Manuscript Details

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Title	A Received Signal Strength RFID-based Indoor Location System
Article type	Research Paper

Abstract

A RFID-based Indoor Location System (ILS) that makes use of Received Signal Strength (RSS) information is presented. The proposed system is derived from a simple Direction Finder (DF) consisting on two antennas tilted one to respect to the other, so that their radiation patterns partially overlap. RFID tags are attached to the person or asset to be tracked. The ratio between RSS values received on each antenna is used to estimate the Angle of Arrival (AoA) of the electromagnetic signals backscattered by RFID tags. Once the AoA is estimated, the absolute RSS values are compared against a free-space propagation model to obtain an estimate of the range or distance. Then, given the AoA and the range, the position of the RFID tags can be obtained. The proposed system, based on a single DF unit, is tested in three real indoor scenarios: the first example is devoted to evaluate the agreement between the theoretical and experimental characterization of the DF system, in terms of the radiation patterns of its antennas as well as the position estimation accuracy within the coverage area, analyzing the robustness of AoA against multipath. Second example shows simple cases of asset tracking. And the third one presents an enhanced system comprising two sets of antennas that improves positioning accuracy. A comparison with state-of-the-art ILS is also presented, in order to put the proposed RFID-based ILS into context.

Keywords	Wireless Sensor Networks (WSN); Indoor Location Systems (ILS); Angle of Arrival (AoA); Received Signal Strength (RSS); Radio Frequency Identification (RFID); Radiodetermination
Manuscript category	Technology

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Suggested reviewers	Paolo Nepa, Paolo Rocca, Raúl Guzmán Quirós

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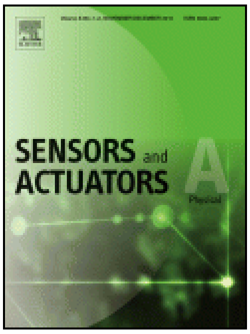

Sensors and Actuators A: Physical

November 15, 2016

Dear Sir/Madam,

On behalf of all the authors (Yuri Alvarez, María Elena de Cos, Fernando Las-Heras), I am re-submitting the paper entitled “A Received Signal Strength RFID-based Indoor Location System” to be considered for publication as a research paper in the *Sensors and Actuators A: Physical* journal. The Associate Editor suggested the re-submission of the paper after revising it according to the comments and suggestions raised by the reviewers.

The requested documentation has been uploaded to the journal website.

Looking forward to hearing from you,

Yours faithfully,

Yuri Alvarez Lopez

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Ms. Ref. No.: SNA-D-16-00895 **Sensors & Actuators: A. Physical**

Title: A Received Signal Strength RFID-based Indoor Location System

Response to the reviewers' comments

First of all, the authors would like to thank the reviewers for their comments, corrections and suggestions. With respect to the previous submitted version, the main novelty is the inclusion of a new example where 2 Direction Finding (DF) units are considered, providing enhanced positioning and tracking capabilities. The example is also devoted to better show the main idea of the contribution, which is the use of the ratio of RSS levels received on the antennas of the DF unit to calculate the Angle of Arrival of the RFID tags backscattered signals.

Besides, Section I. Introduction has been updated, and a new Section V. Discussion has been included.

Modifications with respect to the previous version have been highlighted in blue color.

Reviewers' comments:

Reviewer #1:

In this article, the authors present and evaluate a Direction Finder (DF)-like system composed by two antennas, tilted one with respect to the other, connected to a RFID reader. Moreover, they present a comparison between theoretical values and measurements, demonstrating a good behavior of the implemented setup by means of an uncertainty analysis.

Even though I appreciate the experimental work that have been conducted in this campaign, the adding value (from the scientific point of view) is not strong enough. Basically, the authors proceeded with a performance evaluation and a proof-of-concept study. In Sections I, II and III, the authors present state-of-art studies while in IV demonstrate the performance evaluation.

In order to better present the applicability of the proposed technique, a new example with two Direction Finding (DF) units has been included (Section IV.C). Besides, a comparison with conventional RSS techniques based on free-space propagation model has been presented, proving that the proposed approach is more accurate.

Furthermore, the paper is not well balanced and structured. For instance, *struggled to identify the the scope of the article in the Introduction Section*, since *the authors did not detail their proposal* (rather presenting the state-of-the-art solution and providing briefly certain theoretical background).

The authors disagree with this argumentation, as the aim and scope is detailed in the "highlights" as well as at the end of the "Introduction" section:

"Aiming to improve the accuracy of those RSS-based techniques that make use of theoretical free-space propagation values, a novel approach is proposed in this contribution. Instead of directly minimizing a cost function relating RSS measurements with the theoretical free-space propagation model values [20], it is proposed to first estimate the AoA of the RF signal, and then estimate the range. The position is directly obtained from the knowledge of AoA and range [24],[25].

For this purpose, a Direction Finder (DF)-like system composed by two antennas, tilted one with respect to the other, connected to a RFID reader, is evaluated. A comparison between theoretical values and measurements is presented, showing the good behavior of the implemented setup by means of an uncertainty analysis. Asset tracking applications are also presented.

An important feature of the proposed ILS setup is the fact that positioning is achieved with just two transmitting/receiving antennas that cover an 80º sector. Accuracy can be increased by adding a second DF unit, taking advantage of the fact that most RFID readers are equipped with 4 ports, so up to 4 antennas (i.e. 2 DF units) can be controlled with a single RFID reader."

The authors have complemented this part of the Introduction to better state the goal of this contribution and the novelties with respect to the state-of-the-art.

Besides, the theoretical background presented in Section II explains the operating principle of DF systems, which is the main idea of this contribution. The authors would like to remark that all the presented results are based on measurements, which have been compared with the theoretical models, thus allowing an accurate assessment of the performance of the location and tracking system.

As said before, the authors expect that the new example presented in Section IV.C contributes to demonstrate the feasibility of the system.

Reviewer #2:

Overall, the paper is well written and provides a useful contribution to the field. Although a good number of indoor positioning and algorithms have already been proposed in the literature, this paper presents a useful and practical approach for RFID systems which keeps the hardware requirements to a minimum. The positioning accuracy of the proposed approach is evaluated and the results are very promising compared to other RSS approaches I have come across. A further contribution of the paper is the consideration of the ability of the algorithm to track a moving object following both circular and arbitrary paths. The results are comprehensive and include RSS profiles as well as angle of arrival estimations and subsequently the position estimates and traces of the path followed by the vehicle. The paper has merit.

We would like to thank the reviewer for the positive comments. In order to better illustrate the tracking capabilities of the system, a new example with two Direction Finding (DF) units has been included (Section IV.C).

The introduction is very clearly written and includes an overview of the most relevant techniques for indoor localisation. A little more could be said about alternative angle of arrival approaches reported in the literature, since this is a key aspect of the proposed methodology. The paper flows well and includes a good outline of alternative approaches and useful discussion of their relative merits/application as the paper progresses. Figures are clear and illustrative. The proposed use of two antennas tilted with respect to each other is suitable for the RFID technology of interest and I am not aware of a similarly focused approach being considered elsewhere. An important aspect of the paper is the fact that the antenna radiation patterns have been measured in order to compare and validate the accuracy of theoretical models. The measurements demonstrate that the practical antenna designs are a close match to the theoretical radiation patterns required for the algorithm. A useful comparison of the positioning accuracy of alternative techniques (with relevant scenario information) *is provided in table 1, but this should not appear in the conclusions section as it presents new information*. The noted highlights are appropriate for this paper and make the contributions clear. All photos / figures are clear and fine for inclusion in the paper as they are.

Some minor issues to be corrected:

Say a little more about angle of arrival approaches in the introduction, prior to the more detailed information in the literature review. *Make sure the introduction is balanced in its overview of alternative positioning approaches and their merits/use*.

Done. The review of ILS techniques has been updated as follows:

"A number of ILSs have been proposed in the literature, based on infrared signals [4], ultrasound [5], and radiofrequency mainly. The latter are, in general, range-based distance measurements systems, which can be classified in three main groups: i) Time-of-Flight (ToF) methods [6],[7] are based on the signal propagation time between a transmitter (Tx) and receiver (Rx) node. ii) Angle of Arrival (AoA) [8],[9] measures the direction of propagation of a signal received on an antenna array, thus requiring at least two Rx nodes to calculate the position as the intersection of the two detected directions. And iii) Received Signal Strength (RSS) techniques are based on the minimization of a cost function relating the measured RSS values with a reference ones, that can be calculated from theoretical free-space propagation models [10],[11],[12] or using a database of RSS measurements (usually known as fingerprinting [13],[14],[15]). Multiple reference or anchor nodes with known positions are placed surrounding the scenario where the system is deployed."

Then, a paragraph explaining AoA has been added before explaining ILS technologies:

"While ToF and AoA methods are more accurate than RSS-based techniques, they require more complex and expensive devices. In the case of ToA, receivers capable of measuring wideband signals (corresponding to short-time pulses) are required. Apart from this, wideband or ultrawideband (UWB) standards for Wireless Sensor Networks (WSN) are still under development. The majority of AoA techniques requires an array of 2 of more antennas and coherent detectors in order to measure the phase difference of the signal received on each antenna [8],[9]. Some systems use Time Difference of Arrival (TDoA) instead of phase measurements, but again, wideband signals are required to have enough resolution. Furthermore, existing wireless infrastructure already deployed in indoor scenarios (buildings, warehouses, etc.) can be easily reused for RSS-based ILS implementation [16]."

In addition to this, the state-of-the-art has been completed with some references to AoA and RSS-based ILS.

Please move table 1 and associated comparison of the alternative approaches to a separate discussion section prior to the conclusions. Then *follow this with a more general conclusions section summarising the main points and findings from the paper*.

Done, a new Section V.Discussion has been added. Table 1 has been updated with Section IV.C results to highlight better the positioning accuracy of the proposed ILS.

'Time-of-Fly' should be 'Time of Flight'.

Done.

'In the last years' on page 3 should be 'In recent years'.

Done.

A Received Signal Strength RFID-based Indoor Location System

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Abstract

A RFID-based Indoor Location System (ILS) that makes use of Received Signal Strength (RSS) information is presented. The proposed system is derived from a simple Direction Finder (DF) consisting on two antennas tilted one to respect to the other, so that their radiation patterns partially overlap. RFID tags are attached to the person or asset to be tracked. The ratio between RSS values received on each antenna is used to estimate the Angle of Arrival (AoA) of the electromagnetic signals backscattered by RFID tags. Once the AoA is estimated, the absolute RSS values are compared against a free-space propagation model to obtain an estimate of the range or distance. Then, given the AoA and the range, the position of the RFID tags can be obtained. The proposed system, based on a single DF unit, is tested in three real indoor scenarios: the first example is devoted to evaluate the agreement between the theoretical and experimental characterization of the DF system, in terms of the radiation patterns of its antennas as well as the position estimation accuracy within the coverage area, analyzing the robustness of AoA against multipath. Second example shows simple cases of asset tracking. And the third one presents an enhanced system comprising two sets of antennas that improves positioning accuracy. A comparison with state-of-the-art ILS is also presented, in order to put the proposed RFID-based ILS into context.

Keywords:

Wireless Sensor Networks (WSN)
Indoor Location Systems (ILS)
Angle of Arrival (AoA)
Received Signal Strength (RSS)
Radio Frequency Identification (RFID)
Radiodetermination

I. Introduction

Indoor Location Systems (ILS) have been a major research topic in recent years due to the potential applications in fields such as logistics [1], healthcare [2], and safety applications [3]. This burgeoning interest comes after the popularization of Global Navigation Satellite Systems (GNSS) which provides accurate outdoor location. However, GNSS is not operative in indoor scenarios as there is no direct line-of-sight between the antenna and satellites.

A number of ILSs have been proposed in the literature, based on infrared signals [4], ultrasound [5], and radiofrequency mainly. The latter are, in general, range-based distance measurements systems, which can be classified in three main groups: i) Time-of-Flight (ToF) methods [6],[7] are based on the signal propagation time between a transmitter (Tx) and receiver (Rx) node. ii) Angle of Arrival (AoA) [8],[9] measures the direction of propagation of a signal received on an antenna array, thus requiring at least two Rx nodes to calculate the position as the intersection of the two detected directions. And iii) Received Signal Strength (RSS) techniques are based on the minimization of a cost function relating the measured RSS values with a reference ones, that can be calculated from theoretical free-space propagation models [10],[11],[12] or using a database of RSS measurements (usually known as fingerprinting [13],[14],[15]). Multiple reference or anchor nodes with known positions are placed surrounding the scenario where the system is deployed.

While ToF and AoA methods are more accurate than RSS-based techniques, they require more complex and expensive devices. In the case of ToA, receivers capable of measuring wideband signals (corresponding to short-time pulses) are required. Apart from this, wideband or ultrawideband (UWB) standards for Wireless Sensor Networks (WSN) are still under development. The majority of AoA techniques requires an array of 2 of more antennas and coherent detectors in order to measure the phase difference of the signal received on each antenna [8],[9]. Some systems use Time Difference of Arrival (TDoA) instead of phase measurements, but again, wideband signals are required to have enough resolution. Furthermore, existing wireless infrastructure already deployed in indoor scenarios (buildings, warehouses, etc.) can be easily reused for RSS-based ILS implementation [16].

An exhaustive study of RSS-based ILS limitations has been presented in the literature [17], comparing different methodologies and techniques. The most extended technologies are Bluetooth [14],[18], ZigBee [11],[20],[21],[22] Wireless Local Area Networks (WLAN) [9],[14],[23], and Radio Frequency Identification (RFID) [8],[10],[13],[19],[23],[24]. As justified in [17], RSS algorithms provide similar accuracy for a given scenario, which depends mainly on the number of nodes per surface unit and the number of assets to be tracked, regardless the chosen technology. Thus, in those scenarios where a WLAN is deployed it makes sense to take advantage of that technology to implement the RSS-based ILS. Similarly, in industrial scenarios that make use of ZigBee for data exchange, this wireless infrastructure can be reused for ILS implementation.

In recent years, RFID has become a widespread technology for logistics and goods management, thanks to the low cost of RFID tags, that can store more information than QR codes or barcodes. Besides, RFID readers are now capable of providing additional information about the signals backscattered in the RFID tags, such as RSS, phase, and even Doppler frequency shift, thus allowing radio-frequency (RF) engineers the development of novel RFID-based applications.

ILS are affected by three main sources of error: first, the signal reflection off the obstacles, that creates multipath contributions; second, the signal attenuation when passing through walls and obstacles; and third, the electromagnetic noise and interferences from other RF services. ToF and some AoA techniques are based on Ultra Wide band (UWB) devices, so multipath degradation can be partially removed. However, in the case of RSS, multipath creates signal fluctuations with respect to the free-space propagation model. A quite extended solution is the use of empirical models from a database of RSS measurements collected in the scenario where the system is deployed, i.e. fingerprinting [13],[14],[15]. However, that requires the scenario to be quite invariant in time, apart from the significant effort that requires collecting the measurements.

Aiming to improve the accuracy of those RSS-based techniques that make use of theoretical free-space propagation values, a novel approach is proposed in this contribution. Instead of directly minimizing a cost function relating RSS measurements with the theoretical free-space propagation model values [20], it is proposed to first estimate the AoA of the RF signal, and then estimate the range. The position is directly obtained from the knowledge of AoA and range [24],[25].

For this purpose, a Direction Finder (DF)-like system composed by two antennas, tilted one with respect to the other, connected to a RFID reader, is evaluated. A comparison between theoretical values and measurements is presented, showing the good behavior of the implemented setup by means of an uncertainty analysis. Asset tracking applications are also presented.

An important feature of the proposed ILS setup is the fact that positioning is achieved with just two transmitting/receiving antennas that cover an 80º sector. Accuracy can be increased by adding a second DF unit, taking advantage of the fact that most RFID readers are equipped with 4 ports, so up to 4 antennas (i.e. 2 DF units) can be controlled with a single RFID reader.

The choice of RFID technology over WLAN, Bluetooth or ZigBee is supported by the price and size of RFID tags, allowing attaching several tags to the device to be tracked aiming to ensure that, at least, one RFID tag is detected by the reader regardless the position and orientation of the device with respect to the reader.

II. Theoretical background

II.A. Angle of Arrival

AoA is usually calculated from phase measurements, then applying algorithms such as MUSIC [25],[26],[27],[28]. Even though phase measurements are not expensive, they require more complex devices, and not all the commercial RFID readers are able to provide phase information. Thus, in this contribution, AoA is estimated from RSS measurements, as in some DF devices [29].

AoA calculation from RSS information can be done by partially overlapping two or more antenna radiation patterns [24] so that the relative RSS levels (i.e. range-free estimation) are univocally associated to a certain AoA. However, in [24], the authors propose switched beam antennas capable of a predetermined set of beams. This hardware increases the complexity of the setup, and also the risk of missing short-time signals.

To overcome this limitation, a simpler DF antenna is proposed, consisting of a pair of broad beam antennas tilted one with respect to the other a certain offset angle θ_0, so their beams partially overlap, as shown in Fig. 1. The ratio between the RSS values of each antenna is univocally related to an AoA value.

An unambiguous determination of the AoA as a function of the ratio of the RSS received on each antenna (or equivalently, on each RFID reader port) requires this ratio to be unique for every θ angle. In general, the RSS ratio (RSS_A / RSS_B) and the AoA (θ_{AoA}) do not follow a linear relationship, although a correspondence function can be constructed, $\theta_{AoA} = f(RSS_A / RSS_B)$. Another option is the use of a non-linear expression that has a quasi linear behavior in a certain range, that will be the approach considered in this contribution.

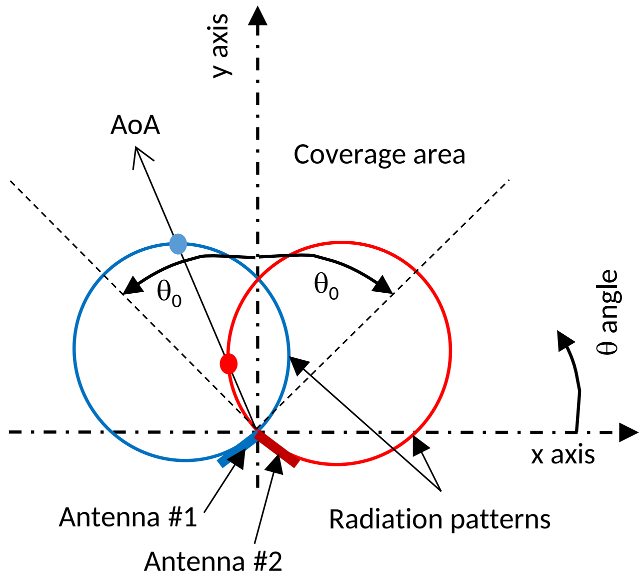

Figure 1. RSS-based AoA estimation using two antennas with partially overlapped beams. Beams are tilted θ_0 with respect to the y-axis.

