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Comparing Decawave and Bespoon UWB location systems: indoor/outdoor performance analysis

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***Abstract*—Several UWB location systems have already been proposed for accurate position estimation. These UWB systems, some available at commercial level, and others implemented as laboratory test-beds, have been individually evaluated for particular applications and under different fusion strategies. In this paper we compare two commercially available UWB systems (Decawave and Bespoon) under exactly the same experimental conditions, in order to generate a critical analysis about their performances. The analysis includes the characterization of the range error in Line-Of-Sight (LOS) and Non-Line-Of-Sight (NLOS) conditions. The NLOS conditions include the propagation/difraction of radio signals across furniture, metallic cabinets and several brick walls in indoor scenarios. The analysis also includes the 2D/3D positioning performance of both UWB systems using a particle filter estimation approach that takes into account NLOS conditions.**

***Keywords*—UWB, Distance Measurement, Indoor localization, DecaWave, Bespoon.**

I. Introduction

Indoor localization is still an open problem. Many different approaches using distinct technologies have been proposed to obtain a usability similar to GPS outdoors [1], [2], [3]. The most difficult challenge for positioning is to find an accurate-enough indoor location method, valid for extended areas, robust to changes to environmental conditions, and at the same time as simple as possible. Different approaches can be used for indoor localization: 1) Vision-based solutions mostly based on cameras (RGB, TOF) configured as a network or carried by the user [4], 2) Beacon-based solutions where a network of receivers/emitters are placed at known locations and one sensor is on the object to locate (Local Positioning Systems-LPS) [5], [6], [7], 3) Solutions that mainly rely on dead-reckoning methods using inertial sensors installed on the person to be located (Pedestrian Dead Reckoning-PDR) [8], [9], [10], and 4) Solutions that create a mesh of radio links crossing an area with the purpose of detecting subareas where a significant signal attenuation comes from; this approach does not require the person to carry any device (Beacon-free solution) also called DFL-Device Free Localization [11], [12], [13].

The most accurate beacon-based LPS localization solutions are those using ultrasound [14], [15], [16] or UWB radio signals [17], [18]. Ultrasound LPS can reach even subcentimeter accuracies in still air conditions [19]. However ultrasound has the drawback of a limited maximum range (about 10 meters) and can not penetrate walls, so its coverage is limited by the number of beacons to install and the partitioning of the building. The UWB positioning systems have lower accuracy than ultrasound (0.2 m in LOS) but has a larger coverage and ranging capability (more than 100 m in LOS). UWB can penetrate walls in buildings and can resolve individual multipath components due to its large bandwidth. Nevertheless, it is still a challenge to use UWB in indoor environments with enough accuracy and coverage [18]. The potential excellent UWB distance measurement accuracy and maximum range is in practice significantly degraded when operating indoors. The NLOS effect causes a deterioration of range measurements with larger dispersion and in-excess ranges (outliers) that could be larger than one meter in typical usage. Also, the maximum measurable range can be reduced to less than 10-15 meters in apartment type spaces.

UWB technology is receiving an impressive attention in recent years for outdoor/indoor position estimation. Many systems are now available at commercial level and others have been implemented in laboratory testbeds. These systems have been individually studied with some detail, and evaluated for particular applications. Other activities have concentrated in modelling the LOS and NLOS conditions for trying to create NLOS identification metrics that allow to implement some NLOS mitigation methods. The NLOS problem, as the main source of error in UWB ranging and positioning, is still an open research topic [20].

Several commercial UWB kits are nowadays available for solutions developers and research labs to evaluate and generate their own conclusions. Among them, apart from the classical and pioneering Ubisense product, new Round-Trip UWB technologies have emerged in recent years such as those provided by Decawave and Bespoon companies. It would be very useful for the comunity to compare these UWB systems in a commom framework under the same test conditions. In this paper we analyze the Decawave and Bespoon systems under the same experimetal conditions. We study the range accuracy in LOS and NLOS conditions, as well as, the positioning performance that can be obtained with a Bayesian position estimation solution that includes NLOS mitigation.

This paper presents a description of the main features and specifications of Decawave and Bespoon systems in section II, the UWB range performance is analyzed in section III for LOS and NLOS conditions. The position estimation performance is analyzed in section IV. Finally, in the last section, we give some conclusions and future work.

II. UWB Localization systems

This section presents the basics of UWB technology and shows some comertially-available UWB systems, giving the main features of the two UWB systems tested in this paper: Decawave and Bespoon.

