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A Cooperative Localization Algorithm for UWB Indoor Sensor Networks

Eva Arias-de-Reyna

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Abstract This paper deals with range-based localization in ultra wideband sensor networks, allowing for the possibility of large range measurement errors because of a failure to detect the direct paths between some nodes. A novel algorithm is proposed that uses only partial knowledge of the service area topology, particularly of the positions of objects which are capable of causing undetected direct path (UDP) propagation conditions. Although the spirit of the proposed approach, because of the lack of information on the range error statistics, is to remove measurements performed under UDP conditions from the computation of the location estimate, these measurements are used implicitly by the algorithm to contribute to the erroneous trial locations being discarded. A cooperative stage is included that allows the probability of localization of a target with an insufficient initial number of accurate range measurements to increase. The proposed algorithm outperforms a variety of alternative positioning techniques, and thus illustrates the capability of this topology knowledge to mitigate the UDP problem, even in the absence of any knowledge about the range error statistics.

Keywords UWB · Indoor localization · Undetected direct path

1 Introduction

The accurate localization of the nodes of a sensor network [1] has received considerable research attention recently, because it is a key feature in a wide variety of applications, such as inventory tracking in warehouses, cargo ships or hospitals; or monitoring of people with

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E. Arias-de-Reyna (✉)
Department of Signal Theory and Communications, University of Seville,
Camino de los Descubrimientos s/n, 41092 Seville, Spain
e-mail: earias@us.es

special needs. In indoor environments, where the Global Positioning System (GPS) does not perform well, ultra wideband (UWB) technology is emerging as a promising alternative [2] because of its accurate ranging and obstacle penetration capabilities, and its potential to offer low power and low cost systems.

In this paper, we focus on indoor range based localization using UWB signals. We consider a sensor network with two kinds of node: beacons, also known as anchors, which have fixed known locations, and targets—which are also known as agent nodes—with locations which are unknown a priori but which are known to lie within a specific service area. The goal is the computation of estimates of the target locations. To this end, the ranges between each of the beacons and each of the targets are estimated using time of arrival (TOA) measurements. Accurate TOA estimates are possible with UWB as long as the ray that propagates along the direct path between the beacon and the target can be detected [3]. However, if the direct path is totally obstructed or is attenuated to below the detection threshold, another ray which corresponds to a longer trajectory will be erroneously regarded as being the direct ray, leading to large estimation errors [4,5]. This situation is referred to as an undetected direct path (UDP) and is one of the most challenging problems in range-based localization. Even when the number of detected direct path (DDP) range measurements is sufficient for accurate target localization, the UDP measurements can strongly degrade the positioning accuracy. It should be emphasized that the meaning of DDP versus UDP does not correspond to the alternative line of sight (LOS) against non-LOS (NLOS) measurements commonly found in the literature. While LOS/NLOS refers to the presence or absence of a physical line of sight, DDP refers to the detectability of a direct path. Thus, DDP may correspond to either LOS or NLOS situations, as long as the energy of the direct path is sufficient to be detected. The UDP conditions for UWB signals have been found to be caused mainly by large metallic objects [6], such as metallic wardrobes, doors and chambers.

We complete this introduction with a brief survey of related work on mitigation of the effects of UDP in the literature and a statement of the main goal of this paper.

1.1 Survey of Related Work

In [7,8] the problem described above is approached without using any prior information. These papers consider tentative combinations of beacons, leading to intermediate estimates that will be weighted according to their reliability to form a final estimate. Unlike [7,8], the approach in [9] uses a great deal of prior information. Although [9] considers a wideband code division multiple access (CDMA) cellular system, the principle can be extended to the problem studied in this paper. In terms of the notation of this paper, [9] requires knowledge of the probability density function (PDF) of the range measurements for the DDP and UDP cases, together with the prior probabilities of DDP/UDP occurrences.

Another approach in the literature consists of trying to identify the propagation conditions (DDP or UDP) of the measurements by processing the received waveforms [4,10–12]. This information can be used either to discard the UDP measurements [4] or to mitigate their effects [11,12]. In [5] the UDP measurements are identified through hypothesis testing based on the range measurements, using knowledge of the range error statistics.

Further approaches are those based on fingerprinting databases [13–15].

In previous work [16], we tested the usefulness of the topology knowledge combined with the knowledge of the range error model for the problem described. The proposed algorithm was found to outperform those in [7–9]. Further simulations indicated the small effect of mismatches between the true and assumed values of the range error statistics.

The topology knowledge is also used in [2], but the approach is different because [2] does not attempt to deal with the UDP case. Instead, [2] concentrates on the DDP NLOS scenario, using information on the range biases related to the excess delays suffered by the direct paths when traveling through some elements of the service area, which in turn depend on the thicknesses of these elements and the materials from which they are made. This approach cannot be extended to the UDP case, where no direct path is available.

1.2 Main Goal

In this paper, motivated by the results in [16], we propose an approach to the range based localization problem without using any range error model information. This approach has the advantage of removing the process step of determination of the range error model from a measurement series. Thus, a totally different approach is required, because the method in [16], which is based on the maximum likelihood principle, cannot be adapted to accommodate the absence of the range error model knowledge.

