Assessment of UWB Ranging Bias in Multipath Environments

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***Abstract*—Ultra-wideband ranging measurements are typically affected by a systematic bias that is usually attributed to the distance between the devices. In this work we carry out two measurement campaigns in a Line of Sight scenario to assess the sources of this bias. The obtained results show that the total receive power, and its value with respect to the receive power of the signal corresponding to the first path, is fundamental to explain the ranging bias. Therefore, only the ranging values are not enough to properly model such a bias, as it is frequently stated in the literature and also by manufacturers.**

I. Introduction

Indoor positioning systems allow for estimating the location of an object or a set of objects in a plane or in the three-dimensional space and in environments where Global Positioning System (GPS) coverage does not suffice. These systems are based on a plethora of technologies [1] and, among them, those that make use of Radio Frequency (RF) signals have gained most of the attention. Examples can be found for personal area networks [2] (e.g. Bluetooth); local area networks [3] (e.g. WiFi); and sensor networks [4] (e.g. ZigBee or Bluetooth LE [5]). Frequently, indoor positioning systems take advantage of additional information provided by other technologies, essentially from inertial sensors [6], [7] and other measurement systems (magnetometer, barometer, etc.), pursuing the fusion of all the information coming from all available systems and technologies [8] with a twofold objective: to improve both the precision and the accuracy of the positioning, and to increase its robustness.

Depending on the target application, not all RF technologies are suitable for indoor positioning [9], although they may appear frequently in the literature due to other reasons, like their low cost or their high availability. Examples of these technologies are Bluetooth and WiFi. However, when the objective consists in locating a mobile object within the three-dimensional space with very good precision, at a very high rate and offering an increased availability, very few technologies can be used, being Ultra-wideband (UWB) among the most used ones (see, for example, [10], [7], [11]). UWB allows for employing different positioning strategies. One of the most attractive ones is the so-called Time of Arrival (TOA)-based ranging [12], which does not require to synchronize the clocks of all nodes involved in the positioning process as it is required by Time-Difference of Arrival (TDOA)-based ranging, for example. Unfortunately, the performance of TOA-based UWB ranging systems strongly depends on the availability of the direct path signal [12], [13], [14], which can be detected under both Line of Sight (LOS) and Non Line of Sight (NLOS) conditions in indoor scenarios [12]. Particularly, in indoor NLOS conditions, estimating the position with high precision by means of UWB ranging becomes a challenge due to the difficulties found at the time of mitigating the multipath effects [14], [15], [12], which are responsible for corrupting the ranging estimates with large positive biases.

Based on the definition of the IEEE 802.15.4a standard, new UWB system implementations have arisen as the basis for future wireless positioning systems [16], [11], allowing for low-cost lightweight and low-power solutions. A prominent example is the DW1000 module available from DecaWave Ltd., which is based on the so-called two-way ranging. As it is explained in [11], such a module provides access to the channel impulse response of the received signals, hence allowing for detecting the first path to estimate the TOA. Under NLOS conditions, however, such a first path detection becomes more challenging. Additionally, the observed ranging error does not only depend on the LOS or NLOS condition, but also on the total receive power and on the multipath components. Although previous works have modeled this bias only as a function of the ranging measurements [17], [18], in this paper we show, by means of measurement results in a multipath LOS indoor scenario, that the total receive power, and its value with respect to the power of the signal corresponding to the first path, is fundamental to explain the ranging bias. Therefore, only the ranging values are not enough to properly model such a bias.

II. Measurement Setup

Two measurement campaigns were carried out to model the bias observed in the ranging estimations provided by the DecaWave UWB equipment[1]. More specifically, two Decawave EVB1000 boards were employed for the measurements, one of them as the anchor and the other one as the tag. These devices include a DW1000 Integrated Circuit (IC) compliant to IEEE802.15.4-2011 [19] UWB standard. The DW1000 supports 6 RF bands from $3.5\,\text{GHz}$ to $6.5\,\text{GHz}$, and offers three working modes with data rates of $110\,\text{kbit/s}$, $850\,\text{kbit/s}$, and $6.8\,\text{Mbit/s}$, whereas the transmit power can be adjusted from $-14\,\text{dBm}$ to $-10\,\text{dBm}$, with a total transmit power

[1]The data recorded during the measurement campaigns is publicly available at https://bitbucket.org/vbarral/gtec-uwb-measurements.

