise, which can be explained by the introduction of many multipath components in the environment. As for the human experiment, we placed an individual at different distances from the tag ranging from 0m (tag attached to the human body) to 3m.

Figure 10 shows that if a tag is attached to the human body, it will stop communicating at a maximum distance of 3m, and the ranging system exhibit high ranging errors from 1m to 1.5m. If we increase the distance between the human obstacle and the tag to 1,2 or 3m, then we notice that the errors are relatively reduced and they keep similar patterns. This behavior is explained by the fact that in the case of an attached tag, the radio waves get attenuated by the human body. However, in the case where we keep a distance between the tag and the human, we were able to receive the diffracted radio waves.

When a car is considered as an obstacle, we defined a distance ’A’ separating the car from the anchor and a distance ’B’ from the tag. We considered two values for the distance A of 1m and 3.6m as show by figure 8. And for both scenarios, we move the tag starting from a 3 m (for A = 1m) and 6 m (for A = 3.6m) until the communication stops.

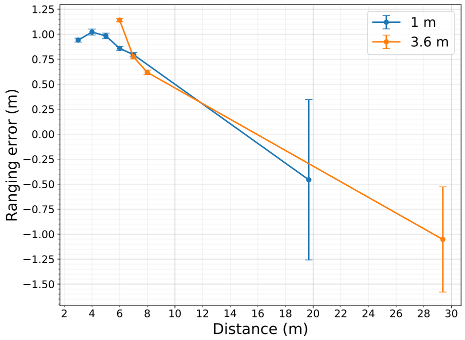

Fig. 11: NLOS effect on the ranging error in an outdoor environment with a car obstacle

Figure 11 shows that for both distances of 1m and 3.6m between the car and the tag, we notice that the error variation is following practically the same pattern. Although it is important to mention that at the distance 3.6m, we notice that we managed to reach higher distances and have a lower standard deviation. We assume that this distance increase is due to the improvement of the radio waves propagation pattern when we provide enough space between the obstacle and the source of the signal.

Finally, regarding the concrete obstacle, we placed the anchor at a distance of 1m from the concrete wall and the tag is placed initially at a distance of 127cm. then we move the tag with a step of 260 cm. In this scenario, we only managed to perform the ranging for the initial distance of 253cm with ranging error reaching up to 2.6m. After that, the communication between the nodes stopped.

We summarized the results of our experiments in table I where we present every scenario parameter and we report the minimum, the mean and the maximum of the ranging error for every configuration.

F. Interpretation

In this section we covered a multitude of possible sources of errors that could affect the ranging error and based on the results of our experiments, we can make three major observations:

- A correlation can be found between the ranging distance and the received power level that affects the detection accuracy of the first path.
- The multipath effect increases the ranging error considerably due to the reception of either delayed signals or reflected signals taking different paths other than the LOS path. In these cases, a NLOS identification and mitigation is required and to the best of our knowledge, there isn’t any existent solution that can be generic to all environments.
- In DW1000 systems, the antenna delay is set as a constant bias and was not evaluated in our study since it is a challenging task that requires precise equipment to estimate the delay required by the antenna to resonate.

Based on the previous observations, and since we want to use these devices with the software provided, we decided to

Environment	Orientation	Height (m)	LOS/NLOS	Min (m)	Mean (m)	Max (m)
Indoor	0	1	LOS	0.0652	0.1652	0.9152
Outdoor	0	1	LOS	0.0000	0.3628	1.1808
Indoor	90	1	LOS	0.0024	0.3456	1.0108
Outdoor	90	1	LOS	0.01	0.3628	1.1508
Indoor	0	1.5	LOS	0.0	0.3252	1.1352
Outdoor	0	1.5	LOS	0.0	0.2476	0.702
Indoor	0	1	NLOS-Wall	0.728	2.0904	2.627008
Outdoor	0	1	NLOS-Human	0.0	0.63	2.08
Outdoor	0	1	NLOS-Car	0.46	0.95	2.24
Outdoor	0	1	NLOS-Wall	0.74	1.71	1.9

TABLE I: Ranging errors summary

develop a statistics-based calibration method that can reduce the ranging errors in LOS scenarios.