The main goal of this paper is to propose a localization algorithm for indoor UWB sensor networks under the assumption that the only information available is partial knowledge of the topology, in the form of a map of the service area, where the only objects marked are those capable of causing the UDP conditions to occur for the UWB signals, which are mainly large metallic objects [6]. Consequently, the proposed approach avoids not only the determination of the range error model or statistics, but also determination of the prior probabilities of DDP/UDP occurrence, and the processing of the received waveforms to identify the propagation conditions. Thus, our approach is different to the methods in the references cited in Sect. 1.1.

The proposed approach aims to discard the measurements made under UDP conditions from the computation of the location estimate, but the way that it is done is different to the existing methods in the literature, where the UDP measurements must be identified first. With the proposed approach, the set of discarded measurements may instead be different for each trial location considered. A novel criterion is used to decide which of the measurements to discard for any given trial location. The UDP measurements are used fully, but not for computation of the location estimate; instead, they are used to help discard the erroneous trial locations.

The proposed algorithm includes a stage based on *cooperative localization* [1,2], that consists of adding the targets for which a location estimate is available to the set of anchors. This is especially useful to localize targets with DDP connections to a small number of beacons.

The rest of the paper is organized as follows. In Sect. 2 the problem is stated and the notation to be used is established. Section 3 describes the proposed algorithm. The range error model used is presented in Sect. 4, and the results are reported in Sect. 5. Finally, Sect. 6 gives the conclusions drawn.

2 Problem Statement and Notation

We consider a two-dimensional environment without loss of generality. Let N and P be the numbers of beacons and targets in the network, respectively. The locations of the targets are considered to be fixed for the duration of the execution of the algorithms under test. We call $\mathbf{z}_i = (x_i, y_i)^T$, $i = 1, 2, \ldots, N + P$ the coordinates of the ith node, where the first

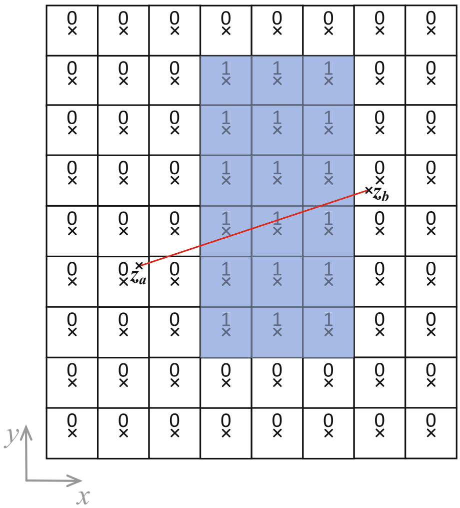

Fig. 1 Portion of the type of binary map stored using the proposed method. In this example, the propagation condition between locations $\mathbf{z_a}$ and $\mathbf{z_b}$ is declared to be UDP because the segment that joins the two locations *crosses squares* that *overlap* with an object that is capable of causing the UDP condition (marked with '1's)

N nodes are the beacons and $i = N + 1, N + 2, \ldots, N + P$ correspond to the targets. The measurement of the distance between the ith and jth nodes, taken at the jth node, is denoted by r_{ij}. The goal is to estimate the target locations. To estimate the location of the jth target, a conventional range-based method uses the values r_{ij}, $i = 1, 2, \ldots, N$. If cooperative localization is considered, then a subset of the inter-target range measurements r_{ij}, $i = N + 1, N + 2, \ldots, N + P, i \neq j$ can also be used . All targets are allowed to cooperate.

3 Proposed Method

In this section, the proposed method is described in detail. The following subsections deal with the information that is available, an overview of the algorithm, a detailed description of the different stages of the process, and the computational complexity.

3.1 Information Available

The proposed algorithm has a map of the service area available, where only the objects that are capable of causing the UDP condition for the UWB signals [6] have been marked. A grid is considered, covering the useful service area and excluding the regions that the targets cannot enter. The grid nodes are the candidate locations to be considered by the different positioning techniques under test. The proposed map consists of a database which assigns a binary value to each grid node: a one if it falls within one of the marked objects on the map, and a zero otherwise. Figure 1 shows a sample section of this binary map. It allows determination of the propagation conditions (DDP or UDP) between any pair of positions within the useful service area. For each pair of locations considered, we must determine the segment that joins the two locations and check whether it crosses any of the marked obstacles. If we go one step further in the implementation details, the service area surface might be divided into small squares which are centered at the grid nodes. A zero is assigned to each square, except for those which overlap the marked obstacles, to which a one is assigned. For any segment that joins two positions, we can check the values associated with the squares that are crossed by the segment, to find whether all of them have ‘0’ values (leading to the decision that the path is under the DDP condition) or if at least one of them has a ‘1’ value (UDP condition).