A. UWB technology

Ultrawideband (UWB) technology was originally used for communication but also has a great potential for accurate ranging and localization [21]. This radio technology consists of emitting very short pulses (Gaussian pulses and their derivatives, usually called monopulses), that is why it is also known as Impulse Radio or IR-UWB. Therefore, as its name reveals, they use a large wide bandwidth, which has the advantage of allowing to resolve any individual multipath components from its direct path. The time of arrival of the received signal can be estimated with high accuracy if the LOS arriving path can be detected. For communication and node identification, several modulation techniques are proposed in the literature using narrow pulses, mainly variants of pulse position modulation (PPM), binary phase shift keying (BPSK) or on-off keying (OOK). In order to not interfere with other equipment, they follow some FCC regulations, which define a maximum emission power and bandwidth limit: an absolute -10 dB bandwidth greater than 500 MHz or a relative bandwidth greater than 20%.

B. UWB commercial systems

There are several commercial companies which develop IR-UWB products, including Timedomain (www.timedomain.com), Ubisense (www.ubisense.net), Zebra (www.zebra.com), Bespoon (bespoon.com) and Decawave (www.decawave.com). Companies like DecaWave and BeSpoon use the 802.15.4a impulse radio standard specification to define its physical layer. The IEEE 802.15.4a (last version IEEE 802.15.4-2011) specifies two physical layers using ultra-wideband (UWB) and chirp spread spectrum (CSS). The UWB layer has three frequency ranges: below 1 GHz, between 3.2 and 4.8 GHz, and between 5.9 and 10.2 GHz. On the other hand, there are some companies which do not use the standard and create custom-made communication and localization solutions, e.g. Time Domain (PulsON -P400 Ranging and Communications Module) and the Ubisense 7000 series sensors.

The following two subsections present the main features of the two UWB systems that we have selected for comparison: Decawave and Bespoon, which are the ones available at our lab following the IEEE 802.15.4a standard.

C. BeSpoon

Bespoon is a French start-up company which has developed a miniature IR-UWB system. They were the first manufacturer to demonstrate that UWB technology can be successfully integrated into a smartphone. The SpoonPhone is a prototype that has been sold to hardware manufacturers and software developers for research and evaluation purposes. One phone plus 6 tags costed to us 1,699 euros (VAT and shipping included). Now they changed the sale strategy and their products are sold as general purpose modular kits (UM100)

Fig. 1. SpoonPhone and tag from the Frech company BeSpoon.

Fig. 2. Decawave EVK1000 node which can be configured as a tag or anchor.

to design your desired solutions. These modules offers the possibility to achieve good precision (down to 10 cm), ranging (up to 880 m in Line of Sight) and receiver sensitivity (down to -118 dBm). It uses UWB channel 2 (3.99 GHz).

The UWB radio can be activated in the SpoonPhone (as WiFi/BLE are enabled) by switching on in the configuration Android-based menu (Fig.1). The UWB antenna is also used for WiFi communication, and it is located top-left when looking at he phone's screen. An SDK API is made available to programmers so as to access in real-time to the ranging data from the phone to the different miniature tags. The average rate of range measurements is 2.5 Hz.

D. DecaWave

Decawave DW1000 modules are fully integrated low power CMOS chips, compliant with the IEEE 802.15.4-2011 Ultra-WideBand (UWB) standard. They make it possible ranging measurements with an accuracy of ± 10 cm using two-way ranging (TWR) time-of-flight (TOF) measurements. The manufacturer estimates a real time location accuracy for a moving

tag of about ± 30 cm in X and Y; using either two-way ranging (TOF) measurements or one-way time difference of arrival (TDOA) approaches. A maximum measurable range of 300 meters is possible in ideal conditions.

This company provides the TREK1000 development Kit. One kit costs 925$ (importation custom charges apart). The kit contains 4 fully functional UWB nodes (see Fig.2), which consist of a DW1000 UWB ranging chip, a processor STM32F105 ARM Cortex M3 and a omnidirectional antenna. The nodes are able to connect among them and estimate their inter-node ranges. An external device (PC) can be USB connected to any of the nodes to collect all inter-node ranges.

Each UWB node can be configured as an anchor or as a tag, by changing the dip-switches available on PCB board. Also using the dip-switches it is possible to select among two channels (2 and 5), respectively at central frequencies (3.99 GHz and 6.48 GHz), and 2 data rates (110 kbps and 6.8 Mbps). By default the configuration settings are: 4GHz as central frequency and 110 kbps data rate. This data rate is the recommended configuration for maximum distance measurement. According to manufacturer, a ranging update rate of 3.5 Hz is expected for one moving tag (update rate is lowered as the number of tag is increased since they are time multiplexed). An experimental update rate of 3.3 Hz was found.

III. UWB Range performance

A. LOS Conditions

In order to tests the LOS ranging accuracy of both UWB systems, we went outdoors in a private road area free of obstacles. The UWB nodes are mounted on two posts of 2.1 m height. One of the posts is fixed and connected to a PC for data collection, and the other post is moved along a straight line in order to change the range between the two posts. On the static post the Decawave node is place on a wooden base on top of the post (see Fig.3), and the other Decawave node is placed on a similar arrangement on the moving post. The Bespoon phone is place on the static post, just below the Decawave node, over another wooden base, while a couple of Bespoon tags are placed under the wooden base on the moving post.