For the sake of simplicity and ease of antenna design and manufacturing, antennas having $\cos(90º-\theta_0+\theta)^2$, and $\cos(\theta_0+\theta)^2$ radiation patterns (e.g. patch antennas) are considered. Given these radiation patterns, the AoA (θ_{AoA}) can be calculated as follows (1):

$$\theta_{AoA} = K\,(20\log_{10}(\cos(90^o-\theta_0+\theta)^2) - 20\log_{10}(\cos(\theta_0+\theta)^2)) = \qquad (1)$$

$$40\,K\,\log_{10}(\cos(90^o-\theta_0+\theta) / \cos(\theta_0+\theta)) = K\,(RSS_A\,[dB] - RSS_B\,[dB])$$

where K is an adjustment constant (e.g. K = 1.5 for $\theta_0 = 40^o$).

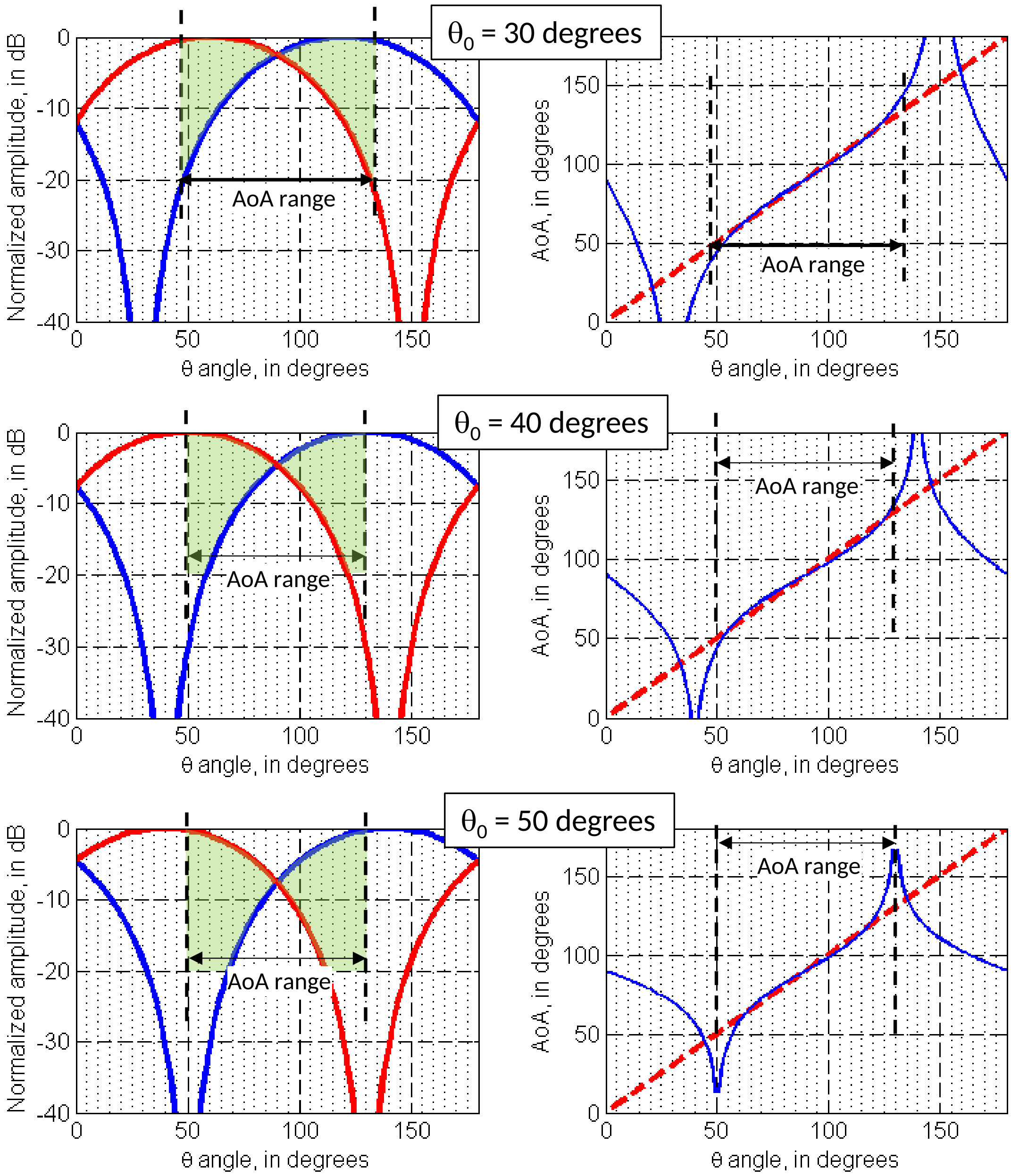

Figure 2. Left column: theoretical antenna radiation patterns (solid red and blue lines). Right column: reference AoA (dashed red line) and theoretical AoA (solid blue line). Different offset angles θ_0 are considered. Regions shadowed in green represent the regions where RSS values are considered reliable to avoid ambiguity.

The theoretical AoA (θ_{AoA}) is plotted in Fig. 2 as a function of the offset angle θ_0; this figure is used to determine the offset angle that maximizes the angular region where the AoA can be calculated without ambiguity. The first restriction is that RSS ratios with the same value yield AoA ambiguous values. Secondly, antenna radiation patterns have a null that, in practice, due to the noise and multipath effects is not observed as such null in measurements. And third, it has been noticed that RSS measurements 20 dB below the antenna pattern maximum exhibit large dispersion. In consequence, pattern values 20 dB below the maximum should be discarded.

From these three restrictions, regions where the RSS ratio yields unambiguous AoA values are plotted in green in Fig. 2, resulting a maximum AoA range of about ±40º. Ideally one could think that the best case is θ_0=45º (an intermediate case between 40º and 50º), so that the radiation pattern maximum of one antenna matches the null of the other antenna. However, due to the fact of the limited dynamic range, it is preferable reducing the offset angle to avoid errors in the RSS values ratio. For this reason, a θ_0= 40º has been chosen in this work as it maximizes the AoA range.

II.B. Received signal strength

Position determination requires both AoA and range. The latter is calculated from absolute RSS values, so this value is more sensitive to RSS measurement uncertainties. In general, a RSS-based ILS makes use of the free space propagation model (2):

$$RSS(r)\ [n.u.] = \beta / r^{\alpha} \qquad \equiv \qquad RSS(r)\ [dB] = 20\log_{10}(\beta) - \alpha\ 20\log_{10}(r) \qquad (2)$$

r is the range or distance, and α and β are coefficients that can be estimated from a non-linear regression that minimizes the root mean square error (RMSE) between a set of measurements and RSS(r). For this purpose, the expression on the right in (2) is already linearized with respect to α and β [30].

If $\theta_{AoA} = \pm\theta_0$, the signal is received in the antenna pattern maximum, which is $G(\theta = \pm\theta_0) = 1$ if normalized. Otherwise, the antenna radiation pattern contribution, $G(\theta)$, has to be taken into account in (2). In addition to this, two RSS values will be obtained for each antenna, and so two distances (3):

$$RSS_A\ [dB] = G_A(\theta_{AoA}) + 20\log_{10}(\beta) - \alpha\ 20\log_{10}(r')$$
$$RSS_B\ [dB] = G_B(\theta_{AoA}) + 20\log_{10}(\beta) - \alpha\ 20\log_{10}(r'') \qquad (3)$$

where subindexes A and B refer to each antenna.

Although ideally r' = r'' = r, RSS measurement uncertainty yield $r' \neq r''$. Furthermore, in theory, except for θ_{AoA} = 0º, $RSS_A > RSS_B$, or vice-versa; thus, in practice, it can be expected that the highest RSS value has less measurement uncertainty, being thus more reliable for range estimation. Thus, range is calculated as $r = \min\{ r' , r'' \}$.

III. RFID-based ILS characterization

The proposed RFID-based ILS consists on a RFID reader capable of providing RSS information [31]. Two of the four available ports of the reader are connected to the RFID antennas. The working frequency of the system can be adjusted within the 865-868 MHz frequency band.

One of the requirements of the proposed system is to have to antennas, tilted one with respect to the other an angle $90º-\theta_0 = 50º$, having a $\cos(\alpha)^2$ pattern. Taking into account the ease of design and manufacturing, two patch antennas [32], depicted in Fig. 3 (a), have been designed to resonate at 866 MHz, using Rogers RO3003 as substrate, then manufactured with laser micromachining. The 868 MHz RFID frequency band has a bandwidth less than 1%, which is also suitable for conventional patch antennas as they are also narrowband. However, due to manufacturing errors and tolerances, antenna resonance can be shifted in frequency. In order to fix this and set the resonant frequency within the 865-868 MHz frequency band, a stub has been welded to each of the two manufactured patch antennas, as shown in Fig. 3 (a). The S11 parameter has been measured as shown in Fig. 3 (b), proving that the resonant frequency is within the 865-868 MHz band (Fig. 3 (c)), and that both antennas are matched with S11 < -10 dB within this band. Commercial RFID antennas with $\cos^2(\alpha)$ pattern are also suitable for this application, as it will be shown in Section IV.C.

DogBone RFID tags (Fig. 4) [34], capable of providing a reading range up to 10 m in line-of-sight conditions at 868 MHz [33], have been evaluated. The tag ID can be easily configured by means of the RFID reader.

Next, the RFID patch antenna patterns are measured. For this purpose, a RFID tag is placed 2 m in front of the RFID system (Fig. 4). Antennas are placed on a rotary mast as shown in Fig. 4. An angular range from $\theta = 0º$ to $\theta = 180º$ is measured in 10º steps. For each angular position, measurements are collected during 10 s, then averaging the result. A second set of measurements is taken again 2 h after the first set, in order to verify the repeatability of the measurements.

Radiation pattern measurement results are depicted in Fig. 5. First, it can be noticed the agreement between the theoretical and measured RFID patch antenna radiation patterns (Fig. 5 (a)). Notice that the ground plane of the patch antennas prevents from backward radiation, as in the theoretical $\cos(\theta)^2$ pattern (with $\theta \in [-90º\ +90º]$). Furthermore, measurements 20 dB below the maximum are corrupted by noise, so the radiation pattern null cannot be detected.

From the radiation patterns, the AoA can be estimated as described in Section II.A. It can be observed the agreement between the theoretical and the estimated AoA within the AoA range defined for this setup (Fig. 5 (b)). AoA uncertainty is also depicted by plotting the AoA estimated for each RSS measurement. Thanks to the fact that up to 10 RSS values are taken per second, RSS values averaging is a feasible solution concerning AoA uncertainty mitigation without jeopardizing real-time tracking capabilities.

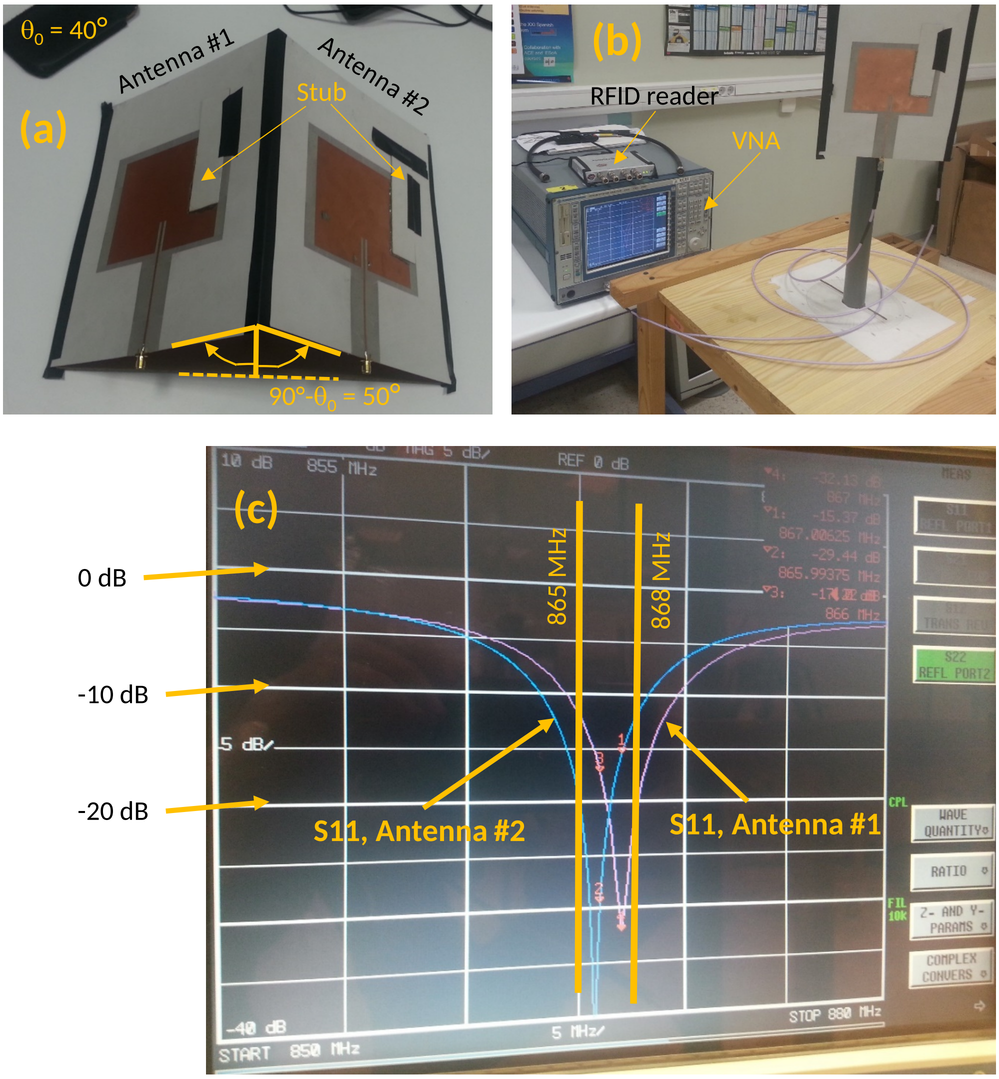

Figure 3. (a) Manufactured patch antennas, tilted 90º-θ_0 = 50º in order to achieve θ_0 = 40º beam tilting. (b) S11 parameter measurement setup. (c) S11 parameter measurement results.

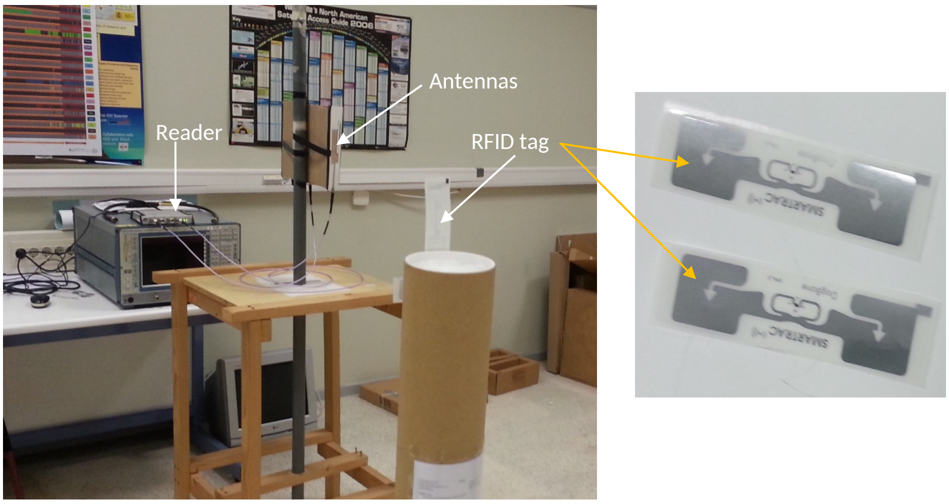

Figure 4. Measurement setup for evaluation of the RFID antenna patterns.

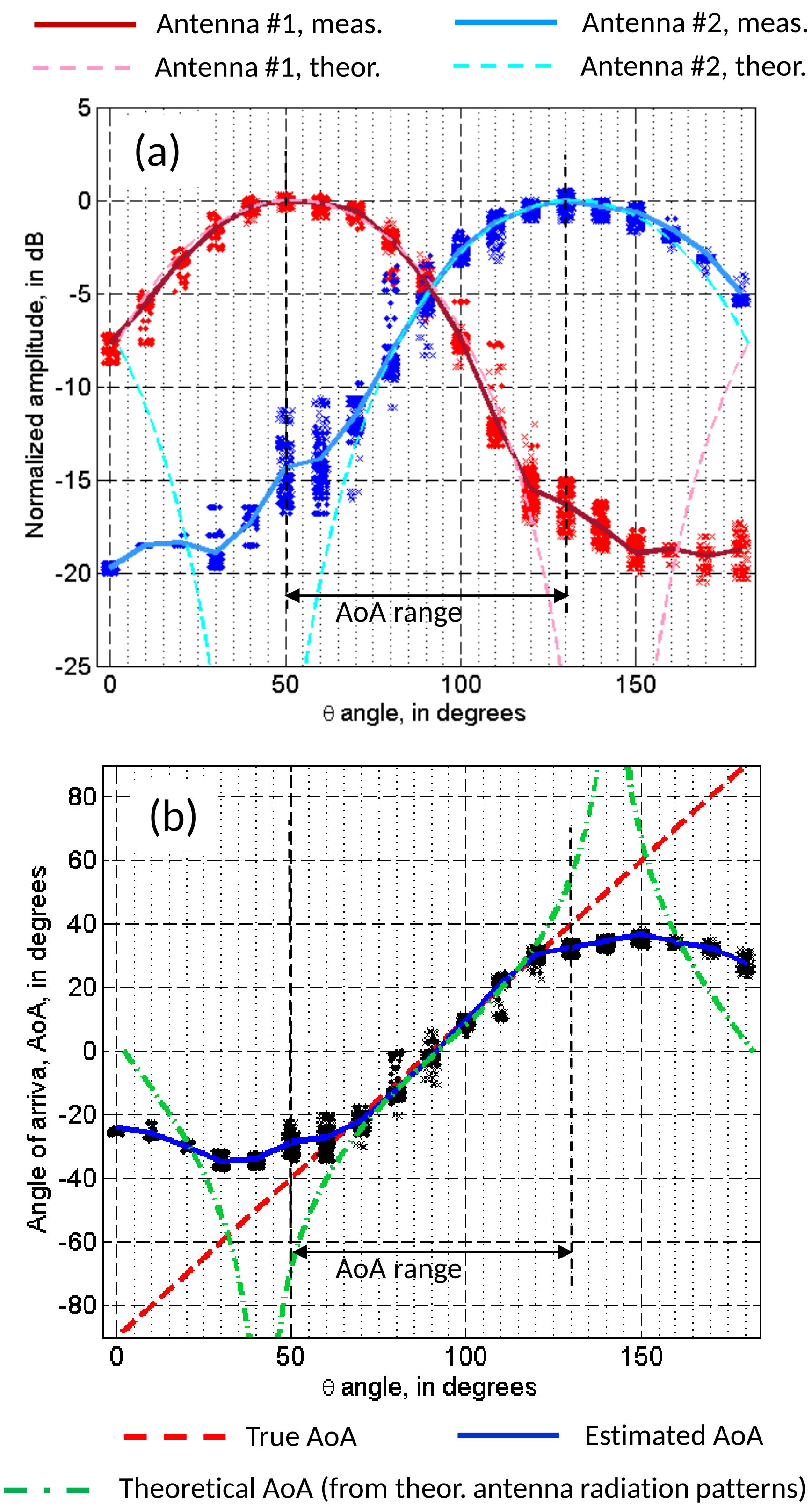

Figure 5. (a) RFID antenna patterns. Points represent the measured RSS levels on each angular position in 2 intervals of 10 s each. Comparison between theoretical and estimated radiation patters are shown. (b) Calculated AoA from the theoretical and estimated antenna patterns, and comparison with the true AoA. Points represent the AoA estimated for each RSS measurement.