IV. SYSTEM DESIGN

As demonstrated in the previous section, we concluded that the error in the DW1000 based ranging system is a function of the ranging distance. A solution to remove these errors would be to perform a calibration. However, using methods like curve fitting may not provide good results due to the shape of the error function, and the fact that the error at every single distance is not constant. As discussed earlier, the error follows a Gaussian distribution with different mean and standard deviation at every distance which needs to be taken into consideration. We assume that the error between two consecutive distances separated by 1m is linear and consequently, using the collected data at every single meter (collected by radino DW1000 platform in an outdoor environment), we can build an algorithm that finds the linear coefficients to estimate the error at any location considering the Gaussian nature of the error.

A. *Z score*

In applications like distance measurement, the most common method considered is the Euclidian distance. However, this distance only considers the distance between two fixed points in an n-dimensional space and does not take into consideration the accuracy and precision of the collected data. To apply such method, the usage of mean for instance is used to provide a fixed representation of the collected data. However, with such practices we are prone to lose important data and can infer wrong results. For this purpose, we need to find a measure that represents a distance not only to a point but to a whole distribution of observations. In statistics, distances like the energy distance, which is a smoothed version of the Wasserstein distance can provide a good representation of the actual distance to a distribution. Equation 2 shows how we can generate an energy distance between two samples or an observation and a sample.

$$\begin{aligned} ED = \frac{2}{mn}\sum_{i=1}^{n}\sum_{j=1}^{m}\|X_i - Y_j\| \\ -\frac{1}{n^2}\sum_{i,j=1}^{n}\|X_i - X_j\| - \frac{1}{m^2}\sum_{i,j=1}^{m}\|Y_i - Y_j\| \end{aligned} \tag{2}$$

where X_i is the observation i in the sample X, Y_j is the observation j in the sample Y and m and n are the cardinalites of X and Y respectively.

However, if two samples (i.e observation and sample) are relatively far from each other, the energy distance will always produce a positive distance. In our application, we need a perform a calibration of noisy observations that can be higher or lower than the mean a sample. Therefore, the distance needs also to localise weather the observation is higher or lower than the mean and provide weather the distance is positive or negative

The Z score by definition is an indicator of the standard deviation of the mean of the sample to the mean of a distribution and therefore, the deviation from the mean in our application can be considered as a distance measure between a sample and a distribution. It can also indicate wheater it is lower or higher based on its sign. Equation 3 shows the zscore calculation of one observation.

$$ZS = \frac{x - \mu}{\sigma} \tag{3}$$

where x is the observation, μ is the mean of the distribution and σ is the standard deviation of the distribution.

B. *Correction algorithm*

The main challenge in our correction algorithm is the error estimation at the location where we are running the ranging algorithm. In absence of ground truth data for that specific location, we rely on the collected data in section III combined with the Z score to have the error estimation. Let's assume that $D \sim D_1, ..., D_{50}$ is the sample of ranging observations collected between 1 meter and 50 meters where $D_i \sim D_{i1}, ..., D_{in}$ is the sample of ranging observations collected at the ranging distance i meter where $i \epsilon \mathbb{N}$. We also note $E \sim E_1, ..., E_{50}$ is the sample of error observations between 1 meter and 50 meters where $E_i \sim E_{i1}, ..., E_{in}$ is the sample of error observations for the ranging samples collected at the ranging distance i meter where $i \epsilon \mathbb{N}$ extracted by calculating $E_{ij} = D_{ij} - i$.

Furthermore, as mentioned earlier, every sample D_i follows a Gaussian distribution making $D_i = \Phi(d_i, \sigma_i^2)$ and $E_i = \Phi(e_i, \sigma_i^2)$.

During the ranging operation, our system collects ranging observations $X \sim X_1, ..., X_m$ located at a distance $x \epsilon \mathbb{R}^+$. The distance x is therefore located between two distances i and i+1. We can, therefore, conclude that for a location x such as $i < x < i + 1$, the minimal Z scores (in absolute value) to the set X are those of D_i and D_{i+1} that we can utilize to build a correction model. Let ZS_i and ZS_{i+1} be the Z scores between X and D_i and X and D_{i+1} respectively. The corrected ranges (CR) corresponding to the ranging samples in X are produced by the equation 4.

$$CR_j = X_j - \frac{e_i ZS_{i+1} + e_{i+1} ZS_i}{ED_i + ZS_{i+1}} \tag{4}$$

Where $j \epsilon [1, m]$ and $i < x < i + 1$. Algorithm 1 shows the full process to correct the collected ranging observations.