The separation between the two posts is controlled by a long measuring tape that is placed along the road (100 m long). The road is mainly flat but some waving is perceived so causing a small inclination of the post over the vertical axis at certain points. This measurement procedure is not ideal but guarantees an accuracy of about 2-3 cm, enough to analyze expected ranging errors of about ± 10 cm. This is specially valid since we want to observe the differences among these two systems and not the exact absolute error which is outside of the scope of this study. It has also been planned to contrast these range errors tests by using a RTK-GPS satellite system with a local differential station, while one of the UWB nodes (Spoonphone and Decawave anchor) is moved on a vehicle. However the expected RTK ground-truth accuracy is about 2-3 cm, so, no significant practical evaluation improvements are expected apart from a larger ranging diversity.

The separation of both posts was incremental, starting with discrete steps every 0.5 m from 0 to 5 meters distance,

Fig. 3. Outdoors tests for LOS range accuracy estimation.

followed by 1 meter-long steps from 5 to 30 meters, and after that separation the steps were every 5 meters up to a maximum separation of 100 meters. With that set of range data (measurements and ground-truth) we could plot the real versus measured distances, as displayed in Fig.4.

The measurement result are almost ideal with no outlier detected. There was some particular distances with some detection problems (ranging was temporally unavailable) that could correspond to fading zones where the radio signals in the direct LOS path interfere with the weaker NLOS signals that come from below after bouncing on the road surface.

In order to see the ranging errors (measured range minus true range) in detail we show in Fig.5 a histogram with the number of occurrences for different range errors. We can appreciate in this figure that the Bespoon errors are larger that the Decawave system. We computed a standard deviation of 11 cm in the Bespoon case and only 5.5 cm for the Decawave case. The mean error of the histogram is not relevant since are only 2.6 cm and 0.35 cm for those systems respectively, and those small errors could be due to mounting error in the experimental setup as noted before.

B. NLOS Conditions

In order to test the UWB systems under significant and even severe NLOS conditions we installed 6 UWB nodes at fixed positions in our lab, and moved one mobile node to 61 different ground-truth positions. In the Bespoon case, the mobile node is the spoonphone, and the fixed nodes are the miniature bespoon tags. In the Decawave case, as the system is prepared to operate with a maximum of 4 anchors and a more flexible number of tags, we configured 6 nodes as tags, that were used as anchors at fixed positions, and one node was configured as anchor but it was used as a moving node.

The exact X-Y-Z position of each of the six Decawave node (labeled as T0, T1, T2,...T5) is: [0 0 0.98; 0 5.2 2.1; 4.8 5.5 1.1; 10.8 5.2 2.15; 10.8 -0.4 0.7; 5.2 -0.4 2.2], respectively. Note that there is some diversity in the Z coordinate with tags between 0.7 m and 2.2 meters in height. This configuration causes more diversity of NLOS paths, with low nodes that can

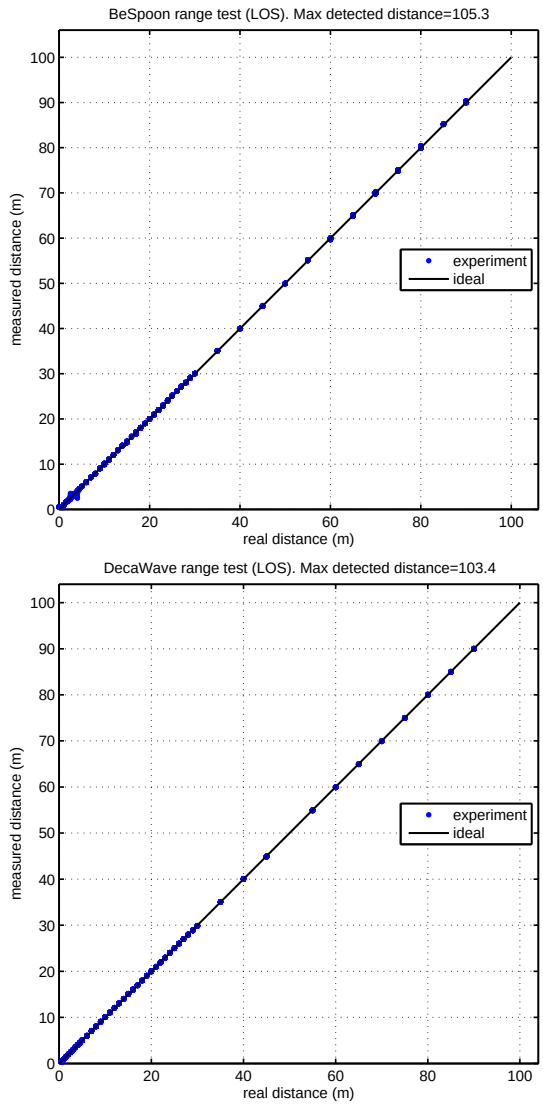

Fig. 4. Real versus measured distances, in outdoors LOS conditions, using the Bespoon (top) and Decawave (botton) systems.