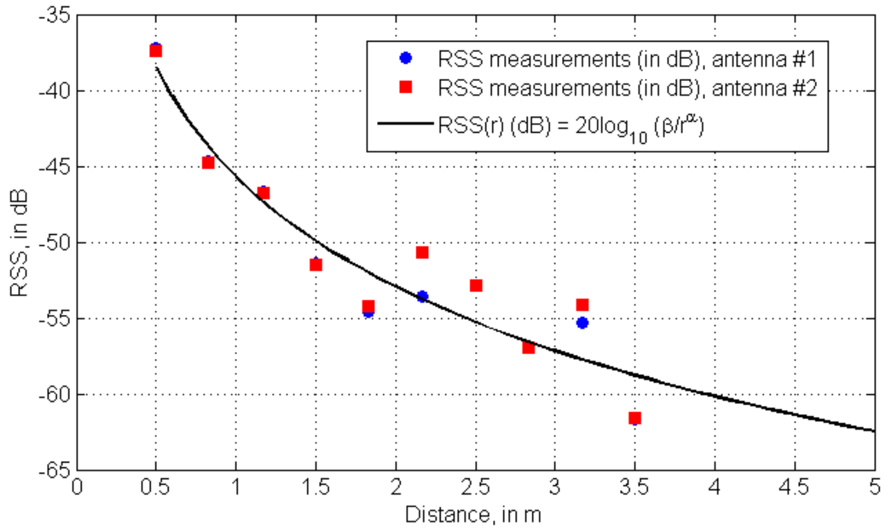

Figure 6. Measured RSS values on each port as a function of the distance from the RFID antennas. Comparison with the exponential curve β/r^{α} that minimizes the RMSE.

Next step is the estimation of the free-space propagation model, Eq. (3). For this purpose, a set of measurements have been collected from r = 0.5 m to r = 3.5 m, in 33 cm-steps, with θ = 90º (i.e. (θ_{AoA} = 0º). Measurements for ports 1 and 2 are depicted in Fig. 6, after averaging the 100 samples collected at each position. The α and β values that minimize the RMSE between the exponential curve (2) and the free-space field decay law are α = 1.3 and 20log10(β) = 38.5 dB. Note that, as α = 1.3, the signal strength decays slightly higher (exponent of 2.6) than the free-space exponent of 2, which is in agreement with the results for indoor propagation [24],[30].

At this point, the RFID-based ILS setup is fully characterized. It must be remarked that just a small set of measurements is required to estimate α and β. Theoretical models for $G_A(\theta)$ and $G_B(\theta)$ are used, although pattern measurements have also been presented in this section to prove the agreement with the theoretical patterns.

IV. Validation

Three application examples for RFID-based ILS validation are presented. The first one analyzes the AoA and position estimation accuracy. The second is devoted to prove asset tracking capabilities with an single set of antennas. The third example shows the improvement on the accuracy and coverage area when a second set of antennas is introduced.

IV.A. AoA and position estimation accuracy

Once the RFID-based ILS has been implemented, next step is the evaluation of the accuracy within the coverage area. For this goal, a 12 m long x 6 m wide classroom has been selected, placing the RFID antennas and the reader in one of the sides. A RFID tag is placed on top of a tripod that is placed at different positions, 33 cm equispaced (see Fig. 7), ranging x = [-1.67 1.67] m, y = [0.5 3.5] m. RSS measurements are collected during 20 s at each position, at an average rate of 5 measurements per second. These measurements are averaged resulting in a single RSS value for each antenna per position.

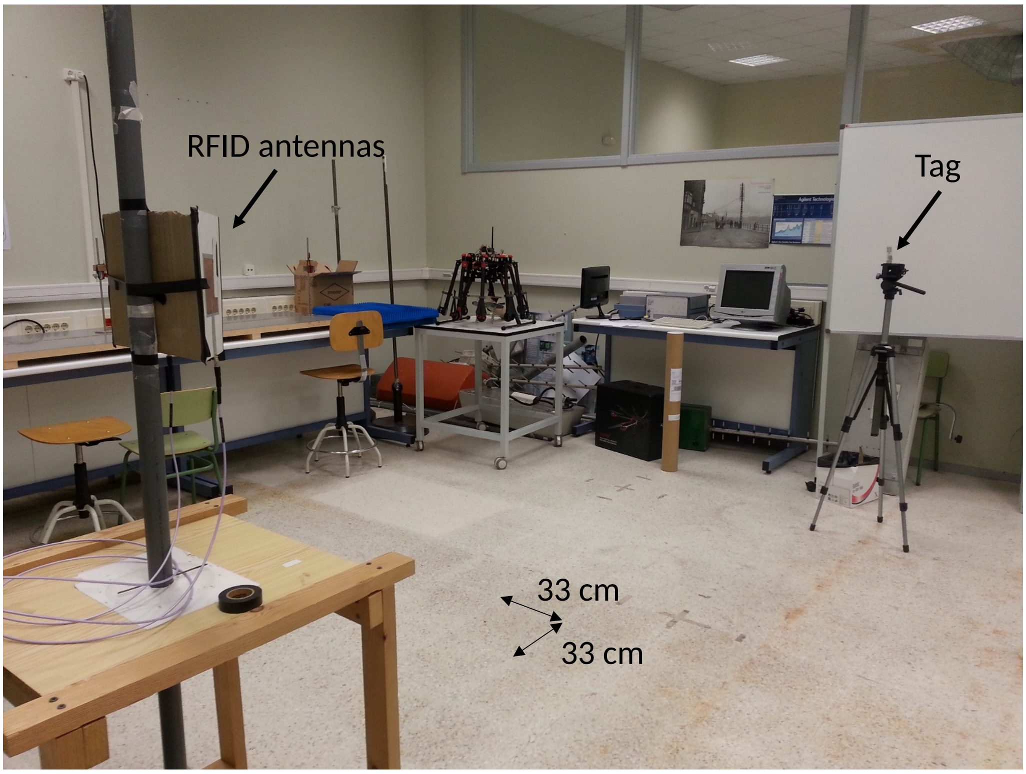

Figure 7. Measurement setup for evaluating RFID-based ILS coverage.

Measurements are depicted in the upper row of Fig. 8. It can be noticed that each of the two antennas covers opposite sectors. Those areas left in blank do not receive signal from the antenna. It must be remarked that concerning AoA and range estimation, RSS data from both antennas is required, otherwise out-of-range position is considered. A theoretical coverage map is obtained by combining Eqs. (1) and (3), by performing a parametric sweep of θ_{AoA} =[-90º 90º] and r = [0.5 5] m. Results are plotted in the center row of Fig. 8. Finally, the difference between measured and theoretical RSS is depicted in the lower row of Fig. 8, where the ripple due to multipath can be noticed (also in the upper row).

Next, from the RSS measurements, AoA is estimated at each position by applying Eq. (1) to the measured RSS values. AoA estimation error is depicted in Fig. 9. On average, the module of the AoA estimation error, $|\theta_{AoA,est} - \theta_{AoA,true}|$ within the coverage area (θ =[50º 130º]) is 5.9º, with a maximum error of 20º (x = -1.67, y = 2.83, see Fig. 9), and a standard deviation of 5.1º. AoA estimation error is less than 8º with 85% confidence. Given the AoA, the range or distance is calculated according to Eq. (3), and finally, the estimated position is calculated as $x_{est} = r_{est} \sin(\theta_{AoA,est})$, $y_{est} = r_{est} \cos(\theta_{AoA,est})$. Position estimation error depicted in Fig. 9 is defined as (4):

$$\varepsilon_{pos}(\%) = 100 \times ((x_{est} - x)^2 + (y_{est} - y)^2)^{1/2} / r, \qquad r = (x^2 + y^2)^{1/2} \qquad (4)$$

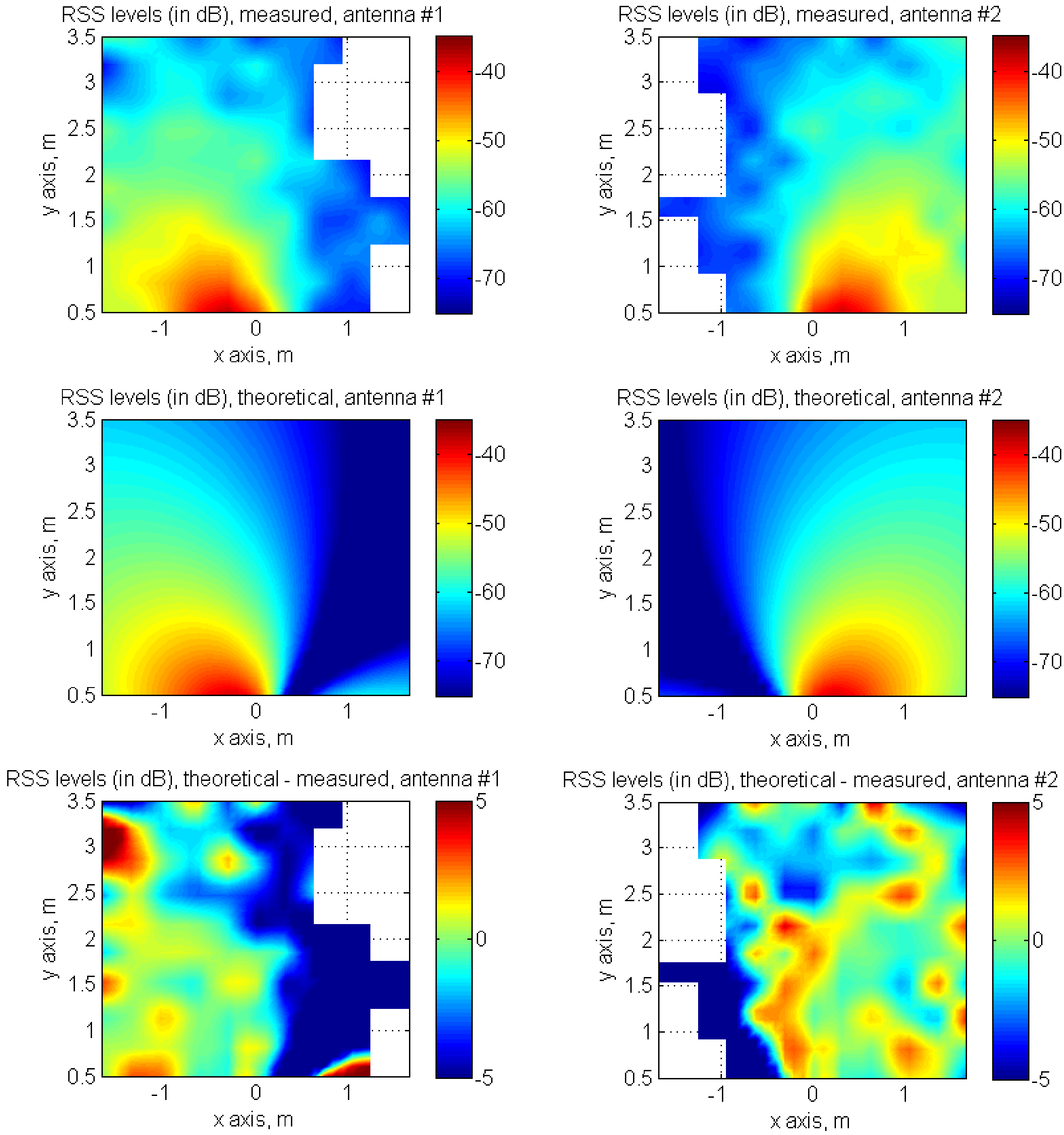

Figure 8. Upper row: measured RSS levels. Center row: theoretical RSS levels according to the theoretical radiation pattern and the free space field decay law. Lower row: difference between theoretical and measured RSS levels.

Within the coverage area, θ =[50º 130º], the average position estimation error is 18%, with a maximum error of 50%, and standard deviation of 10.5%. That means that, for a distance of 3 m, an error of 3 x 0.18 = 0.54 m can be expected. For a confidence level of 85%, the position estimation error is less than 26%. If the absolute position error were plotted, it could be observed that the error increases with the distance between the RFID tag and the RFID antennas, as it can be expected in those systems where a single DF unit is considered, as shown in Fig. 14 of [24]. This effect can be observed also in Fig. 9 (right plot), where those positions further from the RFID antenna exhibit larger position estimation errors (green lines).

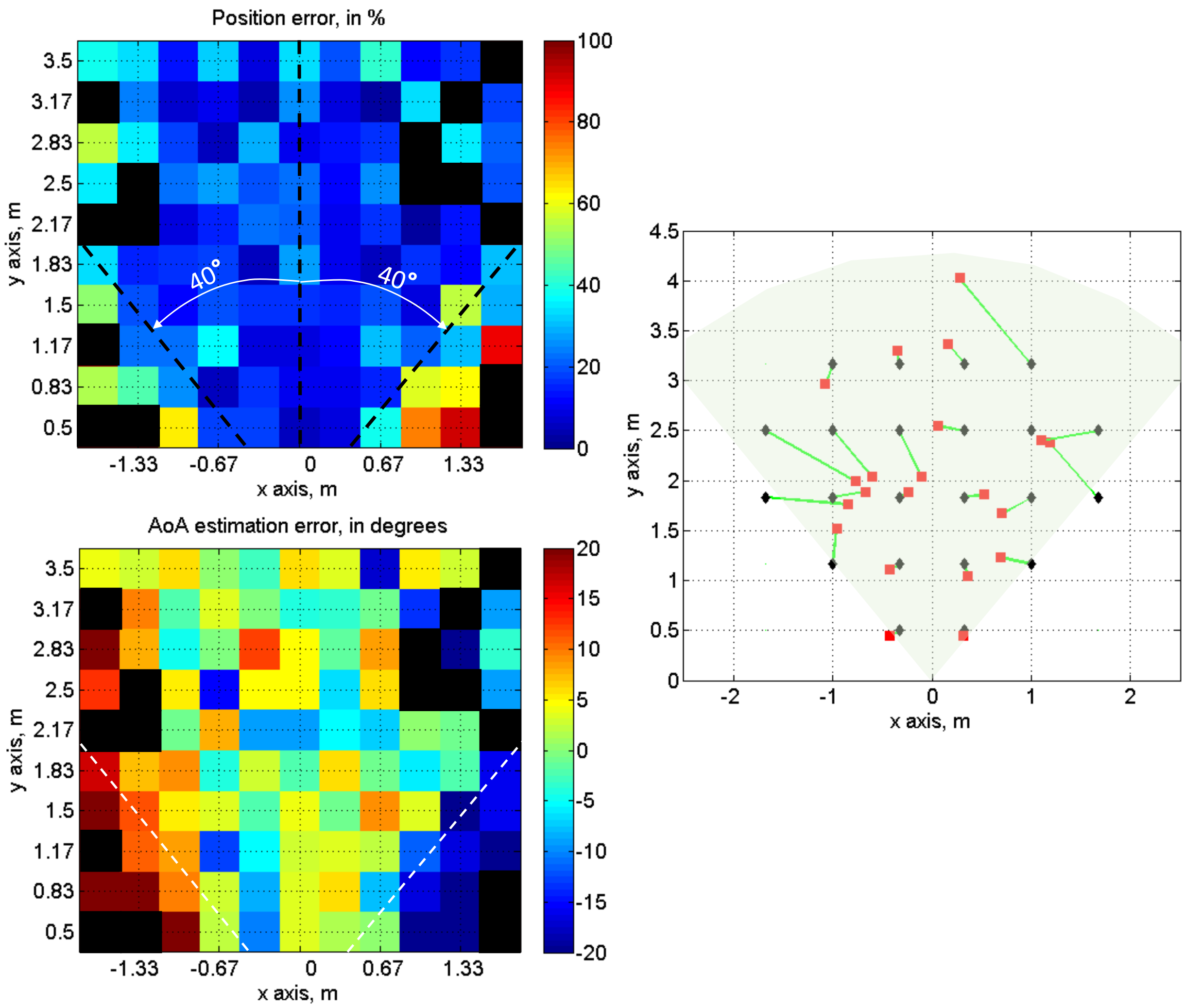

Figure 9. Position error, in %, AoA estimation error, in degrees, and error (green line) between the reference measurement positions (black diamonds) and the estimate given by the RFID-based ILS (red squares). The light shaded region represents the ILS coverage area.

IV.B. Tracking applications

Once the positioning accuracy of the RFID-based ILS has been tested, next step is the validation of the capability for assets tracking.

The same scenario as in Section IV.A is chosen, being the RFID reader and the antennas placed in one side of the classroom. The object to be tracked is a remote controlled (RC) car toy, shown in Fig. 10. In order to have the RFID tags at the same height as the RFID antennas, a cardboard mast has been added. The car can be arbitrarily oriented in the XY plane with respect to the antennas. Thus, 4 RFID tags have been tagged to the cardboard mast, aiming to ensure that, at least, one RFID tag is detected at each position.

The first test consisted on the car describing a 1.5 m-radius circular path, moving at an average speed of 0.5 km/h, totalizing one turn and a half in approximately 120 s. As the RFID reader acquisition rate is 10 samples/s, the overall number of detections is up to 1200, to be split among the 4 RFID tags attached to the cardboard mast. The reason of such low speed of the remote controlled car toy is to have a large number of RSS samples per length unit.