Algorithm 1 Correct the collected ranging samples

```
$D \leftarrow ReferenceRangingSamples$
$X \leftarrow CollectedRangingSamples$
for all $D_i \in D$ do
    $ZS_i \leftarrow ZScore(X, D_i)$
end for
$i, j \leftarrow$ Two Locations With Closest Z score
for all $X_k \in X$ do
    $CR_k \leftarrow X_k - \frac{e_i ZS_j + e_j ZS_i}{ZS_i + ZS_j}$
end for
return $CR$
```

We, therefore, generated an error correction method that estimates the error using the means of the errors in reference locations weighted by the Z score of a sample in regards to the data distribution in the reference locations.

V. EVALUATION

In this section, we want to prove that our correction method is generic and improves the ranging in most of the environments. For this purpose we define three types of environments where the radio waves propagation pattern differs:

- **Indoor environment:** We consider an environment to be indoor if it is a closed environment. That means that the experimental space is surrounded by either walls or doors in all directions.
- **Outdoor environment:** An outdoor environment is a space where the radio waves can propagate through the air in all directions without facing obstacles except the floor on which we will deploy our system.
- **Indoor-Outdoor environment:** This is a hybrid environment where one of the communicating nodes is deployed in an indoor environment and the other node is deployed in an outdoor environment.

Furthermore, every environment at any time can be either unoccupied where the space surrounding the system is static or crowded where we can find a high dynamicity surrounding the nodes. We simulated a crowded environment by adding to the experimental space a set of furniture. We also made sure that the environment is not static by moving around the deployed nodes while moving the furniture.

	Unoccupied bridge			Crowded bridge			Tunnel		
Calib	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
ZS	0.01	0.02	0.04	0.00	0.01	0.05	0.00	0.02	0.04
POW	0.01	0.10	0.12	0.02	0.05	0.12	0.01	0.07	0.12
POL1	0.02	0.08	0.32	0.02	0.09	0.32	0.00	0.09	0.32
POL2	0.01	0.04	0.17	0.01	0.04	0.16	0.01	0.04	0.17
POL3	0.02	0.09	0.12	0.00	0.06	0.10	0.03	0.07	0.15
NNI	0.00	0.03	0.07	0.00	0.03	0.08	0.00	0.03	0.07

TABLE II: Ranging errors calibration in a university hallway for radino 32

	Unoccupied bridge			Crowded bridge			Tunnel		
Calib	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
ZS	0.02	0.05	0.08	0.00	0.02	0.06	0.00	0.01	0.04
POW	0.01	0.05	0.08	0.00	0.05	0.10	0.01	0.08	0.15
POL1	0.01	0.15	0.26	0.00	0.10	0.31	0.00	0.09	0.36
POL2	0.01	0.11	0.15	0.03	0.08	0.15	0.00	0.05	0.20
POL3	0.01	0.03	0.07	0.00	0.04	0.09	0.02	0.10	0.14
NNI	0.00	0.07	0.14	0.00	0.04	0.10	0.00	0.02	0.06

TABLE III: Ranging errors calibration in indoor environment for TREK1000

We also consider two off-the-shelf DW1000 based platforms which are the Radino32 and the TREK1000 platform [21].

A. Ranging error calibration methods

Calibration and ranging error correction is a well-developed field. So, we considered a set of calibration methods proposed by earlier works [13] [11] as a baseline to compare against the proposed method. Three main variations of regression models were discussed:

- Power **POW:** $\hat{x} = a.x^b + c$
- Linear regression **POLY:** $\hat{x} = a.x + b$
- Natural neighbor interpolation **NNI**

We extended our evaluation by also considering other variations of the polynomial fitting by considering three polynomial orders: first order (**POLY1**), second order (**POLY2**) and third order (**POLY3**)

B. Indoor environment

We ran this experiment in two indoor environments: a hallway in the university building and an underground tunnel. The first experiment space is constituted of multiple walls, windows, and a closed door and the second is a completly sealed space with concrete walls to ensure properly that the indoor property is applicable. We collected ranging data at distances separated by 1 meter and we applied our correction method. Table II shows the mean of the ranging after calibration for all environment states (unoccupied hallway, crowded hallway and tunnel) does not exceed 2 cm using the Z score method while other methods can have higher means reaching up to 9 cm. Similar results can be seen in table III.