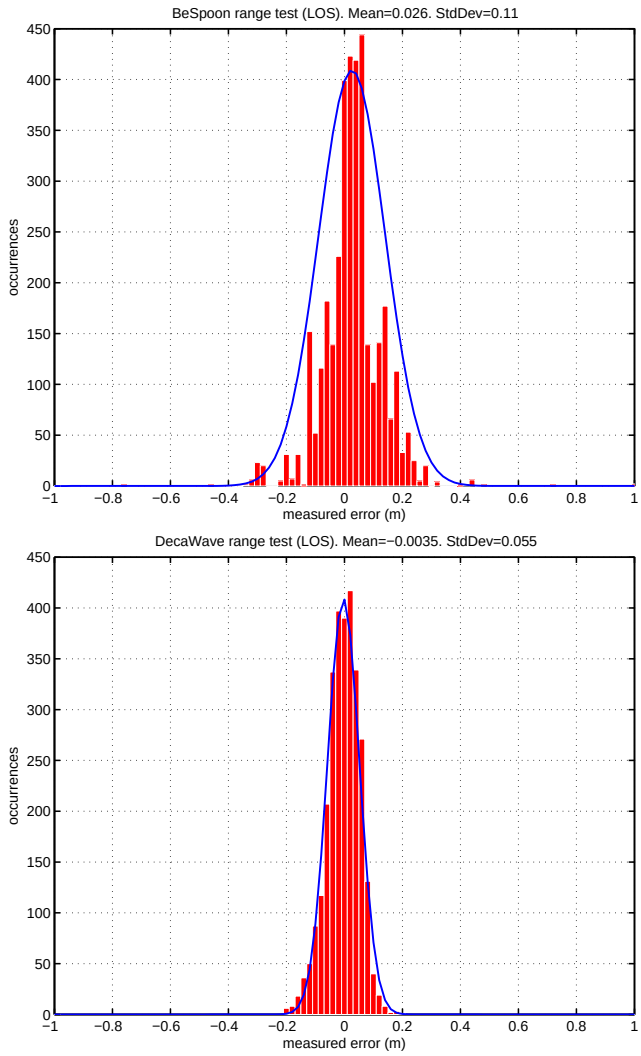

Fig. 5. Histogram of range error, in outdoors LOS conditions, using the Bespoon (top) and Decawave (botton) systems.

be more obstructed by furniture. The position of Bespoon tags is quite similar to the Decawave nodes, a maximum separation of 15 cm with respect to the Decawave nodes exist. This is the XYZ distribution for Bespoon tags: [0 0.08 0.86; 0 5.2 1.92; 4.88 5.5 0.96; 10.8 5.2 1.97; 10.8 -0.47 0.57; 5.2 -0.4 2.02].

The installation of both systems (Decawave and Bespoon) in parallel was intended to do a simultaneous data acquisition. However we rejected this initial approach since interference between both systems was detected. This interference caused a larger range noise and the cancelation of Decawave communication among some of the nodes. Therefore we repeated the 61-point test separetely for each of the two systems, so eliminating any source of mutual interference.

The laboratory where the tests were performed is shown in Fig.6. Here it can be seen, apart from a picture of the lab and some details, the floor plan with the detailed anchor positions and the 61 test points. The grid on the floor corresponds to real tiles of size 40 $\times$ 40 cm. We used this tiling partitioning to define with enough accuracy the 61 test points. The mobile nodes were put on top of a bench with a distance from the antenna to the floor of 0.85 m in the Decawave case and 0.72 m for the Spoonphone. The time in each test position was 30 seconds so about a 6 hundred measurements were captured at each point (6 nodes by 3 measurements to each beacons per second by 30 seconds). The NLOS experimentation included the furniture and walls of the lab but also the presence of one person moving around the bench.

Since the ground truth of the 61 position is available as well as the true position of fixed nodes, we know the real distance among pairs of nodes. With this information we plotted the relationship among the real and measured distances for the NLOS case (see Fig.7). In this case, as opposed to the LOS experiment, it can be seen that the measured ranges are not ideal, many range measurements are longer than their straight LOS path. The error can be as large as several decimeters and even more than one or two meters. The positive aspect is that the NLOS dispersion is almost always in excess, which is the ideal behavior, i.e. there should never be range measurements shorter than the real straight path. Unfortunately, we detected