3.2 Overview of the Algorithm

The proposed algorithm comprises two stages. In the first stage, for each target, the corresponding set of N measurements to each of the beacons is used to provide a location estimate. However, this first stage can also declare that the available information is insufficient to achieve a reliable location estimate and leave the estimation process to a later stage. As a second stage, we take advantage of range measurements between the targets by applying cooperative localization to the first stage procedure. A third optional stage can be applied if the second stage decides that the available information is still insufficient for an accurate estimate. Figure 2 shows the flow diagram of the algorithm for the jth target node. An explanation of the meaning of this diagram will be provided as the algorithm is described in subsequent sections.

Obstruction by obstacles has been considered to be the general cause of UDP conditions. However, an extension to the case in which a large distance between the nodes also causes the UDP conditions because the first echo that arrived falls below the detection threshold [6] is straightforward.

Each of the stages of the proposed algorithm is described below.

3.3 First Stage

The first step taken is to determine, for each trial target location $\mathbf{z}$, the propagation conditions between $\mathbf{z}$ and each beacon. Because the beacon locations are known beforehand, this process may be carried out before the localization process begins, to store a set of N DDP/UDP databases [16] in addition to the map. In particular, the DDP/UDP database for the ith beacon provides, for each trial grid location, a zero if the propagation condition to the ith beacon is DDP or a one if it is UDP. These DDP/UDP databases can be determined from the map described in Sect. 3.1 above.

The following procedure is then carried out for each target. For notational simplicity, the steps are described for the jth target.

1. Consider the set of range measurements from the beacons, $r_{ij},\ i \in \mathscr{I}_{\text{range}}$, where $\mathscr{I}_{\text{range}}$ is the subset of indices in $\{1, 2, \ldots N\}$ which correspond to the beacons within communication range of the jth target.
2. For each trial target location $\mathbf{z}$, discard the range measurements that correspond to beacons with UDP conditions for that location. Let $\mathscr{I}_{DDP,0}(\mathbf{z})$ be the set of beacon indices that corresponds to the remaining measurements and let $N_{DDP,0}(\mathbf{z})$ be the cardinality of this set.
3. For each $\mathbf{z}$, compute the value of a cost function consisting of the normalized sum of the squared differences between the measured ranges and the true distances

$$C_j(\mathbf{z}) = \frac{1}{N_{DDP,0}(\mathbf{z})} \sum_{i \in \mathscr{I}_{DDP,0}(\mathbf{z})} [r_{ij} - ||\mathbf{z} - \mathbf{z_i}||]^2 \tag{1}$$

where $||\mathbf{z} - \mathbf{z_i}|| = \sqrt{(x - x_i)^2 + (y - y_i)^2}$ is the true distance between the ith beacon and the test location $\mathbf{z}$.