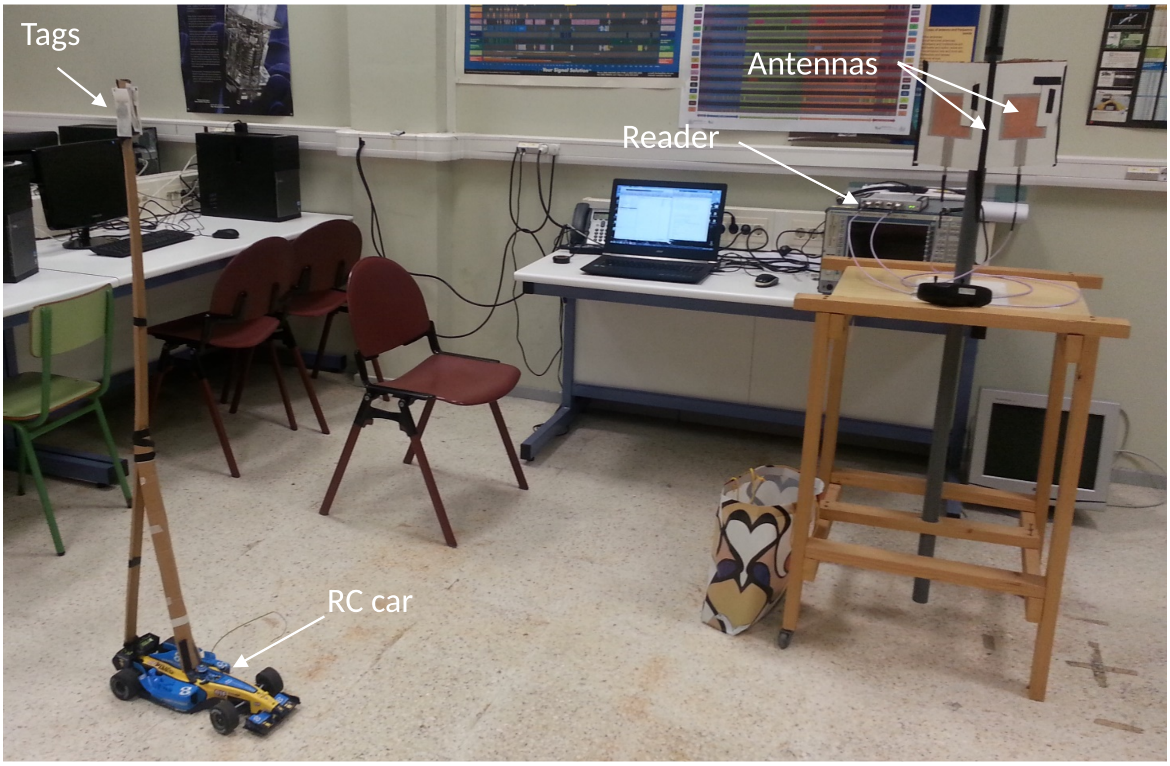

Figure 10. Picture of the scenario for testing RFID-based ILS tracking capabilities.

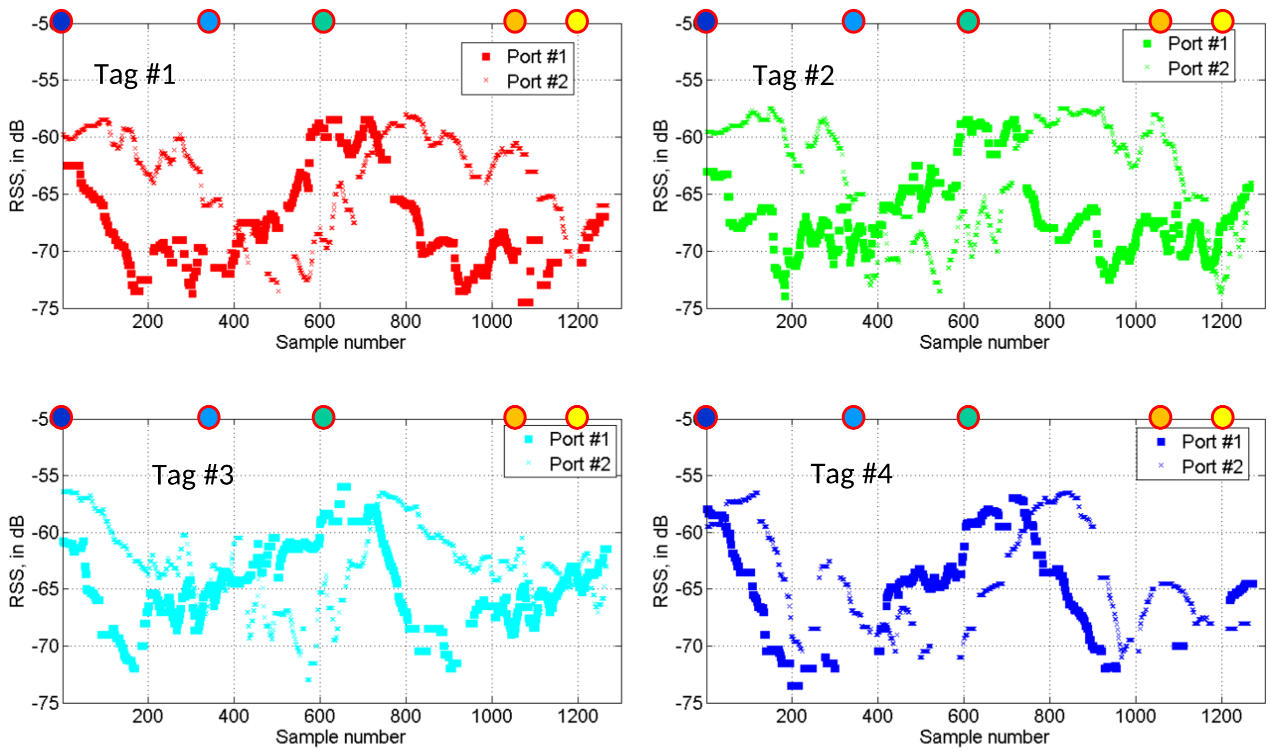

Figure 11. RSS values received at the RFID antennas (or equivalently, RFID reader ports) for each of the 4 tags placed on top of the cardboard mast attached to the remote controlled car. Red-edge circles on top of each plot indicate reference positions (their x,y representation is depicted in Fig. 12, right plot).

RSS values for each one of the 4 RFID tags received on each antenna (or RFID port) are plotted in Fig. 11. It can be noticed that the RSS values follow similar patterns for the 4 tags. Next, these values are processed as described in Section II, retrieving AoA and distance independently for each tag, as depicted in Fig. 12 (left column). Results for each tag are averaged, and a moving average of 10 samples is applied to obtain the combined AoA and distance (Fig. 12, left column, black lines). It can be observed that range estimation is more sensitive to RSS uncertainties as AoA, as the former is based on an empirical model (Eq. (3)), whereas AoA depends on RSS ratio. Note also the larger dispersion of range values (Fig. 12, left column, bottom) with respect to AoA (Fig. 12, left column, top).

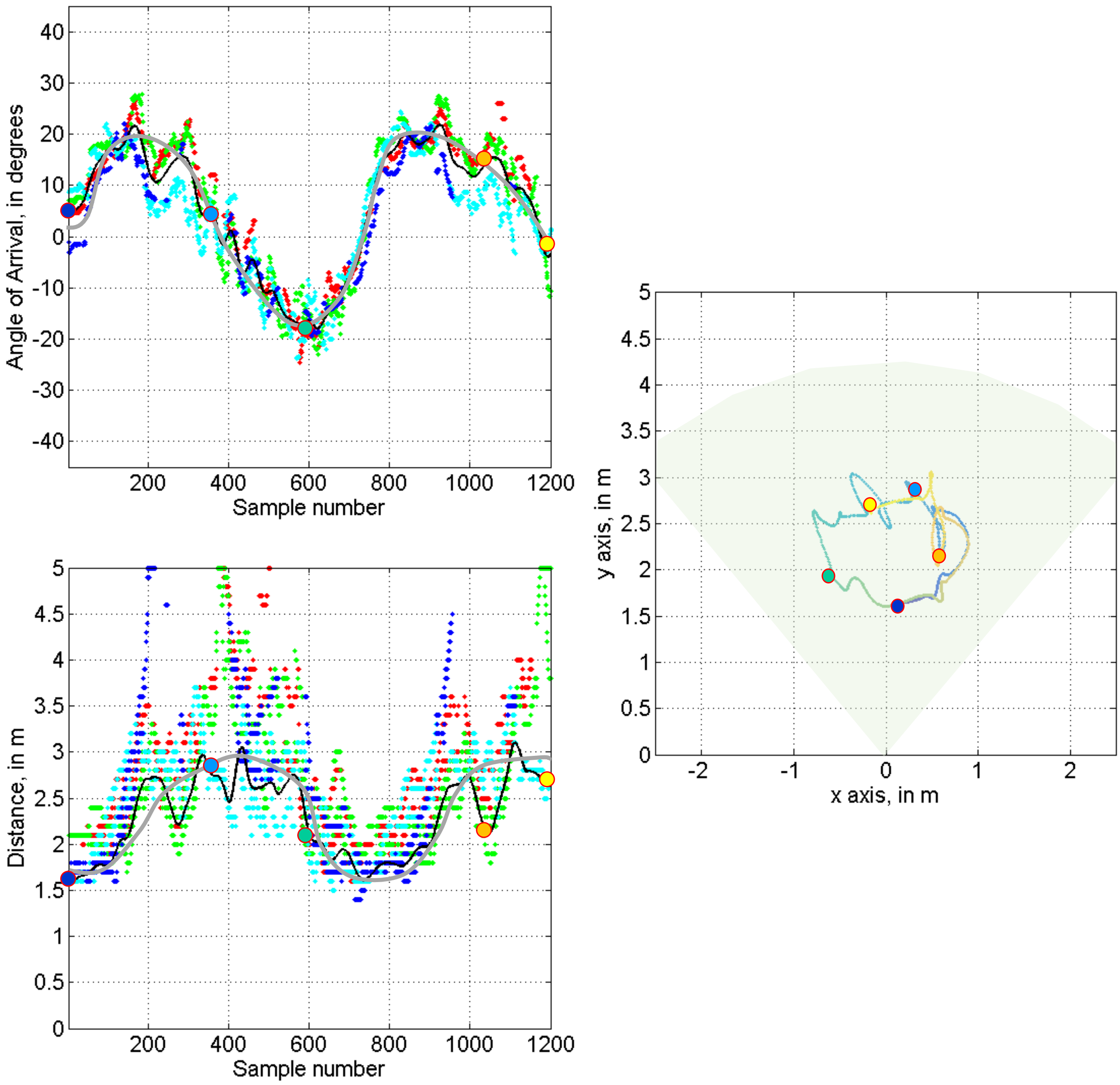

Figure 12. Left: Distance and AoA of the asset describing a circular path: estimated values for each of the 4 tags (different colors), average (black lines) and theoretical (gray line). Right: Estimated position in the XY plane (light green shaded region represents the ILS coverage area). Red-edge circles denote reference positions.

Next, AoA and range values are mapped into a XY grid to represent the estimation of the path followed by the remote controlled car toy, Fig. 12, right. The maximum uncertainty is around 1 m, which is still smaller than the maximum position error of 50% achieved in Section IV.

In the second test, the remote controlled car toy follows an arbitrary path, sometimes exiting the RFID-based ILS coverage area highlighted in light gray in Fig. 12 and Fig. 13. In this test, the speed of the asset ranges from 0 to 3 km/h. The asset is tracked for 2 minutes, resulting again in 1200 RSS samples. Results shown in Fig. 13 confirm that the AoA estimated using RSS values of each detected tag exhibits strong correlation, confirming the robustness of RSS-based AoA estimation against multipath or fading, in contrast to range estimation, where for the same sample, results associated to each position have larger dispersion.

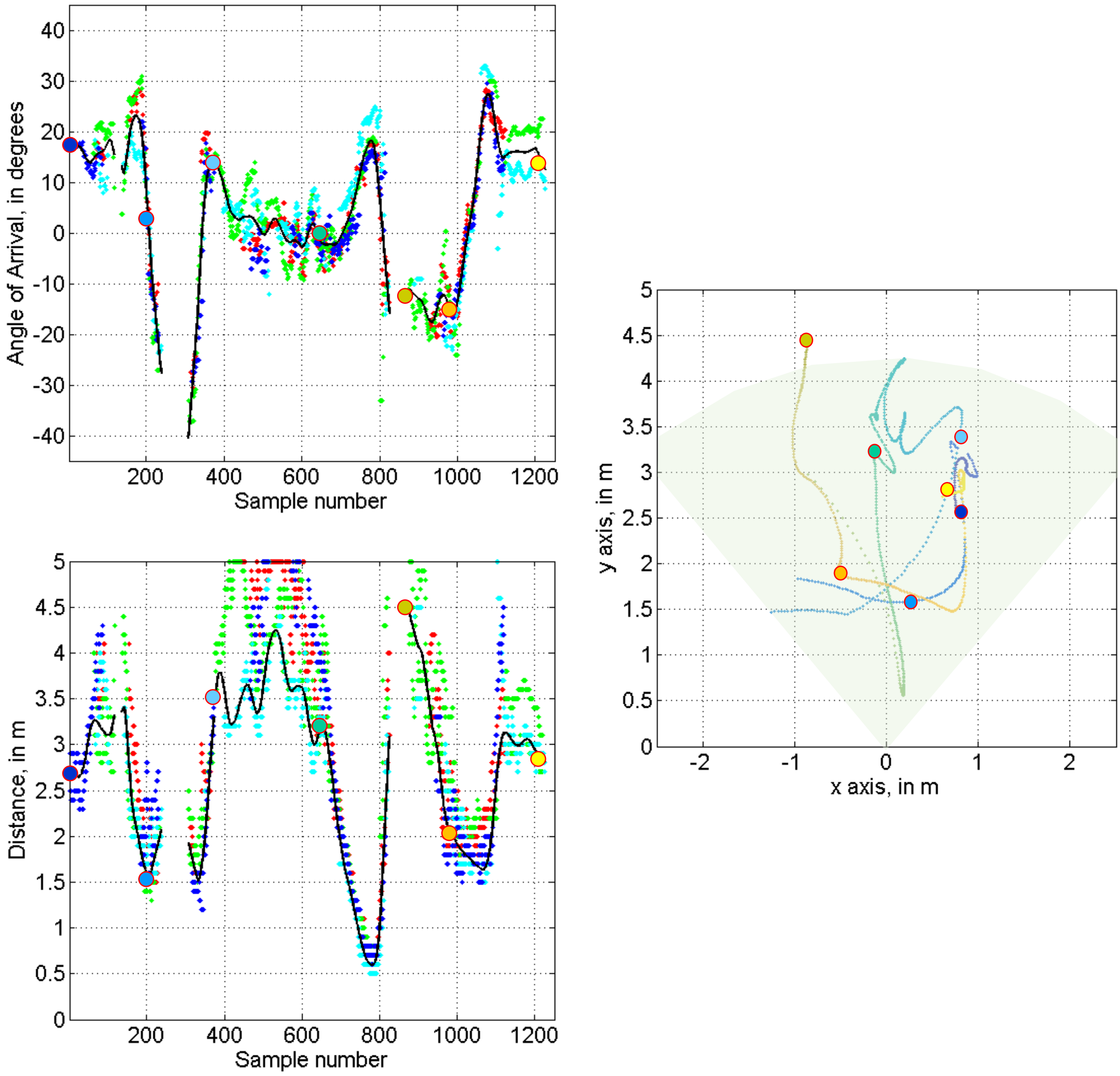

Figure 13. Left: Distance and AoA of the asset describing an arbitrary path: estimated values for each of the 4 tags (different colors) and average (black lines). Right: estimated position in the XY plane (light green shaded region represents the ILS coverage area). Red-edge circles denote reference positions.

IV.C. System evaluation using two sets of antennas

Positioning accuracy can be improved by adding a second DF unit, as depicted in Fig. 14. The idea is to place the two DF units in a 90º angle, so that the coverage areas intersect perpendicularly. The setup shown in Fig. 9 has been implemented in an indoor scenario similar to the one of Sections IV.A and IV.B. Commercial RFID antennas [35] have been considered in order to prove the feasibility of the system with commercial devices (antennas plus RFID reader). Due to mechanical restrictions, the two antennas on each DF set are placed in a wooden frame so that their relative angle is 90º, that is, θ_0 = 45º. These two sets of commercial antennas also exhibit $\cos^2(\theta)$ radiation patterns, as shown in Fig. 15. As the commercial RFID reader [31] has 4 ports, the system can be still implemented with a single RFID reader (2 ports per DF unit are used).

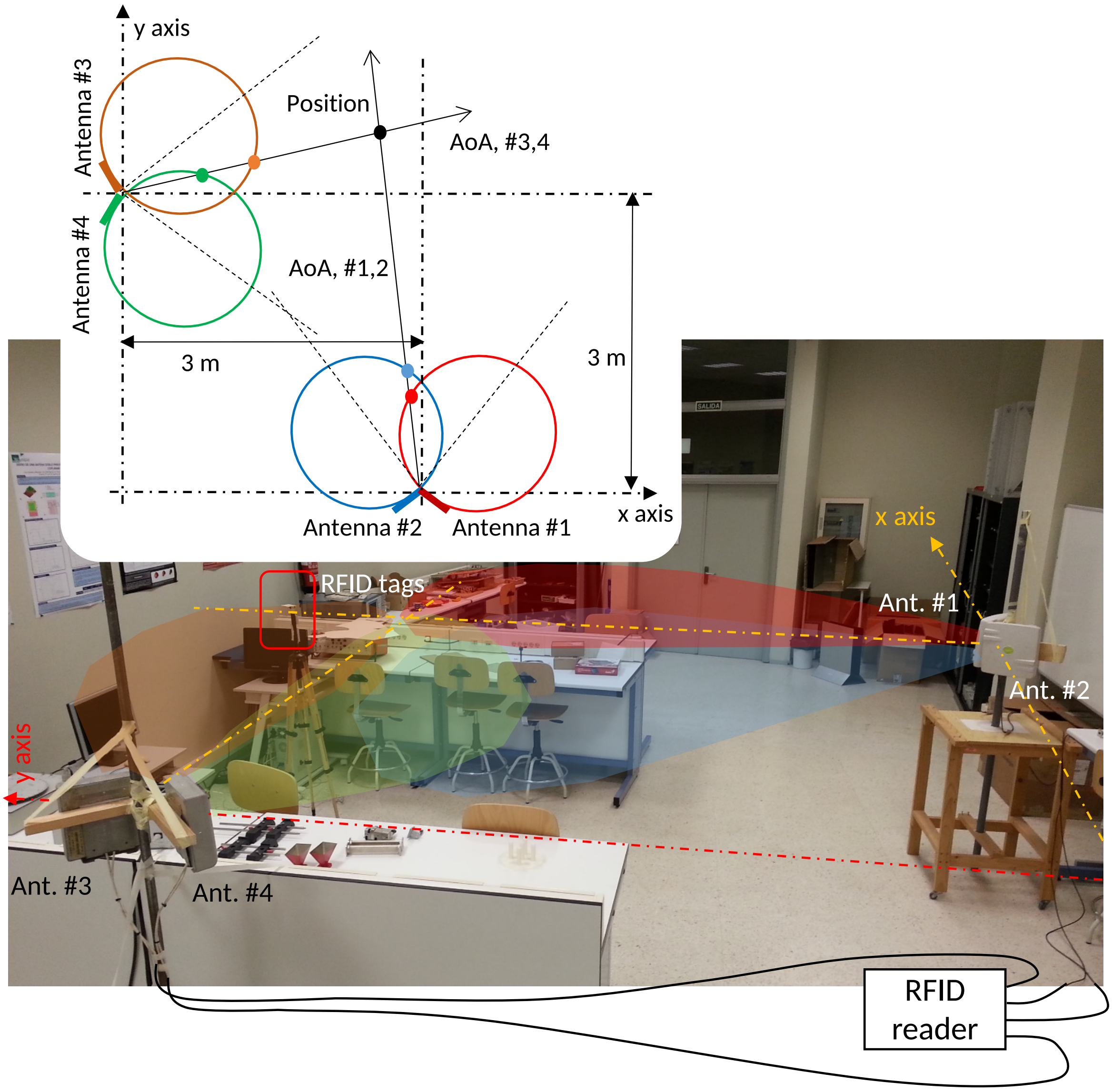

Figure 14. RSS-based AoA estimation using 2 DF sets (2 antennas each) with partially overlapped beams. Beams are tilted θ_0 with respect to the y-axis. Picture of the setup where the RSS-based AoA system is deployed.