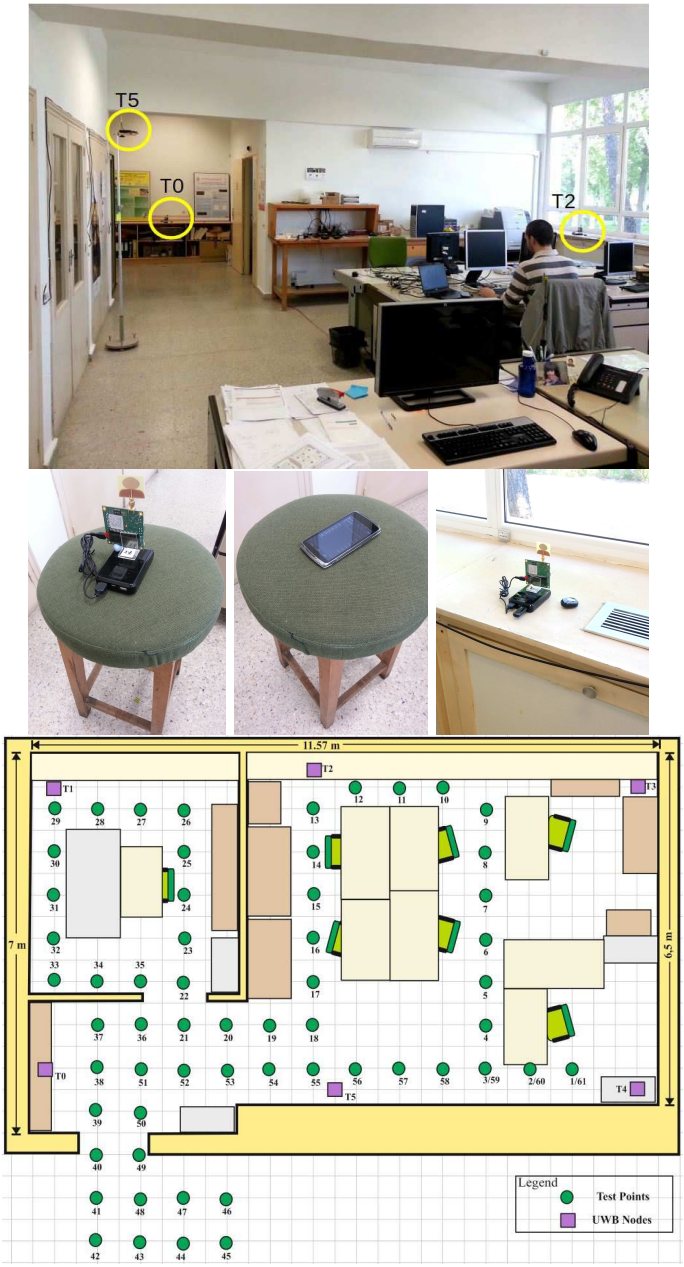

Fig. 6. Indoor tests for NLOS range accuracy estimation in Lopsi Lab. A total of 61 test points were selected providing both LOS and many NLOS conditions with one or two walls and several pieces of furniture (gray boxes are metalic cabinets or tables, brown boxes are wooden tables and shelves, and pale yellow are plastic tables). The lab surface is 80 square meters.

some few cases were the Bespoon system generated ranges shorter than the real distance. This unexpected behavior, that can not be explained by multipath, could be probably caused by multiple-access interference, or maybe due to some peak detection or filtering problem in the software libraries or on the Spoonphone hardware. In the Decawave case, no single measurement of this type was found in our tests.

The ranging error (measured range minus true range) is shown in detail in Fig.8 as a histogram with the number of occurrences for different range errors. We can see in this figure that Bespoon errors are slightly larger than for the Decawave

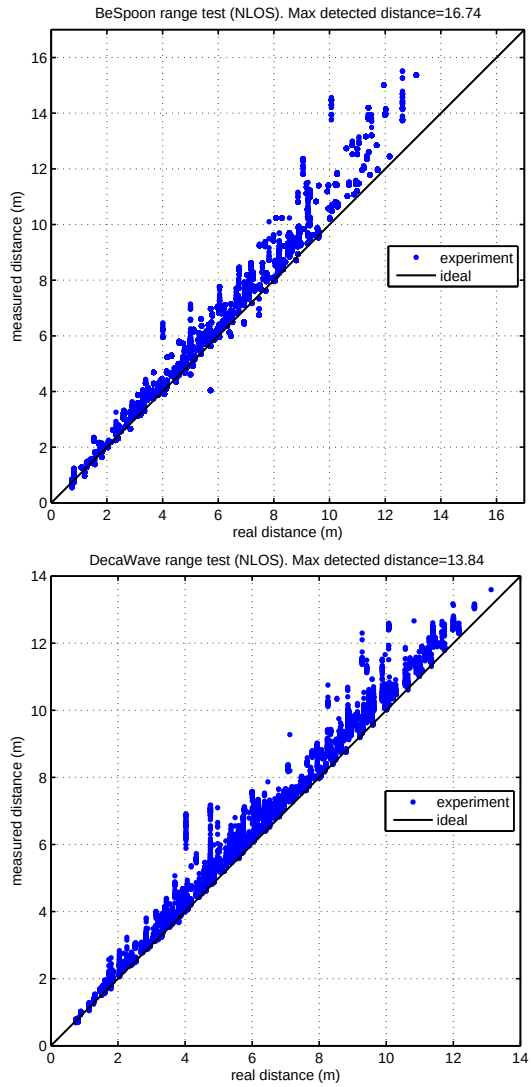

Fig. 7. Real versus measured distances, in indoors NLOS conditions, using the Bespoon (top) and Decawave (botton) systems.