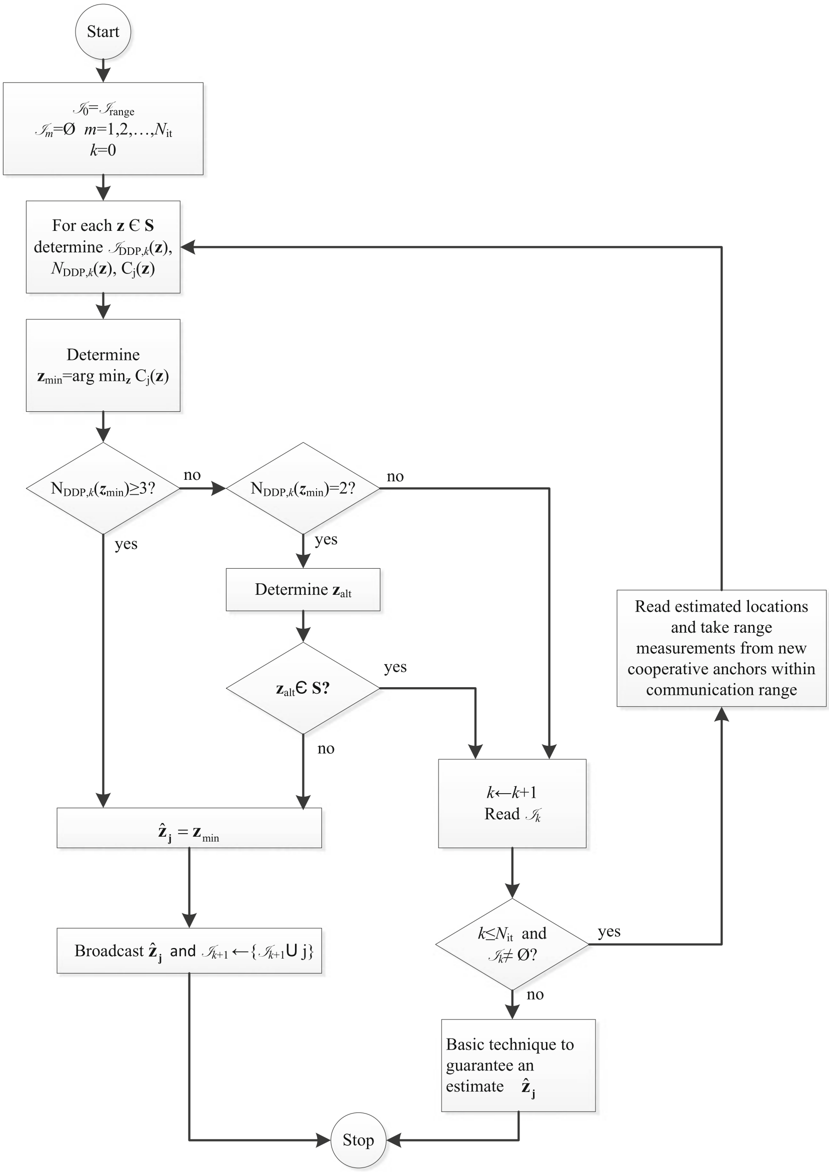

Fig. 2 Flow diagram of the proposed algorithm for the jth target node. The index k indicates the iteration number, is initialized to 0 for the first stage of the algorithm, and is allowed to vary between 1 and N_{it} during the second stage of the algorithm (the 0th iteration thus refers to the first stage of the algorithm). The algorithm handles the sets $\mathscr{I}_k k = 0, 1, \ldots, N_{it}$, which contain the indices of the set of anchors that are used at the kth iteration of the algorithm for the first time, including both the beacons and the cooperative anchors. $\mathscr{I}_0$ is initialized to the set of indices of the beacons within communication range of the jth target, because they are the only anchors used in the first stage of the algorithm, while $\mathscr{I}_k$ $k = 1, 2, \ldots, N_{it}$ are all initialized to empty sets. We use S to denote the set of possible trial locations within the service area. $\mathscr{I}_{DDP,k}(\mathbf{z})$ is a subset of $\mathscr{I}_k$. The cost function $C_j(\mathbf{z})$ is computed according to Eq. (1) if $k = 0$, or according to Eq. (5) otherwise. If the jth target achieves a location estimate at the kth stage of the algorithm, $\mathscr{I}_{k+1}$ is then updated with its corresponding index j so that the target can act as a cooperative anchor from the $k + 1$th stage onwards to help to localize the remaining targets

4. The location corresponding to the cost function minimum, $\mathbf{z}_{\min} = \arg\min_{\mathbf{z}} C_j(\mathbf{z})$, is taken into consideration.
5. If $N_{DDP,0}(\mathbf{z}_{\min}) \geq 3$, $\mathbf{z}_{\min}$ is regarded as the target location estimate: $\hat{\mathbf{z}}_{\mathbf{j}} = \mathbf{z}_{\min}$. If $N_{DDP,0}(\mathbf{z}_{\min}) = 2$, then another test is performed to determine whether there is any ambiguity within the service area, as detailed below. If the answer is yes, then the location estimation process is postponed until a later stage. If the answer is no, then $\mathbf{z}_{\min}$ is regarded as the target location estimate. If $N_{DDP,0}(\mathbf{z}_{\min}) \leq 1$, the available information is considered to be insufficient to produce an accurate estimate, and the location estimation for the target is postponed until a later stage.

The procedure for the case where $N_{DDP,0}(\mathbf{z}_{\min}) = 2$ is based on the fact that if only two DDP measurements are available for a given target, e.g., r_{kj} and r_{lj}, the ambiguity is limited to two positions: the two intersections of the circumferences centered at $\mathbf{z}_{\mathbf{k}}$ and $\mathbf{z}_{\mathbf{l}}$ with radii equal to the measurements r_{kj} and r_{lj}, respectively. $\mathbf{z}_{\min}$ is near one of these intersections. We call the alternative position produced by the ambiguity $\mathbf{z}_{\text{alt}} = (x_{\text{alt}}, y_{\text{alt}})^T$. The proposed method determines $\mathbf{z}_{\text{alt}}$ and checks whether it falls outside the service area to decide whether or not $\mathbf{z}_{\min}$ is regarded as the target location estimate. Figure 3 clarifies the specific procedure needed to determine $\mathbf{z}_{\text{alt}}$, which corresponds to the formulae

$$x_{\text{alt}} = 2\frac{(y_{\min} - y_k)(x_l - x_k)(y_l - y_k) + (x_l - x_k)^2 x_{\min} + (y_l - y_k)^2 x_k}{(y_l - y_k)^2 + (x_l - x_k)^2} - x_{\min} \quad (2)$$

$$y_{\text{alt}} = y_{\min} - \frac{(x_l - x_k)}{(y_l - y_k)}(x_{\text{alt}} - x_{\min}) \quad (3)$$

with the exception of the case where $y_k = y_l$, in which y_{alt} would be determined from

$$y_{\text{alt}} = 2y_k - y_{\min} \quad (4)$$

If $\mathbf{z}_{\text{alt}}$ falls outside the service area, then there is no ambiguity and $\mathbf{z}_{\min}$ is then regarded as the target location estimate: $\hat{\mathbf{z}}_{\mathbf{j}} = \mathbf{z}_{\min}$.