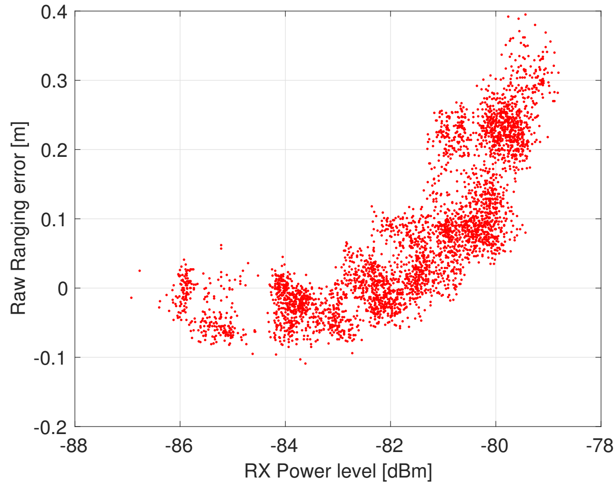

Fig. 1. First setup: raw ranging error over the total receive power considering multiple orientations for the tag.

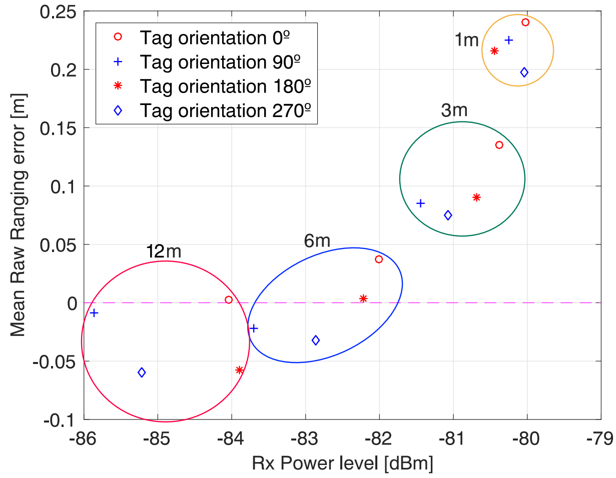

Fig. 2. First setup: mean raw ranging error versus the total receive power, grouped by the different tag orientations and the measurement points.

spectral density bellow -41.3 dBm/MHz (according to legal regulations).

The two measurement campaigns took place in an indoor sports hall of 25 m by 45 m with no obstacles between the transmitter and the receiver. Both the tag and the anchor were placed on two tripods at a height of 1.5 m. In order to model the bias we employed two different setups, both with the same UWB anchor placed in a fixed position, whereas a single tag was located at different distances with respect to the anchor: 1) In the first setup we considered the following 4 orientations for the tag with respect to the vertical axis: 0°, 90°, 180°, and 270°; whereas the anchor was kept fixed at 0°. Ranging measurements were recorded at four spots with a separation between the anchor and the tag of 1, 3, 6, and 12 m. 2) In the second setup both the anchor and the tag were kept fixed at 0°. Ranging measurements were recorded at several spots with a separation between the anchor and the tag varying from 1.5 m to 39 m and a spacing of 1.5 m between consecutive spots. Both measurement setups considered the profile corresponding to a carrier frequency of 3.9993 GHz, a data rate of 110 kbit/s, a preamble length of 1024 symbols, and a Pulse Repetition Frequency (PRF) of 16 MHz.

The following magnitudes were recorded for each measurement campaign: the so-called raw ranging values without any post-processing, the estimations for the total receive power and the power of the signals corresponding to the first path, and finally, the ranging values corrected by the EVB1000 firmware. Given that the raw ranging estimations are affected by a systematic bias related to the received power [20], the k-th raw ranging measurement, r_k, can be modeled as

$$r_k = d_k + B(p_k) + n_k, \qquad (1)$$

where d_k is the actual distance between the anchor and the tag, $B(\cdot)$ is the bias modeling function, p_k is the total receive power, and n_k is the noise component.

Additionally, the EVB1000 firmware provides a corrected version of the ranging that tries to compensate for the bias $B(p_k)$, but taking only the raw ranging values into account, regardless of the total receive power. The idea behind this approach is that the total receive power is related to the distance through a path loss model, i.e. $p_k = P_R(d_k)$, with $P_R(\cdot)$ the considered model of the received power as a function of only the actual distance. In particular, EVB1000 firmware uses a free-space path loss model

$$P_R(d) = P_T + G + 20\log_{10}(c) - 20\log_{10}(4\pi f_c d), \qquad (2)$$

where P_T is the total transmit power, G the antenna gain, c the speed of light, and f_c is the carrier frequency. Consequently, the bias model in Eq. (1) changes to $B(P_R(d_k))$, and thus the bias can be assumed to be a function of the distance.