system, but in any case the error distribution is similar. There is a low-sigma Gaussina distribution (± 0.1m) around zero error (LOS paths in the indoor setup), and additionally a long tail distribution (almost exponential) along the positive error side. This tail corresponds to the in-excess ranges caused by NLOS. The length and size of this error tail will depend on the particular experiment and severity of NLOS conditions, but it is important to highlight that the tail is slightly shorter under the same experimental conditions for the Decawave system. On the other hand, the few but large negative range errors (outliers at the left) only appear for the Bespoon system.

The NLOS error distributions shown in Fig.8 will be used in next section to create a measurement model that can be applied to alleviate the impact of in-excess ranges in localization.

IV. Positioning Performance

This section uses the ranging information obtained from both UWB systems to estimate by trilateration the 3D position

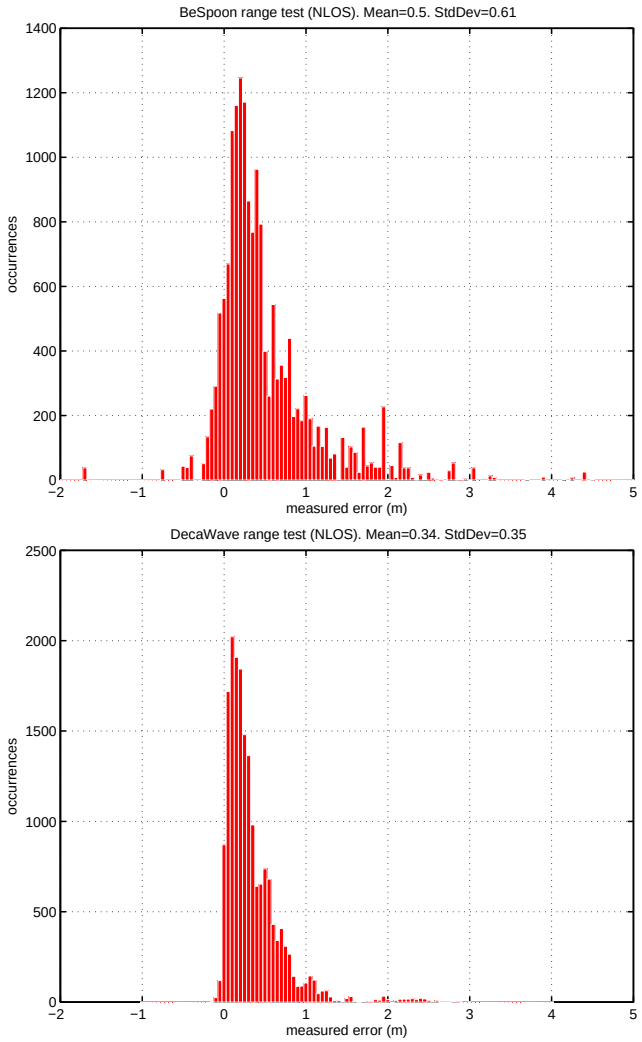

Fig. 8. Histogram of range error, in indoors NLOS conditions, using the Bespoon (top) and Decawave (botton) systems.

of the mobile node. As the positioning estimation in the LOS case is expected to be ideal, since ranges are quite good, we have focused the comparison under NLOS conditions where a clearer difference is foreseen.

A. NLOS mitigation approaches

Several methods for NLOS error mitigation have already been presented in the literature. In this paper we want to do a positioning performance comparison between two UWB systems by using one of the state-of-the-art NLOS mitigation methods. However the focus of this section is not to present any NLOS mitigation method, but to compare both systems under the same NLOS-resistant positioning method.