3.4 Second Stage: Cooperative Localization

Depending on the service area topology and the number and positions of the beacons, the first stage of the algorithm may leave some targets without a location estimate because they have an insufficient number of accurate measurements. We propose a second stage based on cooperative localization [1] to derive a location estimate for these remaining targets. The idea behind this is that when a location estimate is provided for a given target, this target then can be added to the set of anchors to enable us to repeat the procedure of the first stage, using the same partial topology knowledge described in Sect. 3.1. To this end, the ranges between the new anchors and the targets that are still not localized must be measured, and DDP/UDP databases for the new cooperative anchors must be determined. Thus, some targets that were not previously assigned an estimate might now be localized if they are in DDP connection with some of the new cooperative anchors, and they can in turn also be used as cooperative anchors. To this end, each newly localized target broadcasts its location estimate so that the rest of the targets can add it to the set of anchors. The effectiveness of this approach must be assessed by simulation.

Successive iterations of the algorithm can be executed until no further improvement is possible (this happens when an iteration of the algorithm is unable to enlarge the existing set of localized targets).

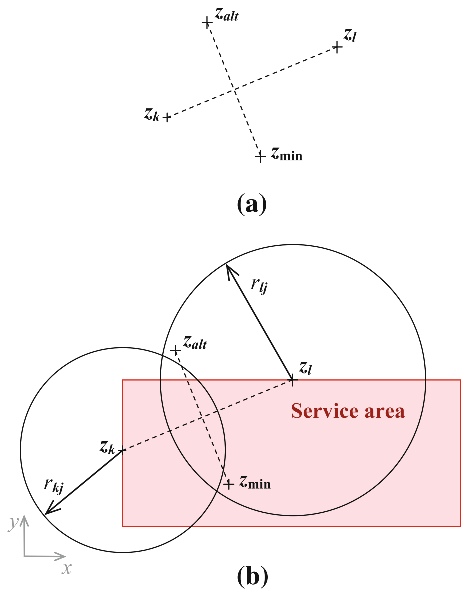

Fig. 3 **a** Illustration of the procedure to determine $\mathbf{z}_{\text{alt}}$ as given by Eqs. (2)–(3): the straight line defined by $\mathbf{z_k}$ and $\mathbf{z_l}$ is determined, and the symmetric point of $\mathbf{z}_{\text{min}}$ with respect to this line is $\mathbf{z}_{\text{alt}}$. **b** The shadowed rectangle represents the service area. The DDP range measurements from the beacons at $\mathbf{z_k}$ and $\mathbf{z_l}$ determine two candidate location estimates: the intersections of the circumferences shown. The first intersection is near the true target location and the grid node corresponding to $\mathbf{z}_{\text{min}}$. $\mathbf{z}_{\text{alt}}$ is near the other intersection location, and, in this example, falls outside the service area. Thus, in this case, there is no ambiguity and $\mathbf{z}_{\text{min}}$ is regarded as a valid location estimate

The cooperative localization stage has a potential problem with error propagation, because there is an uncertainty in the knowledge of the new anchor locations. We propose to mitigate this problem by assigning a weight to the cooperative anchors that will decrease with each iteration of the cooperative stage. The cost function in (1) is thus modified in a way similar to when a least squares (LS) approach is replaced by a weighted LS method [17]. Let $w(m)$ be the weight assigned to the mth iteration of the cooperative stage. Recall that $\mathscr{I}_{DDP,0}(\mathbf{z})$ is the set of indices of the beacons in DDP connection with the location $\mathbf{z}$. Let $\mathscr{I}_{DDP,m}(\mathbf{z})$ be the set of indices of the anchors added at the mth iteration of the cooperative stage that are in DDP connection with the location $\mathbf{z}$, and let $N_{DDP,m}(\mathbf{z})$ be the cardinality of this set. The cost function for the kth iteration of the cooperative stage is expressed as

$$C_j(\mathbf{z}) = \frac{\sum_{i\in\mathscr{I}_{DDP,0}(\mathbf{z})}[r_{ij} - ||\mathbf{z}-\mathbf{z_i}||]^2 + \sum_{m=1}^{k} w(m)\sum_{i\in\mathscr{I}_{DDP,m}(\mathbf{z})}[r_{ij} - ||\mathbf{z}-\mathbf{z_i}||]^2}{N_{DDP,0}(\mathbf{z}) + \sum_{m=1}^{k} w(m) N_{DDP,m}(\mathbf{z})}$$
$$k = 1, 2, \ldots, N_{\text{it}} \qquad (5)$$

where N_{it} is the maximum number of iterations allowed for the cooperative stage.

3.5 Computational Complexity

To estimate the computational complexity of the proposed algorithm, we consider only the dominant terms, which are the terms that must be repeated for each trial location in the service area. Some of the operations must be reproduced for each of the (original or cooperative) anchors. We therefore need a variable $M \in [N, N+P-1]$ to represent the total number of anchors used during the execution of the algorithm. Let us use N_T to denote the total number of trial locations. We assume that $N_{it}, M \ll N_T$. For the jth target, the operations that must be performed MN_T times are the following:

– Determination of the propagation condition between each anchor and each trial location (to generate DDP/UDP databases): this has been described earlier in Sect. 3.1.
– Determination of the quantity

$$[r_{ij} - ||\mathbf{z} - \mathbf{z_i}||]^2 = \left[r_{ij} - \sqrt{(x - x_i)^2 + (y - y_i)^2}\right]^2 \tag{6}$$

for each anchor and for each target location, to be used either in Eq. (1) or in Eq. (5).