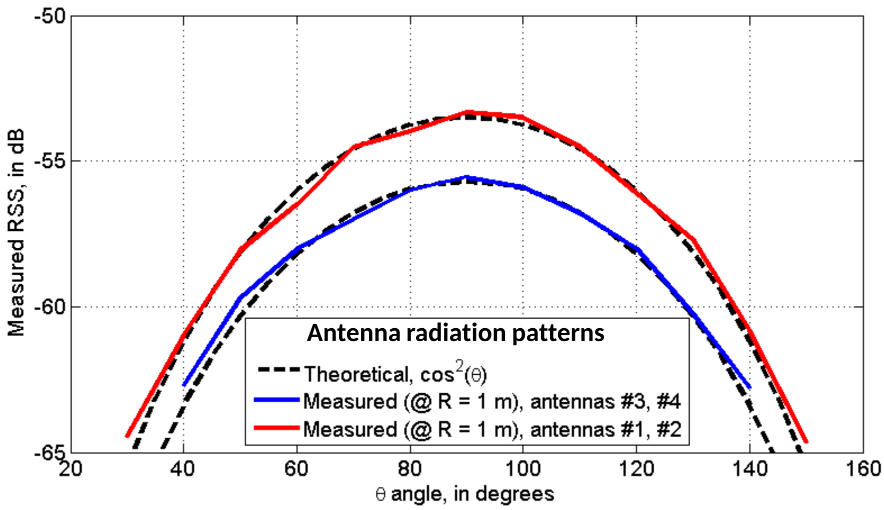

Figure 15. Comparison between the theoretical and measured patterns of the commercial RFID antennas used in the setup shown in Fig. 14.

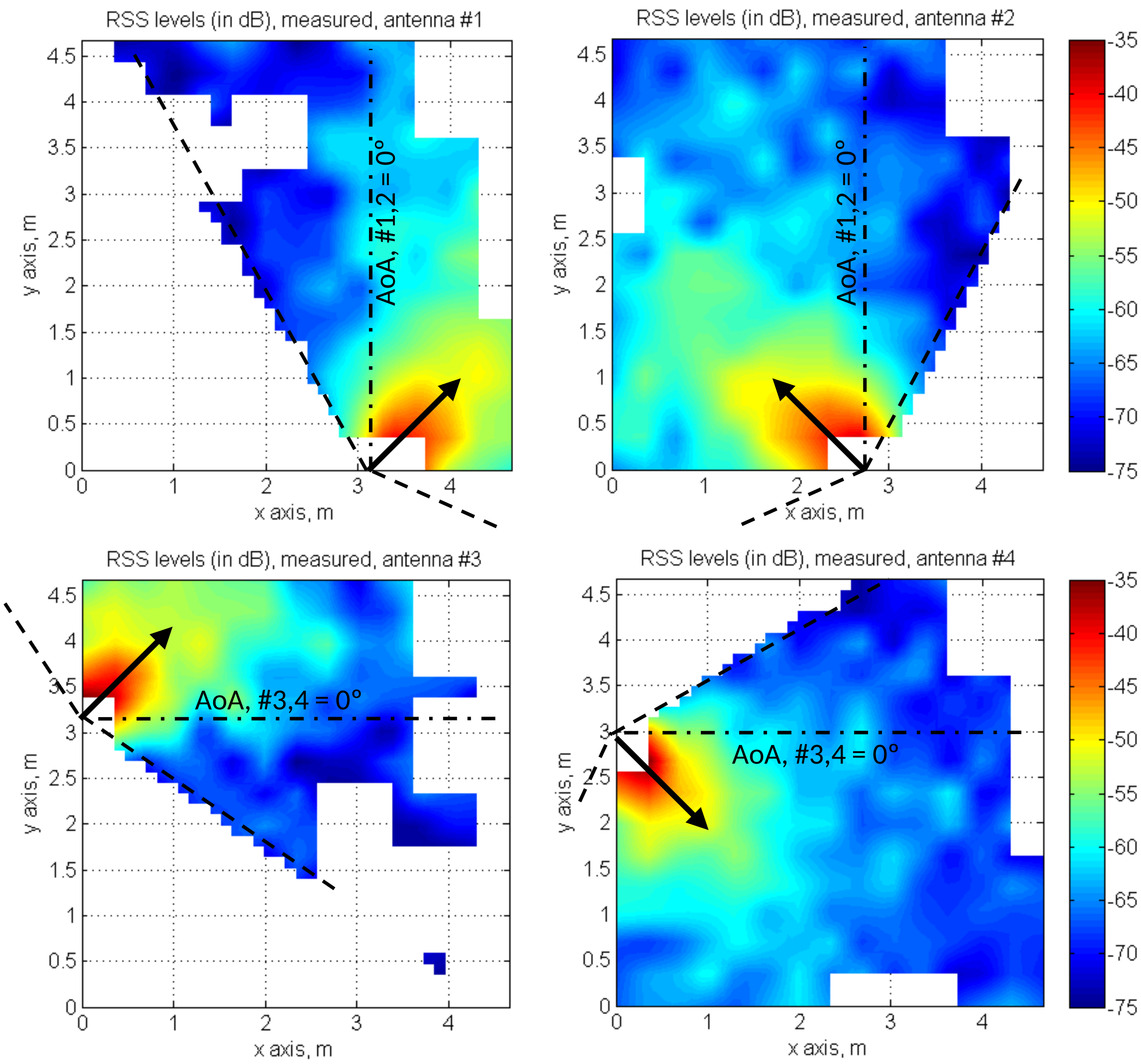

Figure 16. Measured RSS levels for each of the four RFID antennas considered in the setup. Arrows represent the vector normal to the antenna aperture.

First, the coverage area of each antenna is evaluated. For this goal, four RFID tags with different orientation have been attached to a plastic mast at the same height as the RFID antennas (1.5 m approximately). Measurements have been taken every 16.6 cm along x- and y- axes in a 4.67 x 4.67

m grid in all the accessible positions (the presence of laboratory instrumentation prevented from a full acquisition in the area-of-interest). Measured coverage maps are depicted in Fig. 16 for each of the 4 antennas. From these maps, the AoA and the distance, and thus the position, can be calculated.

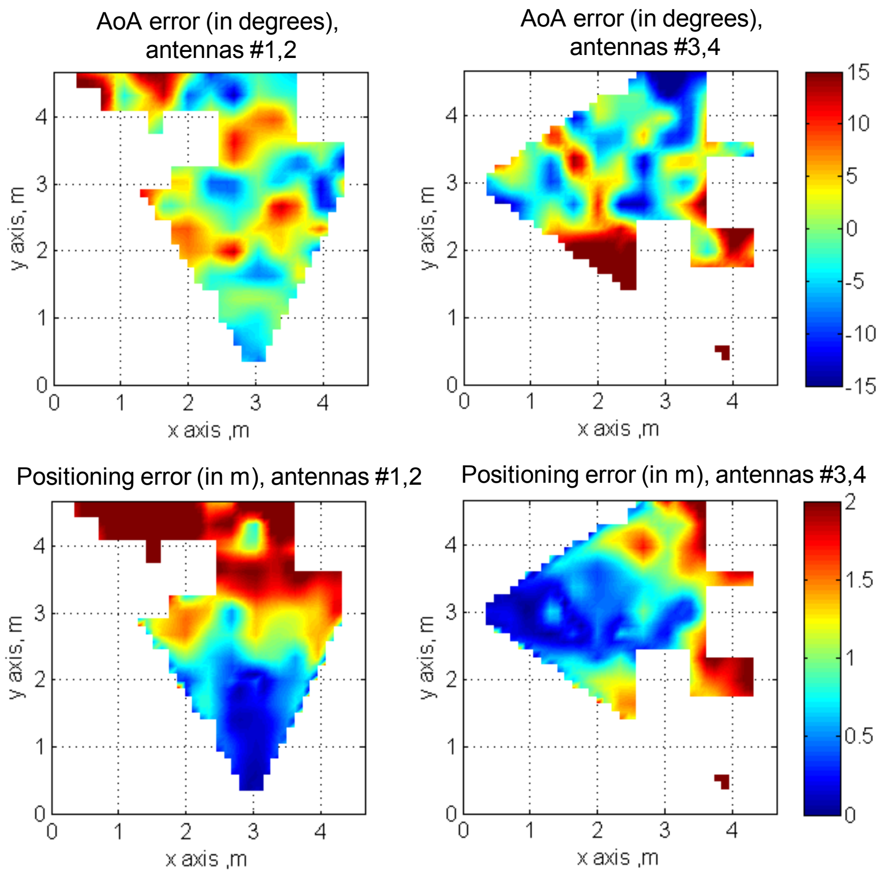

Figure 17. Upper row: AoA estimation error, in degrees. Lower row: positioning error, in m. Estimated position is calculated by by combining AoA and distance information. Errors are calculated only in the coverage area for each set of two antennas: antennas #1,2 (left column), antennas #3,4 (right column).

AoA and position estimation errors for each DF unit are depicted in Fig. 17. Results are within the same order of magnitude as the ones in Fig. 9: AoA estimation error is within the range [-15º +15º] in more than 70% of the coverage area of each DF unit, and position estimation error is below 1.2 m up to a distance of 3 m (40% error at most). In this case, AoA and position estimation can be improved by combining the information of the 2 DF units where the coverage areas overlap, depicted in Fig. 18 (a). In this region, an AoA value is calculated for each DF unit. Thus, the position can be estimated from the intersection of two lines whose AoA is known, as depicted in Fig. 14. The improvement in the position estimation can be observed in Fig. 18 (c), where the positioning error is below 0.9 m in most of the area where the coverage of the DF units overlap. Fig. 18 (c) also shows the overall coverage that includes the areas covered by a single DF unit. The positioning error in the system coverage area is 0.9 m with 90% certainty, and 0.5 m with 50% certainty.

The fact of having 4 antennas also enables positioning using conventional RSS techniques based on cost function minimization as described in [20]. Given the RSS measurements associated to each antenna, and the theoretical propagation model of each, the position is calculated as the (x',y') set that minimizes the difference between measurements and the theoretical RSS values if the transmitter (the RFID tag) were at such (x', y') position. This method has been tested in the area where the coverage areas of the 4 antennas overlap, depicted in Fig. 18 (b). Positioning error is slightly higher than the DF-based system, being 1.15 m with 90% certainty, and 0.75 m with 50% certainty. It must be remarked that the RSS information is the same for both the RSS-based AoA method presented in this contribution and the RSS-based technique of [20]. As RSS-based AoA is based on relative RSS values, it is more robust that RSS-based positioning algorithms that make use of free-space propagation models.

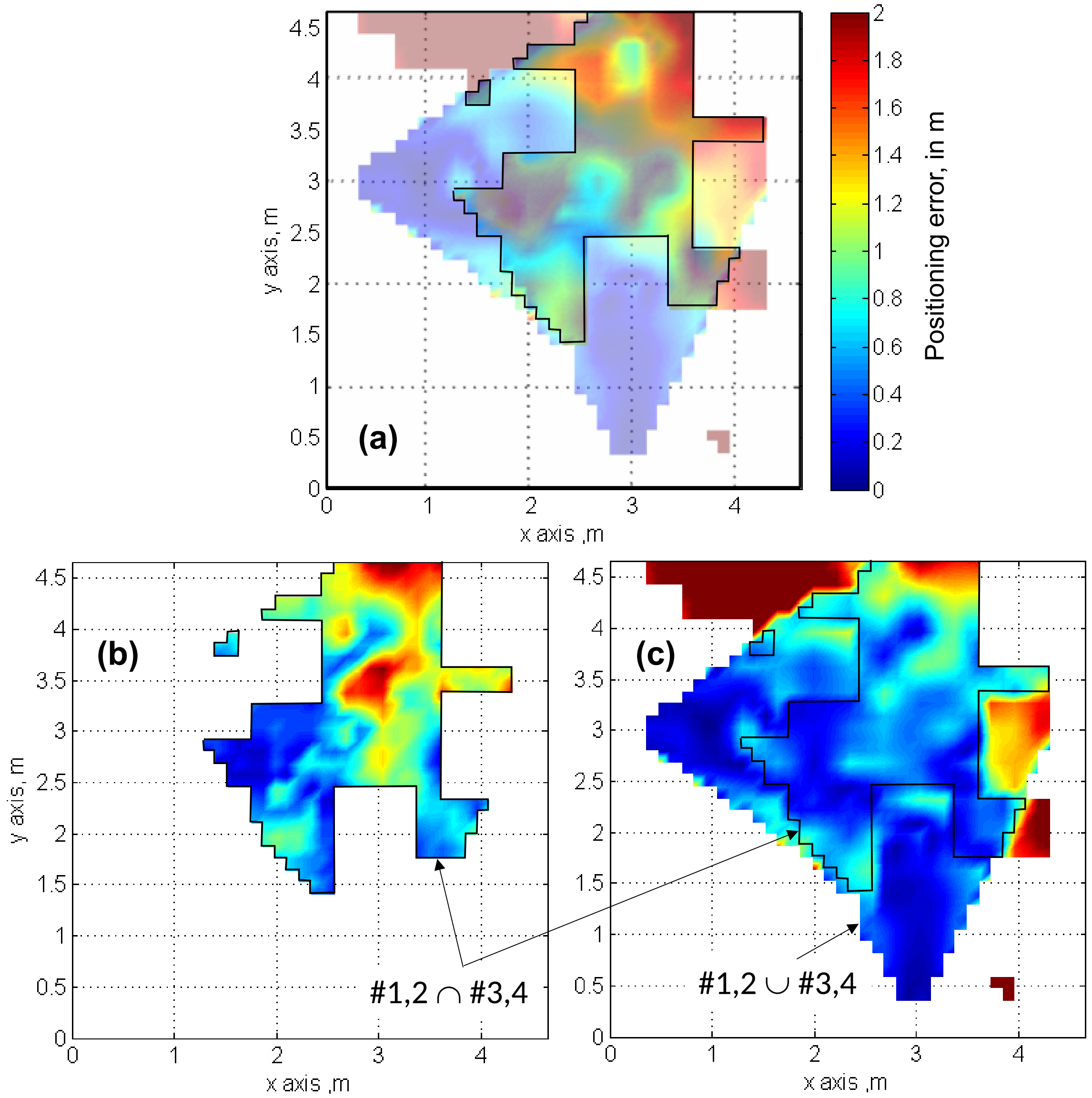

Figure 18. (a) Overlapping of coverage areas of antennas #1,2 and antennas #3,4, showing the positioning error, in m. (b) Area covered by the four antennas simultaneously. Positioning error with conventional RSS technique based on cost function minimization [20]. (c) Area covered by the four antennas simultaneously and by each set of two antennas. Positioning error with the hybrid AoA-RSS technique.

Once the accuracy of the system with 2 DF units has been tested, the capability for tracking objects and people is assessed. First, 4 RFID tags have been tagged on a cotton sweater worn by a person: one on his torso, another on his back, and two on the left and light arms respectively, so that at least one tag is seen by each DF unit regardless the orientation of the person. Some examples of paths are depicted in Fig. 19. It can be observed that the positioning error is below 1 m provided the person walks within the coverage area (underimposed in the plots of Fig. 19). Finally, 4 RFID tags have been attached to the landing gear of a drone (Phantom II model [36]). Due to the size of the laboratory, the drone flights along the y-axis (from y = 1.2 m to y = 2.8 m) for x ~ 2.5 m. A video showing real-time tracking of the flight can be watched in the following link: https://goo.gl/RHDOr8.

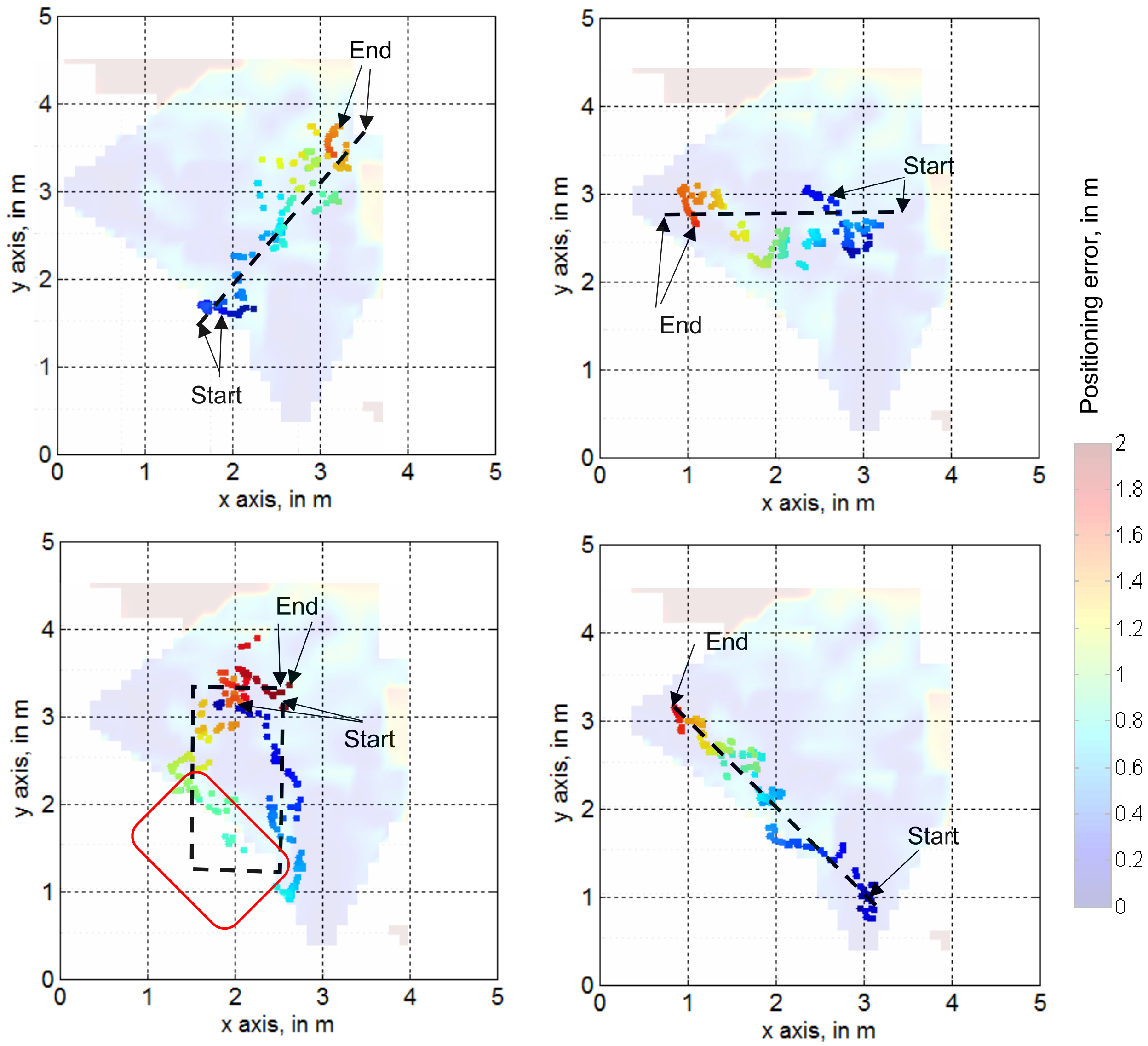

Figure 19. Examples of asset tracking for different paths. Positioning error is underimposed with light shading. The area depicted with a red circle in (c) denotes the part of the path outside the coverage area.