However, in a real-world environment propagation conditions diverge from those expected in a LOS scenario –e.g. obstacles that partially absorb the transmit power, reflections on nearby objects– and corrections based solely on the values of the raw ranging are distorted by the typical features of the signal propagation in multipath indoor environments.

III. Measurement Results

Fig. 1 shows the estimations of the raw ranging error, obtained as $\hat{b}_k = r_k - d_k$, with respect to the estimated total receive power and considering the first setup. A correlation between the estimated total power and the error is appreciated. However, the trend is different for high and low total receive power values. For high receive power values, small variations in the receive power lead to large variations in the error. The documentation provided by the manufacturer states that the DW1000 IC underestimates the received power in this regime, and this could account for the steep variations of the error when compared to the estimated received power.

Fig. 2 shows the mean raw ranging error over the estimated total receive power, grouped by the different tag orientations and the measurement points at 1, 3, 6, and 12 m. We can see how a simple change in the tag orientation impacts on the total received power, yielding a variation in the raw ranging

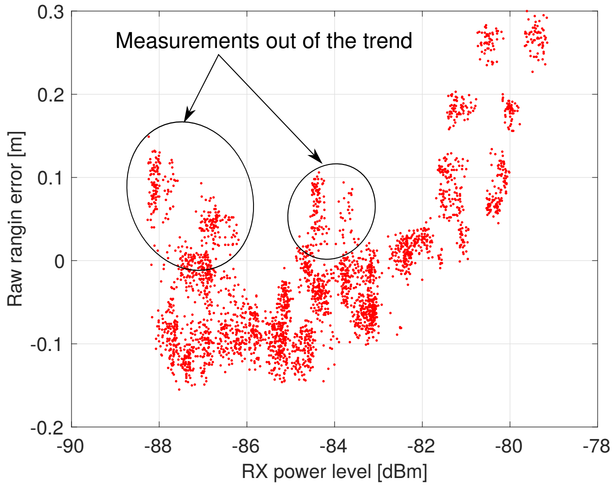

Fig. 3. Second setup: raw ranging error over the total receive power considering a single tag orientation.

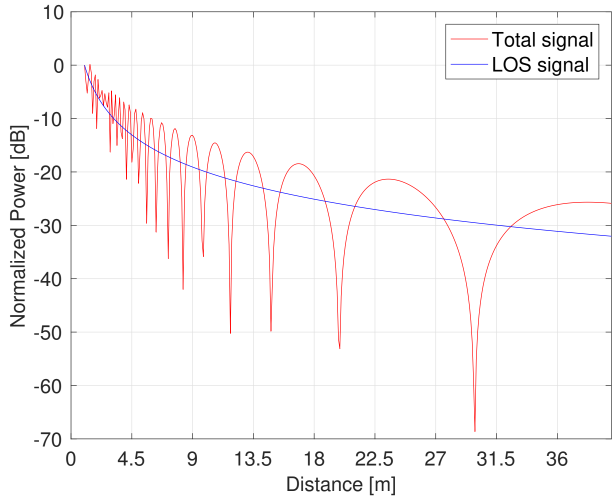

Fig. 5. Theoretical two-ray propagation model applied to the measurement scenario.

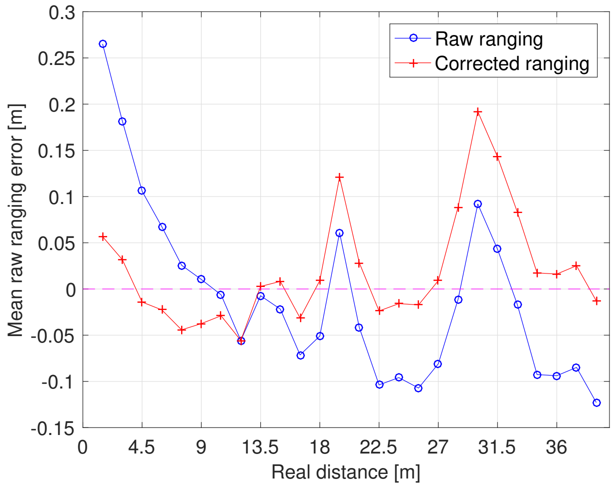

Fig. 4. Second setup: mean raw and corrected ranging error versus distance between the tag and the anchor.

bias as well. We can see also how this effect seems to grow according to the distance.