There are also some operations that, although they do not need to be repeated M times, have a number of operations that include terms of the order of MN_T. In particular:

– Determination of $\mathscr{I}_{DDP,k}(\mathbf{z})$, $N_{DDP,k}(\mathbf{z})$ from the DDP/UDP databases for the different anchors.
– Computation of the quantities $C_j(\mathbf{z})$ in Eq. (1) or in Eq. (5) (this last operation is performed a maximum of N_{it} times).

Taking all these operations into account, the computational complexity of the proposed algorithm can then be described as

– A number of sums of the order of $MN_T^{\frac{3}{2}}$
– A number of multiplication operations of the order of $MN_T^{\frac{3}{2}}$
– A number of division operations with an upper bound of $(M + N_{it} + 1)N_T$
– MN_T square roots

3.6 Optional Additional Stage

It may be that, even after the cooperative localization stage, the algorithm does not declare a valid location estimate for all targets. This is reasonable because, if the algorithm succeeds in discarding all the UDP measurements from the computations, then the remaining measurements (including those corresponding to cooperative anchors) may be too few to produce a result. Nevertheless, the proposed algorithm may be complemented with a third stage using any other approach for the remaining targets to guarantee an output for 100% of the targets, with a warning that the derived estimate is released with a likely degradation in accuracy (root mean square error (RMSE)). The approach chosen for this third stage must not require more information than that available to the originally proposed algorithm. In the simulations reported in Sect. 5, for the targets that are still not localized after the cooperative localization stage, we have chosen to apply the method given in [7], to ensure fair comparison with the other tested methods, by involving the whole set of targets. With regard to the computational complexity, this technique involves operations that combine the quantities in Eq. (6), which have already been computed. If the total number of combinations considered in [7], N_c, is small when compared to $\sqrt{N_T}$, then the order of magnitude of the number of operations in Sect. 3.5 is unaffected by the addition of the third stage. If not, an additional term of the order of $N_c N_T N$ must be taken into account in the number of sums (we assume that $N_c \ll MN_T$).

4 Range Error Model

To test the performance of the range-based localization algorithms, we must generate a set of simulated values for the range measurements according to a realistic model. Some statistical models that can be used for these range measurements, built on experimental data, can be found in the literature [2,6,18]. Ref. [18] obtains a model from TOA estimation and distinguishes between two cases, depending on whether the ray corresponding to the direct path between the nodes can be detected (the DDP case) or not (the UDP case). We constructed our range measurement error based on [18].

In the case where the direct path from the ith to the jth node can be detected, the range measurement can then be expressed as

$$r_{ij} = d_{ij} + \varepsilon_{ij,DDP} \tag{7}$$

where d_{ij} is the true distance between the ith and jth nodes

$$d_{ij} = ||\mathbf{z_j} - \mathbf{z_i}|| = \sqrt{(x_j - x_i)^2 + (y_j - y_i)^2} \tag{8}$$

and $\varepsilon_{ij,DDP}$ is the range error.

According to Alavi and Pahlavan [18], the main cause of this range error is multipath, and is modeled as

$$\varepsilon_{ij,DDP} = \gamma \log(1 + d_{ij}) \tag{9}$$

where γ is a Gaussian random variable with a mean of m_γ and a standard deviation of σ_γ. The values of these parameters for a variety of signal bandwidths are provided in [18]. Thus, $\varepsilon_{ij,DDP}$ is Gaussian with a mean of $m_\gamma \log(1+d_{ij})$ and a standard deviation of $\sigma_\gamma \log(1+d_{ij})$. We can see that the longer the propagation path becomes, then the larger that the mean and the standard deviation of the error become.

In the case where the propagation condition between the ith and jth node is UDP, the first arriving echo corresponds to a ray that has propagated along a path that is longer than the direct path. Thus, the shortest path from the ith to the jth beacon has a length that is larger than d_{ij}, which we call $d_{ij}^{(s)}$. The extension of the DDP case to this situation leads us to

$$r_{ij} = d_{ij}^{(s)} + \varepsilon_{ij,UDP} \tag{10}$$

with

$$\varepsilon_{ij,UDP} = \gamma \log(1 + d_{ij}^{(s)}) \tag{11}$$

where γ is as given in Eq. (9). Thus, $\varepsilon_{ij,UDP}$ is Gaussian with a mean of $m_\gamma \log(1 + d_{ij}^{(s)})$ and a standard deviation of $\sigma_\gamma \log(1 + d_{ij}^{(s)})$.

Each range measurement simulation requires a previous computation of the shortest path length between the corresponding pair of nodes. In the DDP case, the true distance between the ith and jth nodes, d_{ij}, is given by Eq. (8). In the UDP case, we applied a ray tracing algorithm to the service area map to compute $d_{ij}^{(s)}$.