V. Discussion

Results presented in this contribution prove the location and tracking capabilities of a RFID-based ILS derived from a simple DF architecture, consisting on two antennas tilted one respect to the other. It has been found that AoA is less sensitive to multipath and RSS values fluctuation than range estimation, as the former depends on the ratio of RSS values (i.e. range-free), whereas the latter is based on a theoretical free space propagation model adjusted from a set of measurements.

Reference	Technology	Scenario size	Nodes, sensors (*)	Nodes / 100 m^2	Absolute error	Relative error
[25]	RFID (phase measurement)	3 x 3 m	3	33.3	0.21 m avg. 2.39º AoA error, avg.	5 % avg.
[10], scenario Fig. 10 (b).	RFID	10 x 5 m	6	12	0.83 m	7.4 % avg.
This contribution	RFID, 2 DF RSS-based AoA units.	3.5 m x 3.5 m	2	16.3	0.9 m	14.5 % (90% confidence)
[20]	ZigBee	12 x 6 m	6	8.3	0.5-0.6 m 2 m max.	3.7 % avg. 15 % max.
[24] (simulations)	RFID, RSS-based AoA.	8 m x 8 m	4	6.25	0.75 m avg. 1.8 m max.	6.7 % avg. 16 % max.
[23] (section 5.2)	Hybrid RFID (HF, UHF) and WLAN	10 x 12 m	12: 5 WSN, 4 RFID antennas, 3 HF badge readers	10	2.44 m avg.	15.6 % avg.
[15]	WLAN + fingerprinting (radiomap)	7.4 x 14 m	3	2.9	2.5 m max.	16 % (80% confidence)
This contribution	RFID, 4 antennas	3.5 m x 3.5 m	2 (2 groups of 2 ant.)	16.3	1.15 m	18.5 % (90% confidence)
[14]	WLAN, Bluetooth + fingerprinting	23 x 23 m	4 (with 62 training points)	0.75	5 m	21 % (90% confidence)
This contribution	RFID, single-DF RSS-based AoA.	2.5 x 4.5 m	1	8.9	0.45 m avg. 1.7 m max. 5.9º AoA error, avg.	18 % avg. 26 % (85% confidence)
[21]	ZigBee	5.8 x 4 m	12	51.7	2 m	28 % (90% confidence)
[18]	Bluetooth	4.5 x 5.5 m	4	16.2	3.8 m max.	28 % max.

(*) Number of nodes, sensors placed in physically different locations.

Table 1. Comparison of RSS-based ILS, sorted by position estimation error (avg.: average error, max.: maximum error).

When a single DF unit is considered (Section IV.A and IV.B), position accuracy is found to be around 18% of the range on average, with 26% error for 85% confidence level in an angular sector of 80º, and a maximum distance up to 4 m, that is 11 m^2. Accuracy is improved to 14.5 % (90% confidence level) when a second DF unit is considered, covering a diamond-shape area of 10.5 m^2 (Section IV.C)

A comparison with existing RSS-based ILS is presented in Table 1. An important parameter for a fair comparison is the number of nodes or sensing devices per surface unit (nodes/m^2). In this contribution, 1 DF unit is capable of covering a 12 m^2 area. From Table 1 it can be concluded that better accuracy is achieved for a higher density of nodes/sensors per surface unit. For a similar density of nodes (from 8 to 12 nodes per 100 m^2), the relative error ranges from 7.4% to 18%, depending on the supporting technology (RFID, Bluetooth, WLAN, ZigBee, or a mix of them). The proposed RFID-based ILS is not as good as RSS-based RFID [10] or ZigBee [20] methods, but it provides a location accuracy similar to [23],[21], and not too far from fingerprinting-based methods [14],[15]. When a second DF unit is considered, then, location accuracy is as good as in contribution [24] but at the expense of a higher density of nodes.

IV. Conclusions

Validation of a RSS-based ILS for location and tracking objects and people has been presented. The main novelty is the fact that the sensing units are based on two antennas tilted one with respect to the other, so that the patterns partially overlap. The AoA of a received signal can be calculated as the ratio between the RSS values measured on each antenna.

It has been proved that, for the same network infrastructure, RSS-based DF technique improves existing RSS-based location algorithms based on cost function minimization [20], reducing the positioning error from 18.5% to 14.5%. This is mainly due to the fact that the DF technique relies on the RSS relative levels, whereas [20] is based on a free-space propagation model which is not accurate enough in the case of indoor scenarios suffering from multipath.

The technique has been tested using RFID technology, but it could be implemented using other WSN (e.g. ZigBee). Besides, the limited coverage of passive RFID tags can be enlarged by means of active RFID tags.

Acknowledgements

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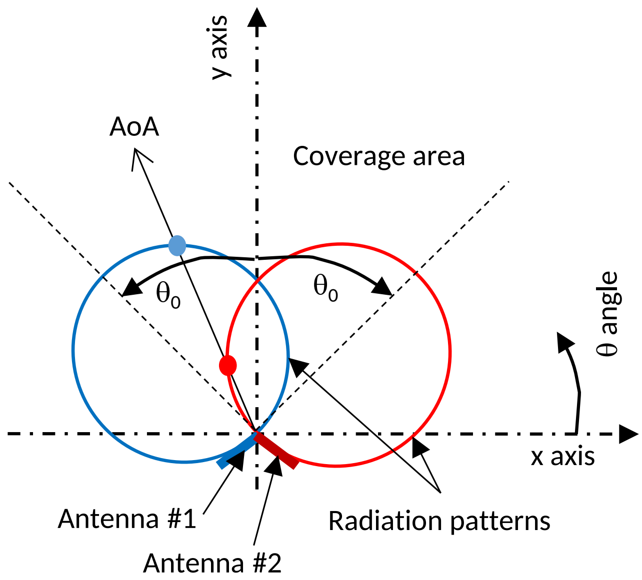


Figure 1. RSS-based AoA estimation using two antennas with partially overlapped beams. Beams are tilted θ_0 with respect to the y-axis.

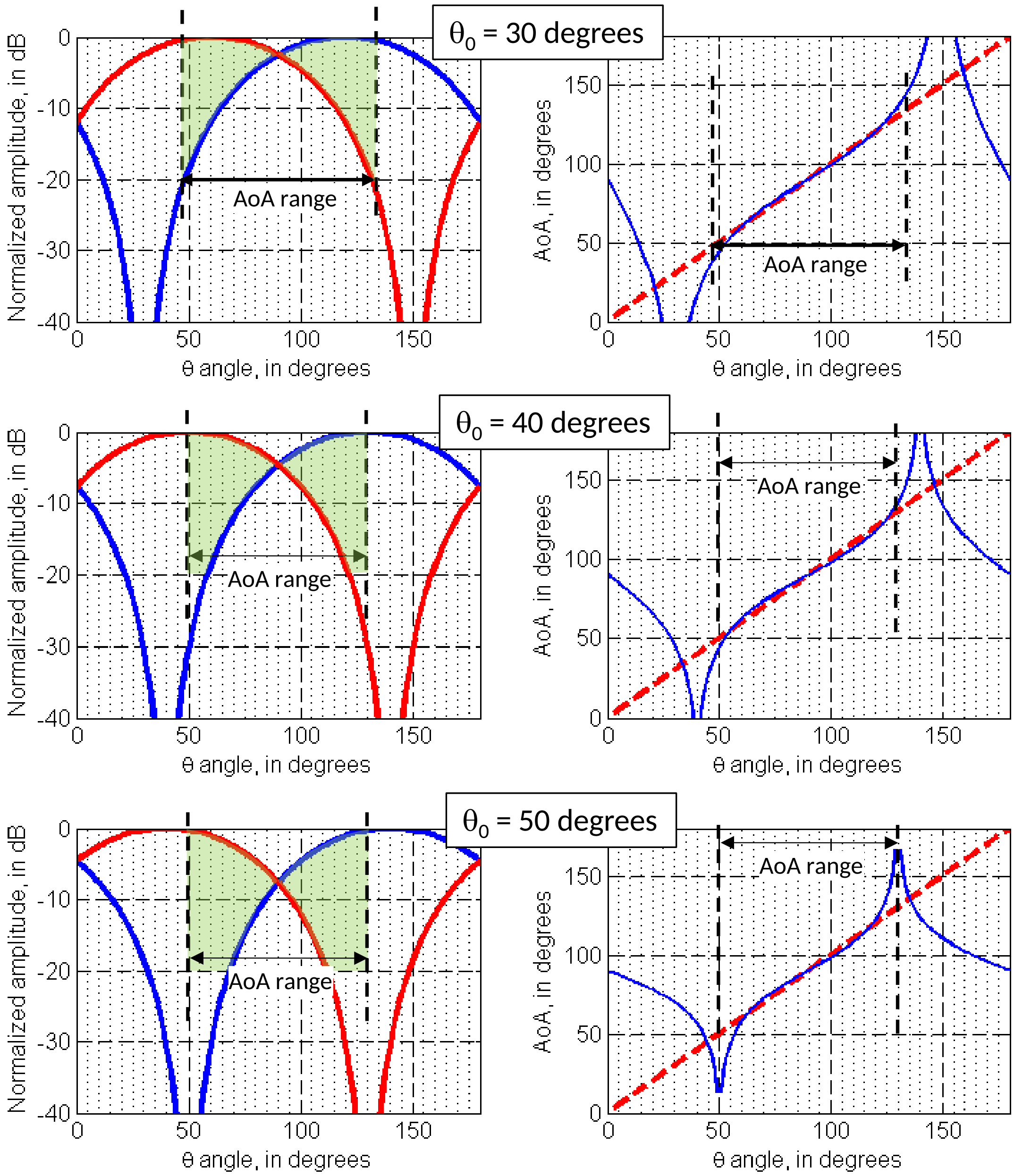


Figure 2. Left column: theoretical antenna radiation patterns (solid red and blue lines). Right column: reference AoA (dashed red line) and theoretical AoA (solid blue line). Different offset angles θ_0 are considered. Regions shadowed in green represent the regions where RSS values are considered reliable to avoid ambiguity.

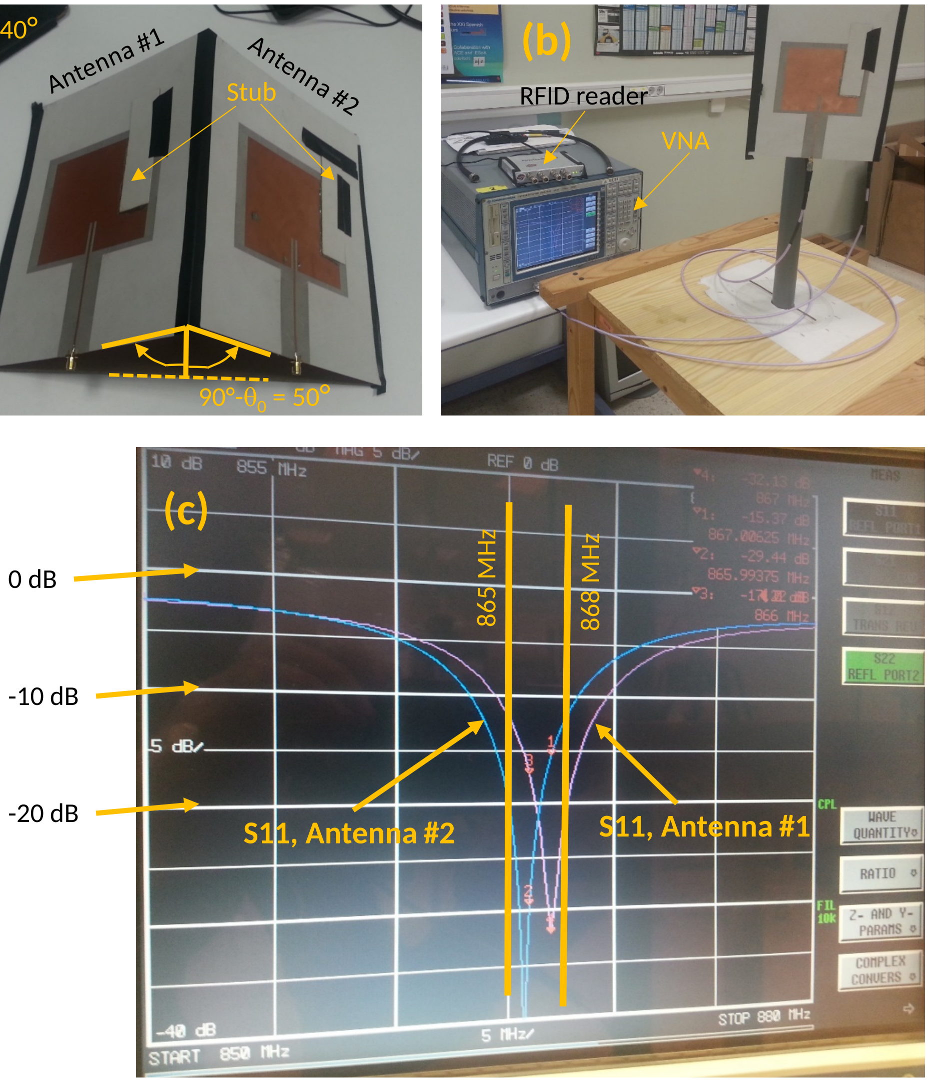


Figure 3. (a) Manufactured patch antennas, tilted 90º-θ_0 = 50º in order to achieve θ_0 = 40º beam tilting. (b) S11 parameter measurement setup. (c) S11 parameter measurement results.

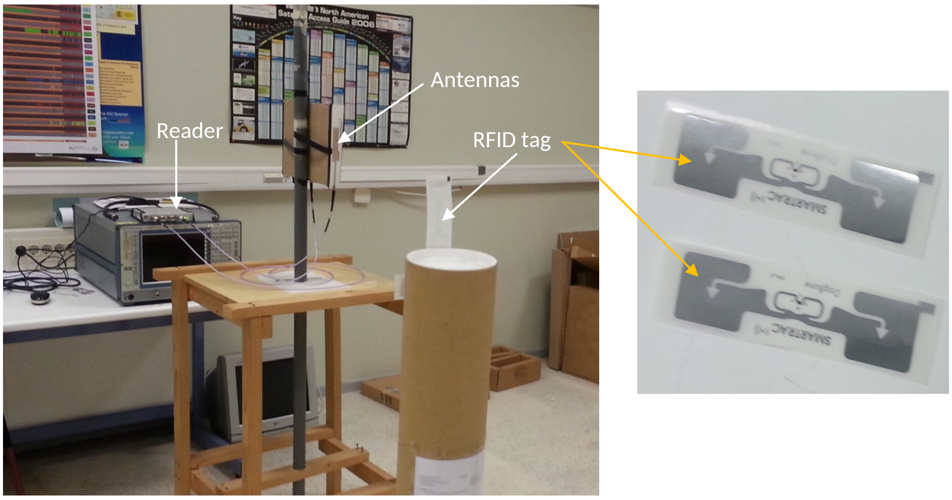


Figure 4. Measurement setup for evaluation of the RFID antenna patterns.

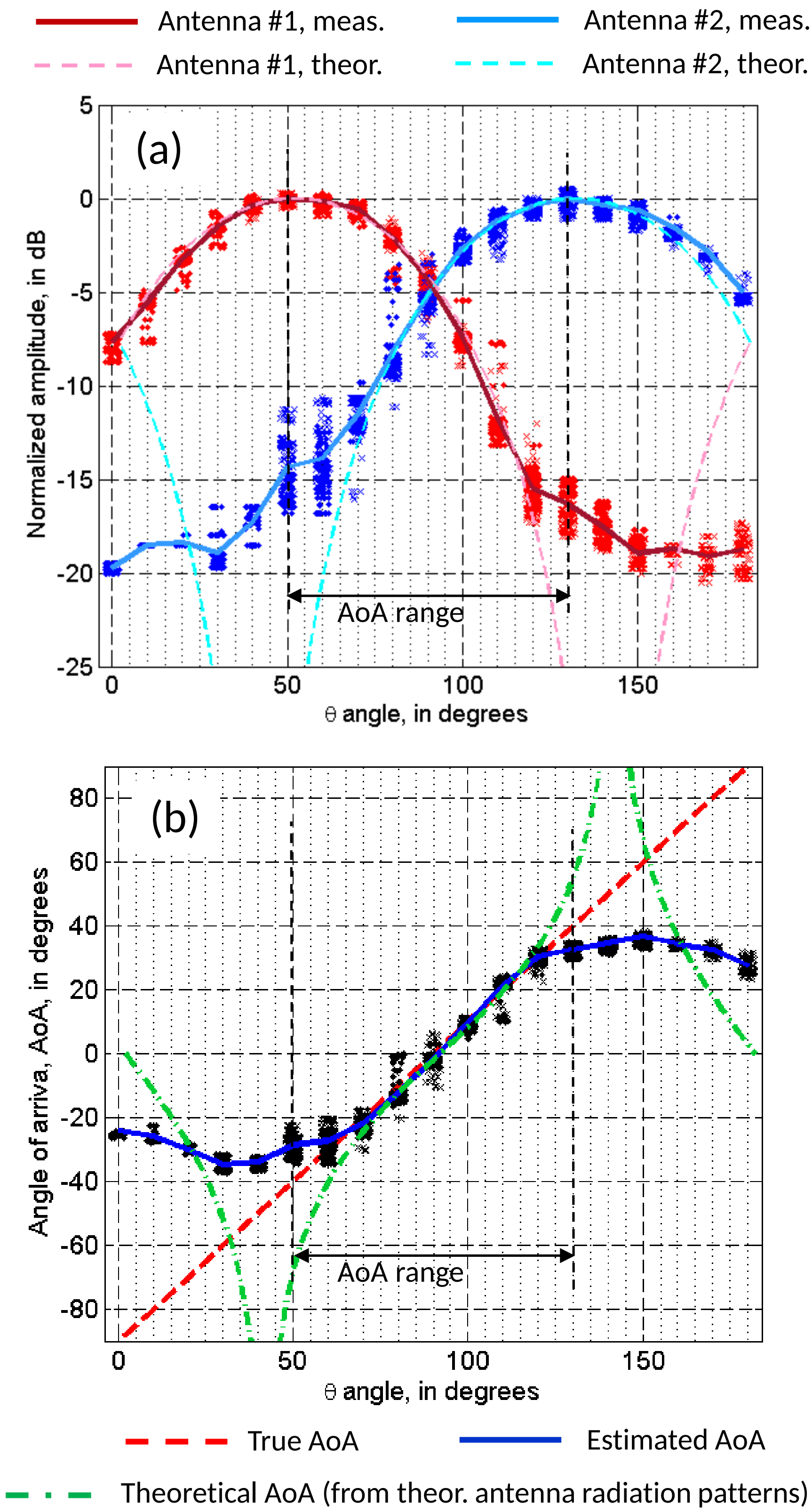


Figure 5. (a) RFID antenna patterns. Points represent the measured RSS levels on each angular position in 2 intervals of 10 s each. Comparison between theoretical and estimated radiation patters are shown. (b) Calculated AoA from the theoretical and estimated antenna patterns, and comparison with the true AoA. Points represent the AoA estimated for each RSS measurement.