There are several approaches for NLOS mitigation:

1) Those who assume a larger standard deviation of measured ranges under NLOS conditions [22]. They consider that the mobile device to localize is in motion and therefore the number of obstacles between emitter and receiver changes with time, and consequently the ranging distribution varies more than in LOS conditions. Assuming a calibrated LOS measurement model, any range measurement sequence with a larger standard deviation is considered affected by NLOS, so it can be rejected or under-weighted in a trilateration phase.
2) A second NLOS approach makes use of the UWB signal, analyzing the peaks and strength of the first and the secondary peaks in the signal [23]. They try to do an optimal selection between the thresholds and the time interval of neighboring peaks in order to select the most likely range. Range and delay statistics such as the kurtosis are usually proposed.
3) A different approach assumes that there is a redundant number of beacons for trilateration, so it is possible to apply robust filtering techniques [24]. One approach can be based on the selection of several subgroups of beacons, and after analyzing the residuals among the different trilateration solutions, select the solution with a larger consensus. This approach to be successful must satisfy that the number of affected NLOS ranges is lower than the number of LOS ranges.
4) A more flexible and general purpose approach tries to find probability distribution models that can adapt to skewed and heavy-tailed measurements distributions [25], [26]. Instead of using Gaussian assumptions they model range error distribution by skew t-distributions.

In our case we can not assume that the mobile node is moving since most of the time the device is motionless. Also, we can not assume that the number of LOS ranges are larger than the NLOS ones, since as seen in Fig.6, in a significant testing region (points 22 to 35 and 40 to 49) the number beacons with ranges crossing one or two walls is 5 (out of 6). We also do not have access to the UWB signal, but only to the range measurement, so we can not analyze the peaks in the signal for NLOS attenuation. However, we can try to cope partially with NLOS by using an approach similar to the fourth one revised above [25], [26]. We will use a tailed UWB ranging measurement model fitted to the experimental measurements presented in last section (Fig. 8).

A simple long-tail measurement model for NLOS conditions is the exponential distribution. In our case we will use a model that combines a Gaussian distribution (for the LOS measurements) and a Gamma distribution (for the NLOS cases) and a constant value to cope with additional uncertainty and spurious measurements. This is the model:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} + \lambda \cdot e^{-\lambda x} \cdot \frac{(\lambda x)^{k-1}}{\Gamma(k)} + cte \qquad (1)$$

where x is the range measurement error, σ is the standard deviation in LOS conditions, μ is equal to 0.1 m, and for modeling NLOS λ is 3.5 and k equals 2. The last term, *cte*, is equal to a 3% of the model's peak. Those parameters were found fitting the model to experimental data. The representation of this combined LOS+NLOS model is displayed in Fig.9 with a blue line. It corresponds to the addition of the LOS Gaussian distribution (black line), the NLOS Gamma distribution (green line) and a constant term.

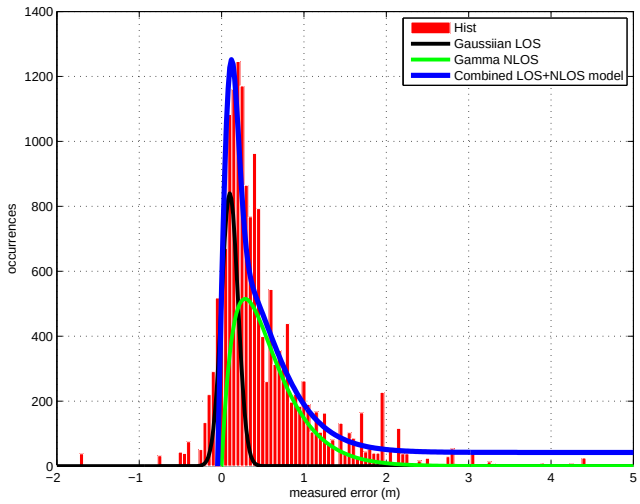

Fig. 9. Measurement model used for trilateration (blue plot) that corresponds to equation 1. Histogram data points in red are for Bespoon phone.

B. Positioning under NLOS Conditions

The NLOS test presented above with 6 fixed nodes of each UWB technology, and one mobile node of each type at 61 positions, will be used here to test the positioning performance of both UWB systems. The fixed nodes were distributed with a good geometry (mean Dilution of Precision or DOP of about 2.5) so it is possible to estimate 2D and 3D position with certain accuracy. Nevertheless, as the horizontal (X-Y) node separation is larger than the vertical (Z) separation, the positioning accuracy in Z axis is expected to be much worse due to a larger vertical DOP.

We used a particle filter with 3 states (i.e. X Y and Z) in order to estimate the 3D position of the moving node. In this case no movement information is available (no wheeled or pedestrian odometry) so we use in our particle filter a measurement model that generates some random particle motion once every second. Once a range measurement to a beacon is available, then the distance among all particles and that beacon are calculated. The range error is the difference between both data. This error is used together with the model in eq.1 and Fig.9 to change the weight of each particle.

The position of the moving object is obtained by computing the weighted mean position of all particles. The positioning results for a trajectory that moves along the 61 points in our lab (stopping 30 seconds in each one) is displayed in Fig.10 (top) for the Bespoon equipment. Exactly, the same algorithm, used for the Decawave system generates the trajectory appearing in Fig.10 (bottom). The estimation in the X-Z vertical plane is shown in 11 (top for BeSpoon and bottom for Decawave).