5 Results

5.1 Case Study and Simulation Setup

We have adopted a challenging scenario as a case study, with a high probability of UDP occurrence. The floor plan is rectangular, with dimensions of 20 m × 10 m (i.e., $x \in [0, 20\,\text{m}]$ and $y \in [0, 10\,\text{m}]$), and contains two metallic obstacles, which are square in shape with a side length of 4 m, centered at (5 m, 5 m) and (15 m, 5 m), that cause UDP conditions. It must be emphasized that these two metallic squares are not necessarily the only objects in the service area. The random presence and position of further objects, which do not cause UDP conditions, is already accounted for by Eq. (9).

We considered a number of beacons in a range between 4 and 8. The first 4 beacons were placed at the four corners of the rectangular area. The next two beacons were located at the mid points of the longer sides of the rectangle. The positions chosen for the 7th and 8th beacons were the mid points of the shorter sides of the rectangle.

A grid with a mesh size of 10 cm was considered. The useful service area includes the nodes of the grid that are inside the perimeter of the service area and outside the metallic obstacles, which cannot be entered by the targets.

We chose a bandwidth of 500 MHz, for which $m_\gamma = 21$ cm and $\sigma_\gamma = 26.9$ cm, according to Alavi and Pahlavan [18].

The algorithms included in the comparison can be classified according to the information used:

- The classical LS method and the methods in [7,8] do not use any prior information.
- The method in [9] has knowledge of the PDFs of the range measurements for both the DDP and UDP cases, and of the prior probabilities of DDP and UDP occurrence, which were extracted from the stored map.
- The proposed method uses only partial topology knowledge, as explained in Sect. 3.

For [9], the statistics for the UDP case were extracted from a set of simulated measurements for the case study considered here.

5.2 Simulation Results

The number of targets in the sensor network, P, was varied between 1 and 6. For each test simulation, a set of P targets was randomly distributed over the useful service area, following a uniform distribution. Thus, the case $P = 1$ corresponds to the absence of the possibility of cooperation. Range measurements were generated according to the model in Sect. 4 and the algorithms were tested. The performance metric computed was the RMSE of the location estimates, which is defined as the square root of the average of $\|\mathbf{z}_{\text{true}} - \hat{\mathbf{z}}\|^2$ taken over $\mathbf{z}_{\text{true}}$, where $\mathbf{z}_{\text{true}}$ is the true target location for the different test simulations. The simulation for each pair of values (N, P) gives a total of 18,000 possible random target locations.

For the cooperative stage of the proposed algorithm, a maximum of $N_{\text{it}} = 3$ iterations was allowed. Preliminary results with identical unity weights for the beacons and the cooperative anchors added in the different iterations showed an important degradation in the accuracy of the estimates with each iteration of the cooperative stage. This effect indicated the convenience of a significant decrease in the weights assigned to the localized targets as the cooperative stage proceeds. The results shown from here on correspond to a weight $w(k) = 0.5^k$ for the kth iteration of the cooperative stage, which gives a unity weight for the particular case of the beacons ($k = 0$).

First, the proposed algorithm was tested without completing it by using any third stage, to determine the percentages of the targets for which the two-stage algorithm provides an output. Figure 4 shows the results as a function of the number P of nodes that were allowed to cooperate. For each value N of the total number of beacons, the percentage of localized targets was observed to increase with P. With a sufficient number of anchors (which can be either the original beacons or the cooperating nodes), the third stage of the algorithm becomes unnecessary. This increase in the percentage of localized targets is the main achievement of

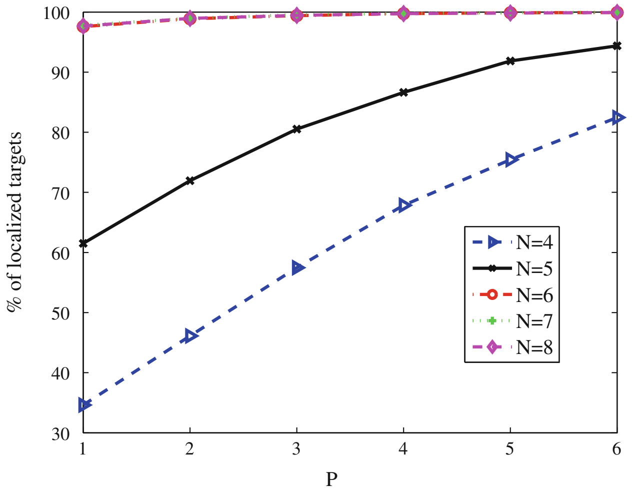

Fig. 4 Percentage of targets localized by the proposed two-stage algorithm, as a function of the number of targets allowed to cooperate (P), for different total numbers of beacons (N)