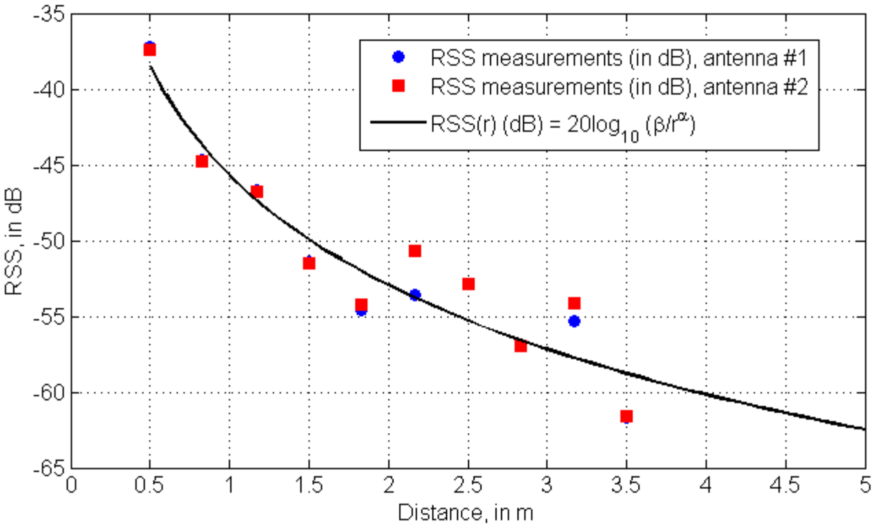


Figure 6. Measured RSS values on each port as a function of the distance from the RFID antennas. Comparison with the exponential curve β/r^{α} that minimizes the RMSE.

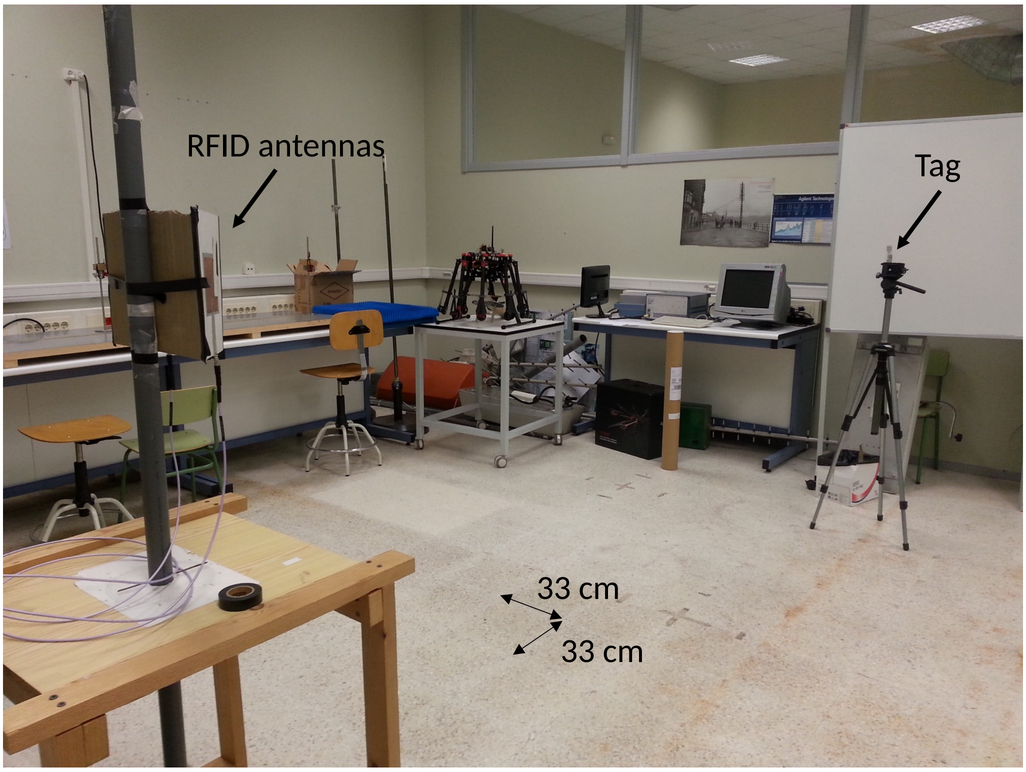


Figure 7. Measurement setup for evaluating RFID-based ILS coverage.

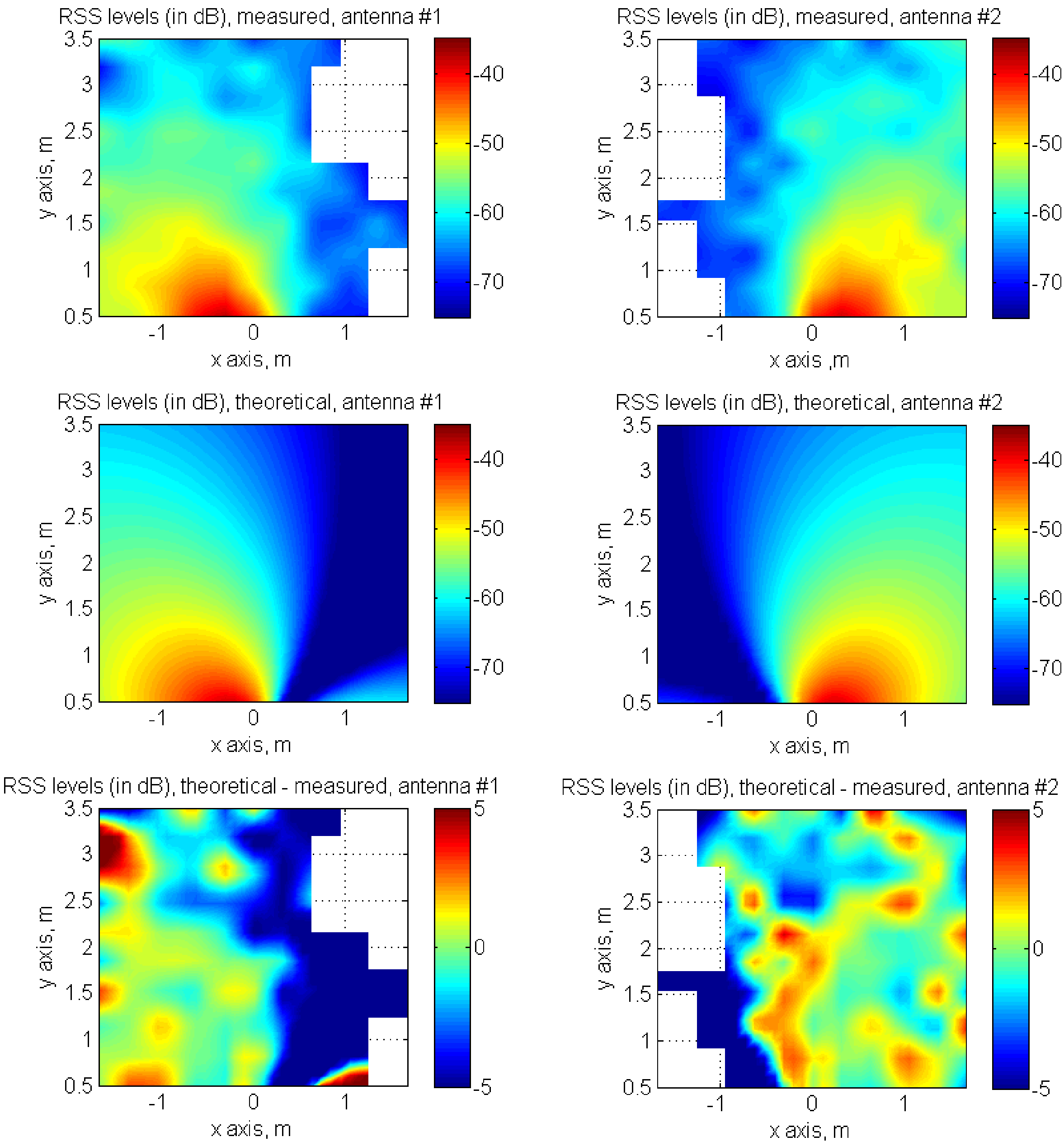


Figure 8. Upper row: measured RSS levels. Center row: theoretical RSS levels according to the theoretical radiation pattern and the free space field decay law. Lower row: difference between theoretical and measured RSS levels.

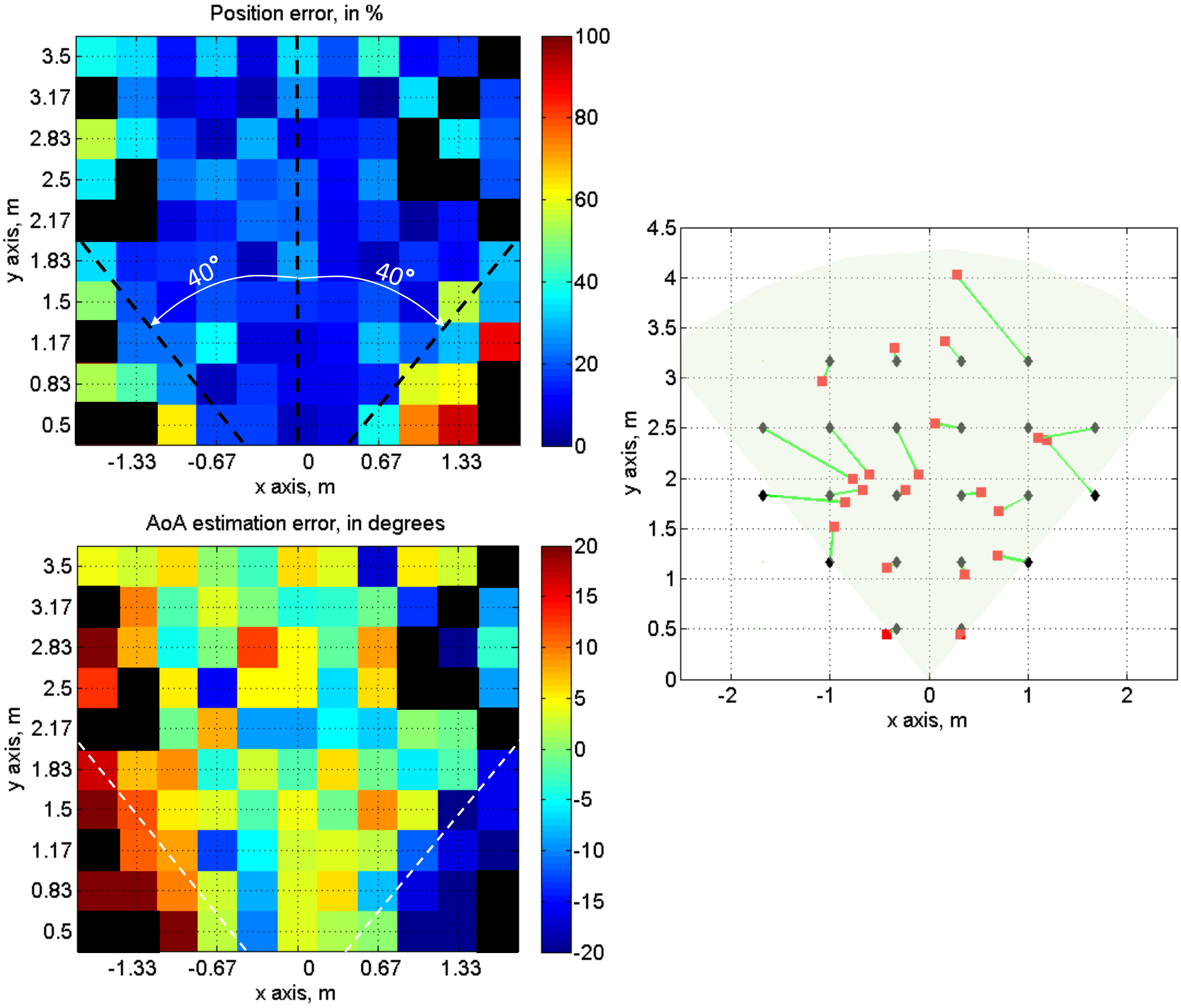


Figure 9. Position error, in %, AoA estimation error, in degrees, and error (green line) between the reference measurement positions (black diamonds) and the estimate given by the RFID-based ILS (red squares). The light shaded region represents the ILS coverage area.

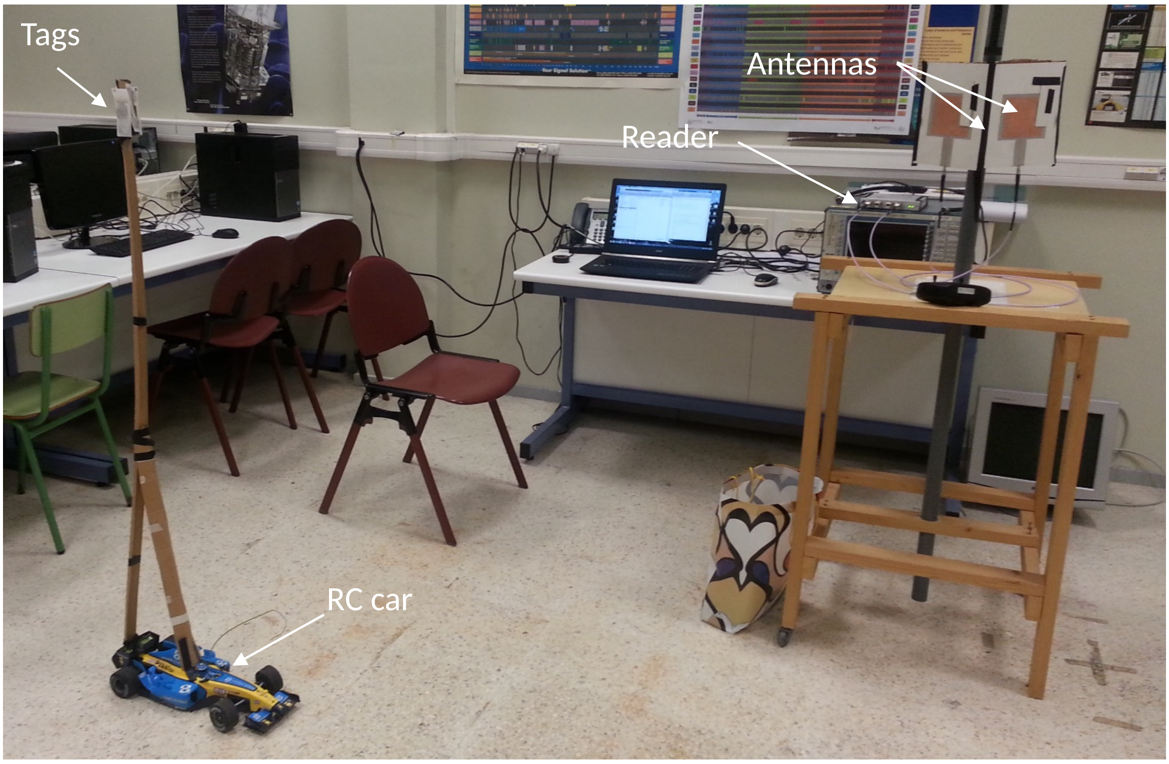


Figure 10. Picture of the scenario for testing RFID-based ILS tracking capabilities.

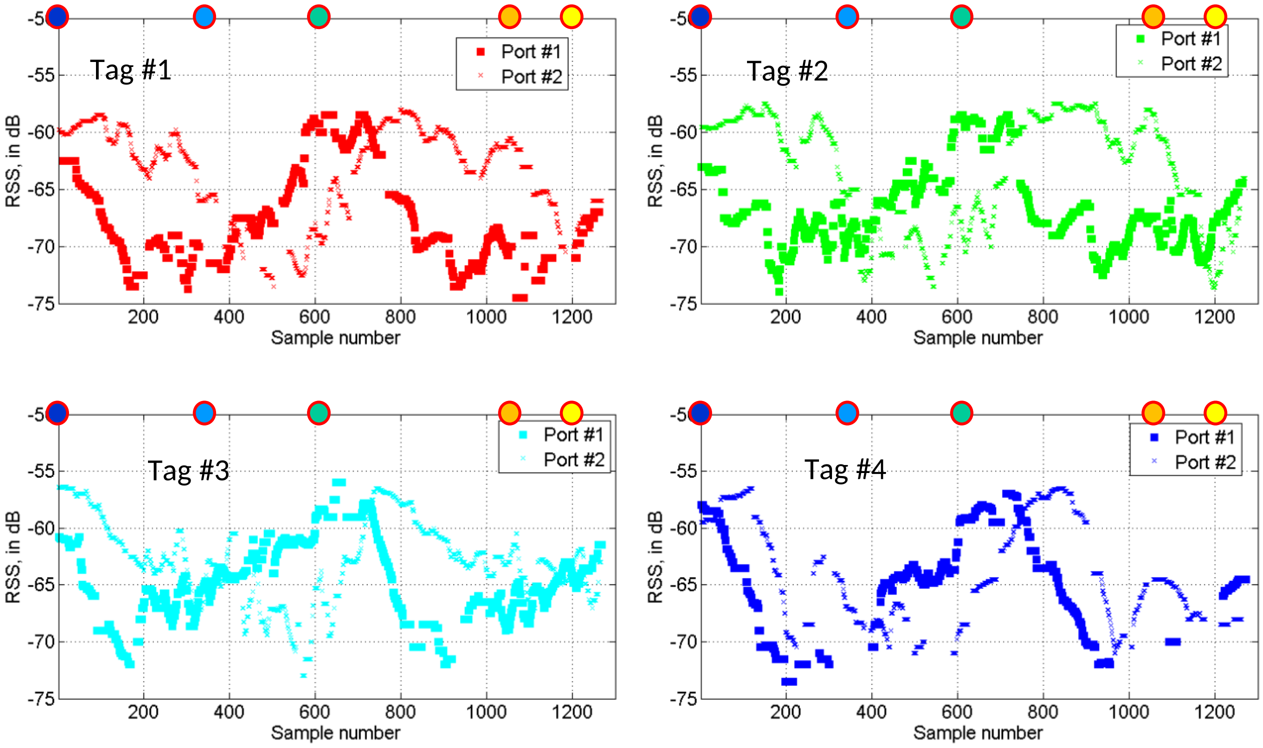


Figure 11. RSS values received at the RFID antennas (or equivalently, RFID reader ports) for each of the 4 tags placed on top of the cardboard mast attached to the remote controlled car. Red-edge circles on top of each plot indicate reference positions (their x,y representation is depicted in Fig. 12, right plot).