Fig. 3 shows the results obtained for the second setup, where the ranging error is represented against the estimated total receive power. Again, it can be appreciated some correlation between the estimated total receive power and the error. However, in this setup there are some ranging measurements that seem to be out of the trend when compared to Fig. 1. We can see this effect in Fig. 4, where the mean raw ranging error is plotted against de actual separation between the anchor and the tag. For some separation values abrupt variations in the error that do not follow the bias trend with the distance are appreciated. The mean error corresponding to the corrected ranging provided by the EVB1000 firmware is also plotted in Fig. 4. Although the maximum mean error is around ± 0.05 m, for the aforementioned distance values the error raises up to ± 0.2 m because at these points the ranging bias cannot be correctly predicted from the raw ranging values.

Although our measurements were carried out in a semi-open environment (a sports hall) without obstacles and the walls were far enough to have a negligible effect, we still have a source for multipath: the floor. In this situation, we can consider the two-ray reflection model [21], [22], where it is considered the direct path and a reflected path coming from the reflection on the floor. In our case, we have located the tag and the anchor at a height of 1.5 m hence, considering the UWB carrier frequency, the two-ray reflection model yields the plot shown in Fig. 5. In this figure, we can see the normalized power of the LOS path and the combination of both paths with respect to the distance between the tag and the anchor.

We can observe deep fades that are produced by the destructive combination of both rays (due to opposite phases). These fades appear around the distances: 12, 15, 20, and 30 m. Therefore, considering the discrete resolution of our measurements (in steps of 1.5 m), we can see how this fades match almost perfectly with the abrupt changes in the raw ranging error shown in Fig. 4.

Even when considering a proper correction of the ranging error for each distance, we need to identify whether we are in a destructive contribution of the different paths, which is going to appear very often as soon as we introduce a more complicated environment with walls, ceiling, and obstacles.

Although the two-ray model can explain the source of distortion in the measurements, it does not explain the variations of the raw ranging bias shown in Figs. 3 and 4, where we can see how the raw ranging error changes not only with the estimated total received power, but also with a different factor.

Fig. 6 shows the raw ranging error against the difference between the total estimated receive power and the estimated receive power of the signals corresponding to the first path (that is, the one which is used to estimate the ranging) in the anchor. When the difference between these two magnitudes is larger than $\approx$ 6 dB, a correlation with the ranging error appears. These measurements correspond with those taken at the points where the bias trend presents an abnormal

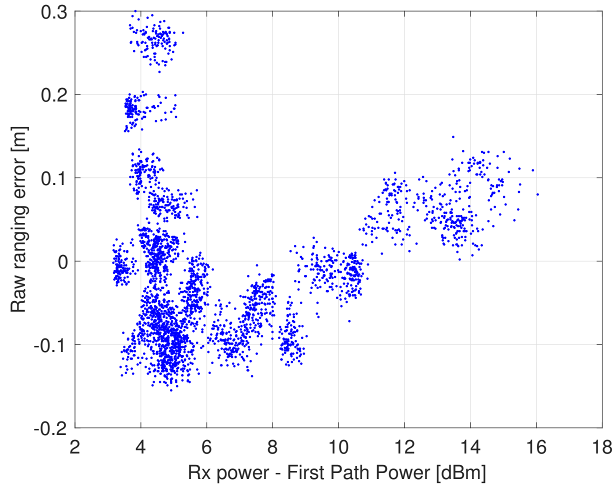

Fig. 6. Raw ranging error with respect to the difference between the total receive power and that of the signals corresponding to the first-path.

behavior in Fig. 4. There is a relationship between the bias and the difference of the aforementioned power values. Hence suggesting that an appropriate bias model should consider also this difference besides the total receive power.

IV. Conclusions and future work

In this work we have carried out two different measurement campaigns with two distinct setups to assess the bias that affects the UWB ranging estimations. The manufacturer of the DW1000 states that this bias is related only to the total receive power. We showed that antenna rotations affect the estimated received power, thus the related bias value is affected as well.

We have also observed experimentally how in a theoretically pure LOS scenario the obtained ranging error values at specific points were affected by the multipath, and that this effect was very well explained by a two-ray propagation model.

We can infer that the ranging bias is related not only to the total receive power, but also to the difference between the total receive power and the power of the signals corresponding to the first path. Thus, bias estimation methods that rely only on the raw ranging measurements will be affected by a systematic error. This is because a path loss model must be used to estimate the bias corrections according to distance, but this model can mismatch with the actual environment. For instance, in typical NLOS scenarios, corrections of this type could introduce larger range estimation errors.

In a future work we will model the bias according to the experimental findings reported in this work. In particular, we are working on a model that does not relay only on the raw ranging measurements. We expect to build a ranging estimator more robust against typical indoor propagation conditions.

Acknowledgments

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