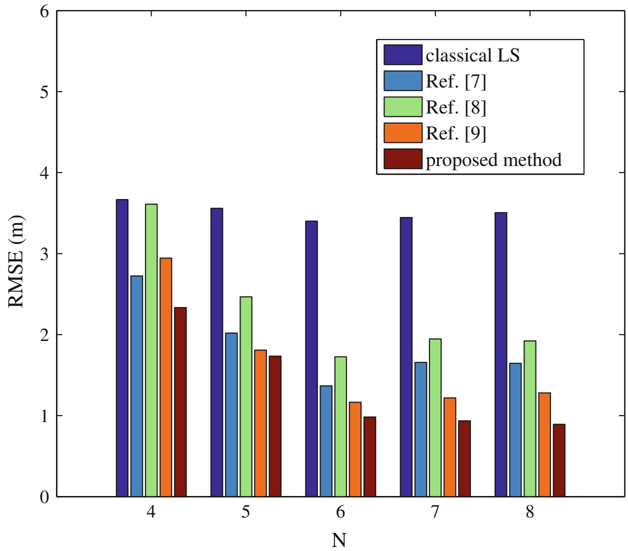

Fig. 5 RMSE of the positioning error for different algorithms as a function of the number of beacons. The maximum number of targets allowed to cooperate for the proposed method is 6

the cooperative approach in the proposed method, and is especially significant when the total number of beacons is low.

In the simulations reported below, to ensure fair comparison with other techniques that provide an estimate for 100 % of the targets, the proposed algorithm was completed with a third stage based on [7] for the targets that were still not localized after the cooperative localization stage, as anticipated in Sect. 3.

Figure 5 shows the RMSE as a function of the number of beacons for the methods included in the simulations, with $P = 6$. The plain LS method shows the worst performance, illustrating the strong influence of the UDP measurements when no attempt is made to mitigate

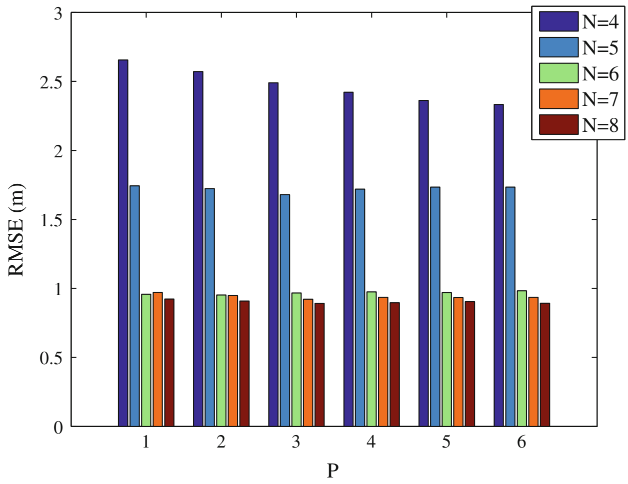

Fig. 6 RMSE of the positioning error for the proposed technique as a function of the number of beacons, N; and the number of targets, P

their effects. The methods of Chen [7] and Casas et al. [8] generally achieve a considerable improvement in comparison to the classical LS technique, especially the method of Chen [7]. For the method of Cong and Zhuang [9], the knowledge of the PDFs of the range measurements leads to a decrease in the RMSE when compared to Chen [7] and Casas et al. [8]. Finally, the proposed method with the topology knowledge outperforms the rest of the algorithms under test, with more significant improvements in the cases with higher numbers of beacons. The good results for the proposed algorithm indicate the validity of the design choices.

The effect of the number of targets that were allowed to cooperate, P, was also studied. Figure 6 shows the RMSE of the proposed method for the set of values of P considered. The rest of the algorithms have not been included in the graph because their RMSEs remain as shown in Fig. 5, regardless of the value of P, which affects only the cooperative stage of the proposed technique. Figure 6 shows that the RMSE of the proposed method decreases as the number of beacons increases for any value of P. In general, the RMSE is barely affected by the value of P, which means that the error propagation effect has been successfully mitigated, and that the main consequence of the cooperative approach, as shown in Fig. 4, has been to increase the percentage of localized targets without resorting to the less accurate third stage.

6 Conclusions

The use of topology knowledge for TOA based localization in indoor UWB sensor networks has been studied. Prior results in the literature on the causes of DDP and UDP propagation conditions for UWB have been used as a starting point. A novel algorithm has been proposed that uses only partial knowledge of the service area topology, in the form of a map of the limited set of objects that are capable of causing UDP propagation conditions.

Simulation results using a realistic range error model from the literature that was built on experimental data provide a comparison between a variety of methods. The proposed algorithm outperforms the previously published methods, thus illustrating the usefulness of the partial topology information that was chosen for the problem considered here, even in the absence of any knowledge of the range error statistics. The proposed algorithm includes a cooperative stage that deals successfully with the frequent insufficiency of the DDP measurements in a challenging scenario with numerous UDP situations, and achieves a significant increase in the percentage of targets that are localized by the proposed two-stage algorithm.

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Author Biography

Eva Arias-de-Reyna received the degree in Telecommunication Engineering and the Ph.D. degree from the University of Seville, Spain, in 2001 and 2007, respectively. Since 2002, after working in the industry for a year, she has been with the Department of Signal Theory and Communications at the University of Seville, where she is now Profesora Contratada Doctora. Her current research interests include wireless communications and localization techniques, with emphasis on Ultra Wideband technology.