C. Outdoor environment

We considered three outdoor environments. The first is a bridge separating two university buildings in two states

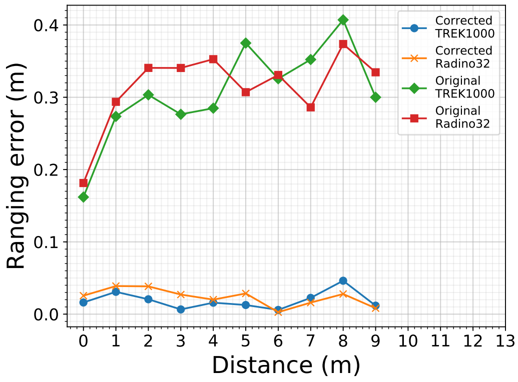

Fig. 12: Comparision of ranging errors before and after Z score correction in hybrid environment

	Unoccupied Hallway			Crowded Hallway			Park		
Calib	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
ZS	0.00	0.02	0.04	0.00	0.02	0.04	0.00	0.02	0.08
POW	0.04	0.10	0.20	0.03	0.10	0.2	0.02	0.09	0.30
POL1	0.02	0.11	0.39	0.02	0.12	0.38	0.00	0.06	0.50
POL2	0.01	0.06	0.23	0.00	0.06	0.22	0.00	0.04	0.33
POL3	0.00	0.09	0.16	0.01	0.09	0.15	0.02	0.10	0.26
NNI	0.01	0.03	0.07	0.00	0.02	0.05	0.00	0.03	0.14

TABLE IV: Ranging errors calibration in outdoor environment for radino 32

	Unoccupied Hallway			Crowded Hallway			Park		
Calib	Min	Mean	Max	Min	Mean	Max	Min	Mean	Max
ZS	0.00	0.01	0.02	0.00	0.01	0.03	0.00	0.02	0.09
POW	0.05	0.06	0.13	0.05	0.06	0.12	0.00	0.03	0.09
POL1	0.00	0.06	0.34	0.00	0.06	0.33	0.01	0.07	0.19
POL2	0.00	0.01	0.18	0.00	0.01	0.17	0.00	0.04	0.07
POL3	0.04	0.08	0.12	0.03	0.08	0.11	0.01	0.04	0.09
NNI	0.00	0.02	0.06	0.00	0.01	0.05	0.00	0.03	0.17

TABLE V: Ranging errors calibration in outdoor environment for TREK1000

(unoccupied and crowded). The second is a large park with no surrounding obstacles to reduce as much as possible the radio wave reflections. We assume that the outdoor environment property is applied here since the bridge is not covered and the barriers on the sides are assumed to have no effect. We performed the same experiment as for the indoor environment and we noticed that the Z score method is still performing better than the other calibration methods for all platforms with a mean ranging error of 1-2 cm as show by the tables IV. We also noticed that the the standard deviation of the corrected samples are reduced considerably which improves the precision of the ranging operation.

D. *Indoor-Outdoor environment*

We confirm that our correction method is generic for all environments by combining the indoor and outdoor environments into one hybrid environment. for this purpose, we opened the door separating the hallway and the bridge and we placed one of the nodes 2m inside the indoor environment while we kept changing the location of the second node covering a full distance of 10 meters as shown by the figure 12. Experimental results show that our correction method improved the ranging errors considerably reaching a maximum of error mean of 3 cm for radino32 and 5 cm for TREK1000.

VI. CONCLUSIONS

In this paper, we studied the behavior of the ranging error in different conditions, and analyzed the effect of received power level, distance, antenna orientation, antenna height and NLOS on the error trends. We also built a statistics-based calibration model based on the Z score. The proposed technique was evaluated against different state-of-the-art calibration methods, and we confirmed that it improves the error reduction with a maximum error mean of 5cm

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