A Cumulative Distribution Function (CDF) is shown in Fig.12. The performance of the Decawave system is always superior to the BeSpoon system. This can be also seen in Table I where the mean, median, 90% and RMS positioning error is computed for both cases.

V. Conclusions

We have presented an experimental evaluation of two commercially available UWB positioning systems. The evaluation

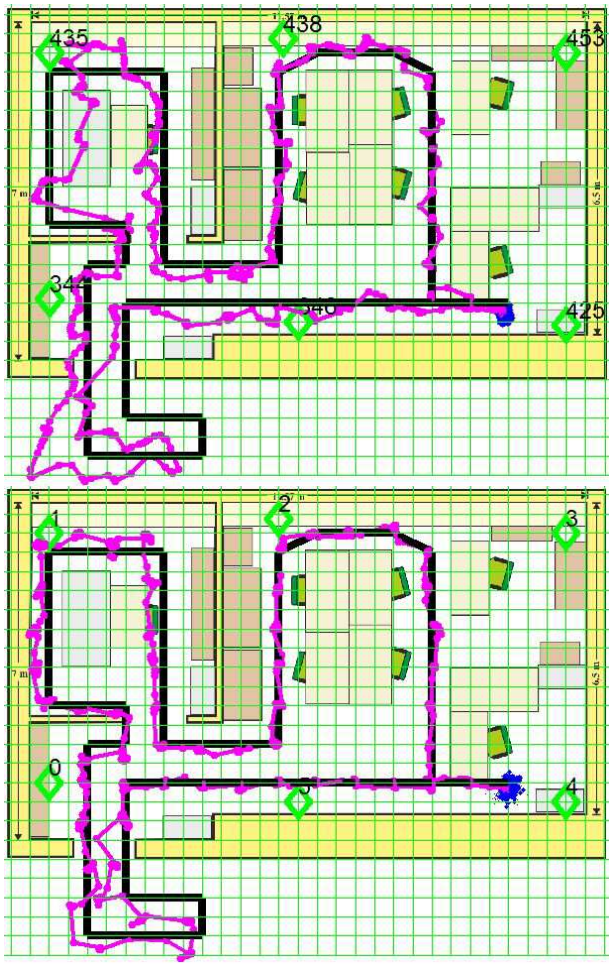

Fig. 10. Position estimation using BeSpoon (top) and Decawave (bottom) UWB systems. This is a zenithal or X-Y view. The Black line is the ground truth trajectory; the magenta line is the estimation using a particle filter with no movement model. Grid size is 0.4 by 0.4 meters.

Fig. 11. Position estimation using BeSpoon (top) and Decawave (bottom) UWB systems. This is a lateral or X-Z view. The Black line is the ground truth trajectory; the magenta line is the estimation using a particle filter with no movement model. Vertical span between higher and lower nodes is 1.5 m.

UWB System	Mean	Median	RMS	90%
Decawave	0.24	0.18	0.30	0.51
BeSpoon	0.51	0.46	0.59	0.99

TABLE I. Positioning errors (in meters) for both UWB systems in NLOS conditions

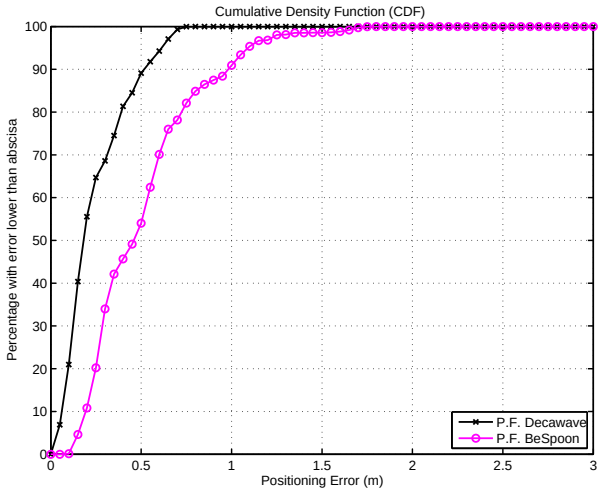

Fig. 12. Cumulative Distribution Function showing the errors in 3D position estimation corresponding to experiments in Fig. 10 and 11 for Decawave and BeSpoon systems.

has been done in LOS and NLOS environments. The performance of Decawave system is slightly better in LOS conditions and also more reliable in NLOS, than the BeSpoon system. However, the BeSpoon system does not use an optimized antenna for better signal emission and reception. The BeSpoon system is able to obtain quite good results taking into account that the system is of miniature size and integrated in a mobile phone.

Future research will consider the use of millimeter-accurate positioning systems for outdoor long-range tests (such as total stations or Differential RTK-GPS). We would also like to compare theses results with other UWB systems such as the Ubisense solution. The use of this systems in dynamic scenarios for vehicle location and tracking, making use of fusion techniques combining UWB with inertial or other motion information is another topic of future study.

Acknowledgment

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