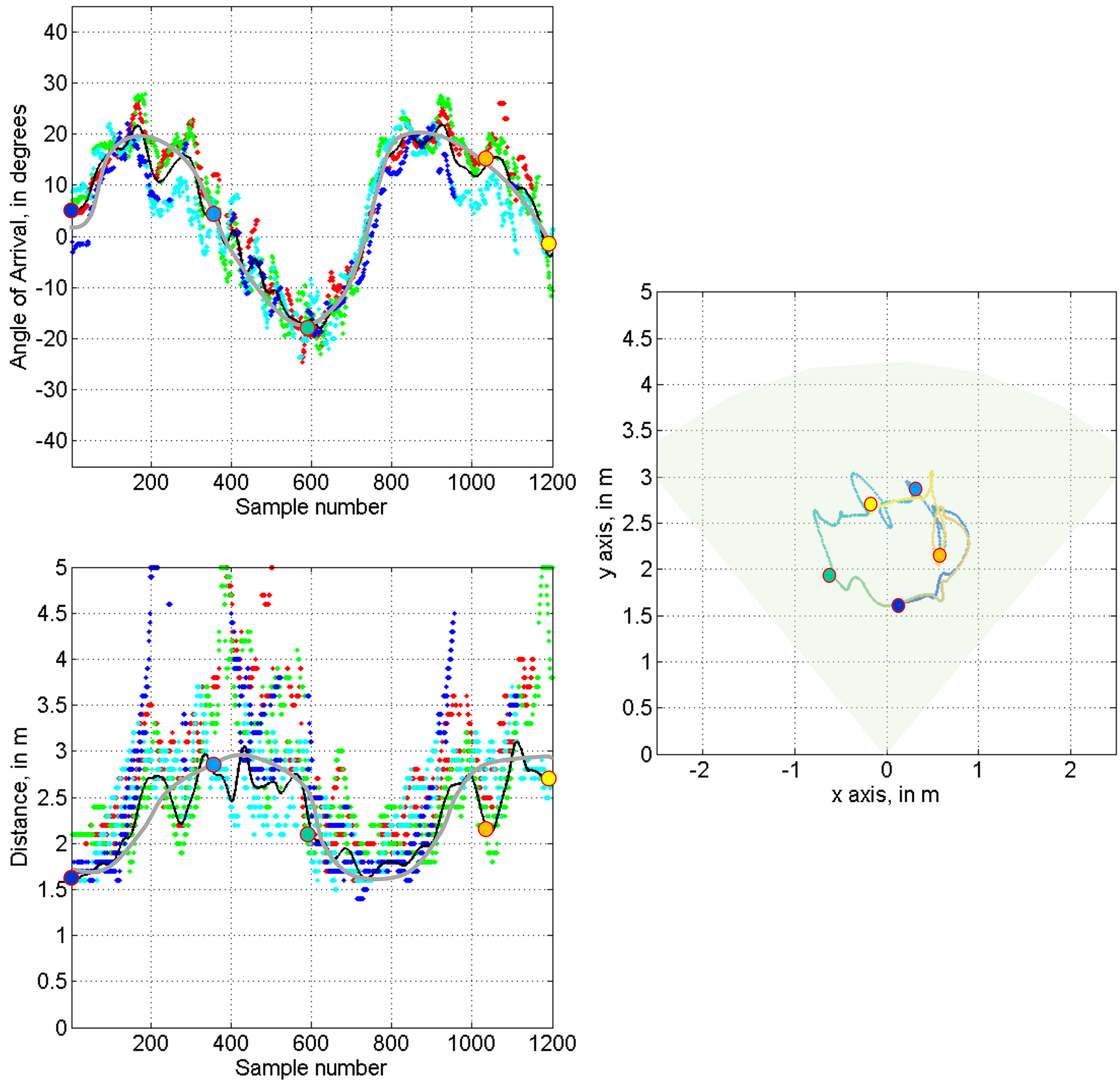


Figure 12. Left: Distance and AoA of the asset describing a circular path: estimated values for each of the 4 tags (different colors), average (black lines) and theoretical (gray line). Right: Estimated position in the XY plane (light green shaded region represents the ILS coverage area). Red-edge circles denote reference positions.

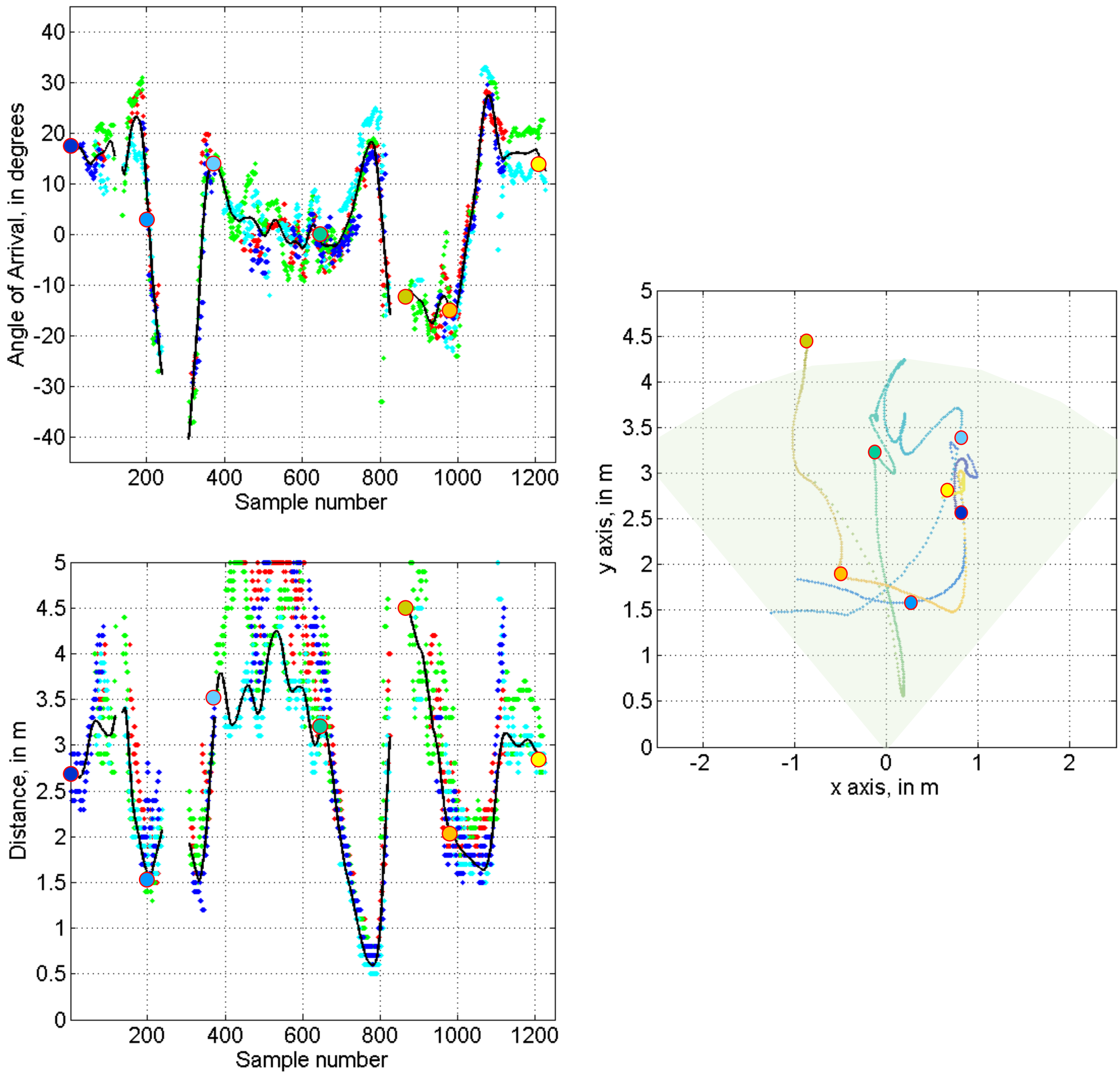


Figure 13. Left: Distance and AoA of the asset describing an arbitrary path: estimated values for each of the 4 tags (different colors) and average (black lines). Right: estimated position in the XY plane (light green shaded region represents the ILS coverage area). Red-edge circles denote reference positions.

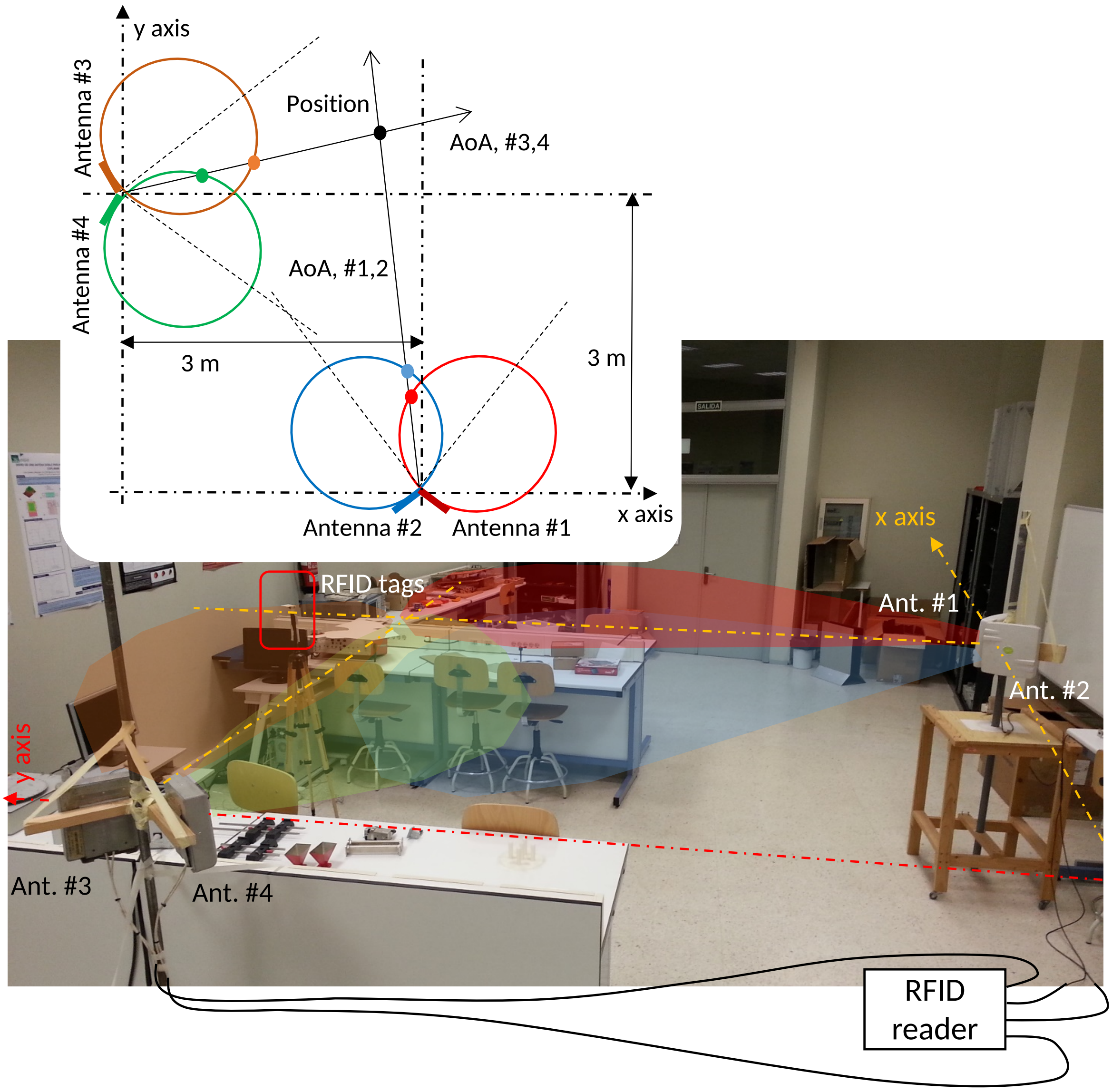


Figure 14. RSS-based AoA estimation using 2 DF sets (2 antennas each) with partially overlapped beams. Beams are tilted θ_0 with respect to the y-axis. Picture of the setup where the RSS-based AoA system is deployed.

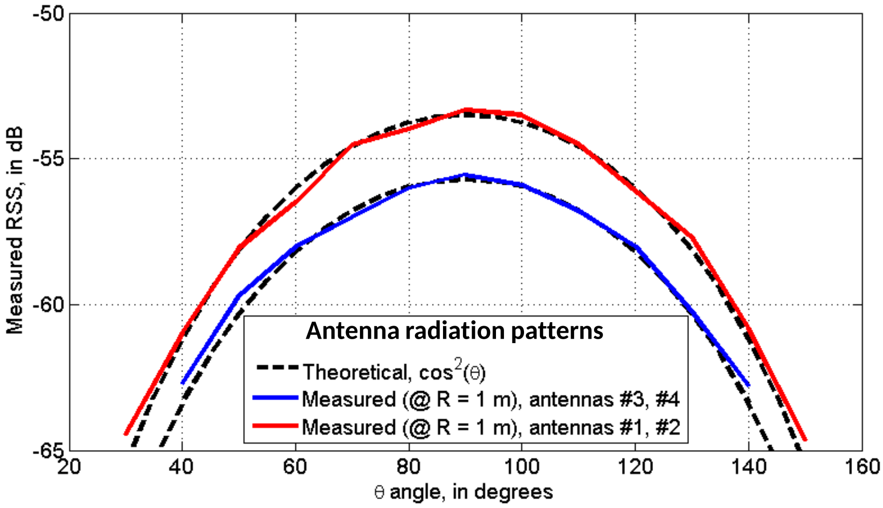


Figure 15. Comparison between the theoretical and measured patterns of the commercial RFID antennas used in the setup shown in Fig. 14.

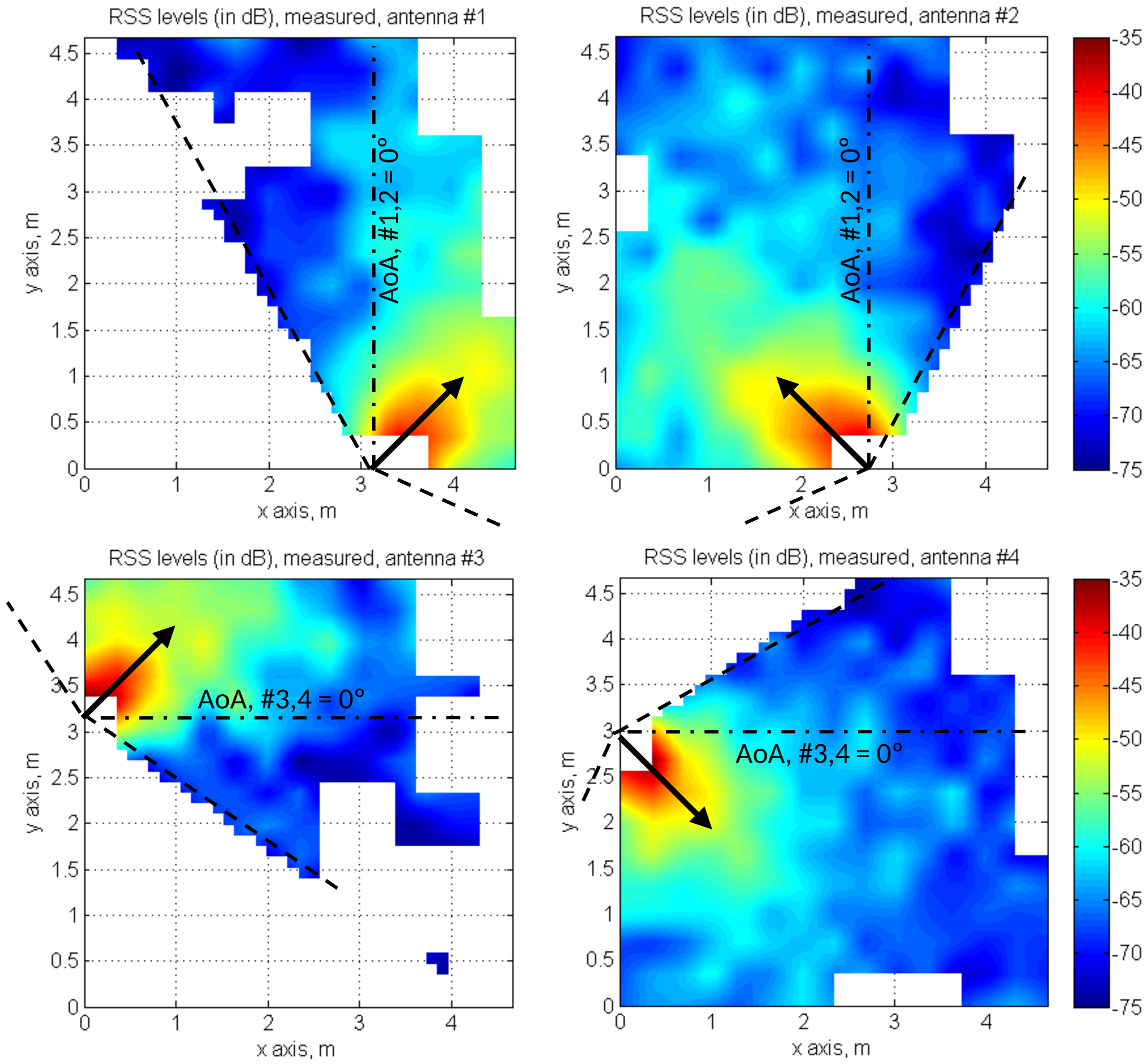


Figure 16. Measured RSS levels for each of the four RFID antennas considered in the setup. Arrows represent the vector normal to the antenna aperture.

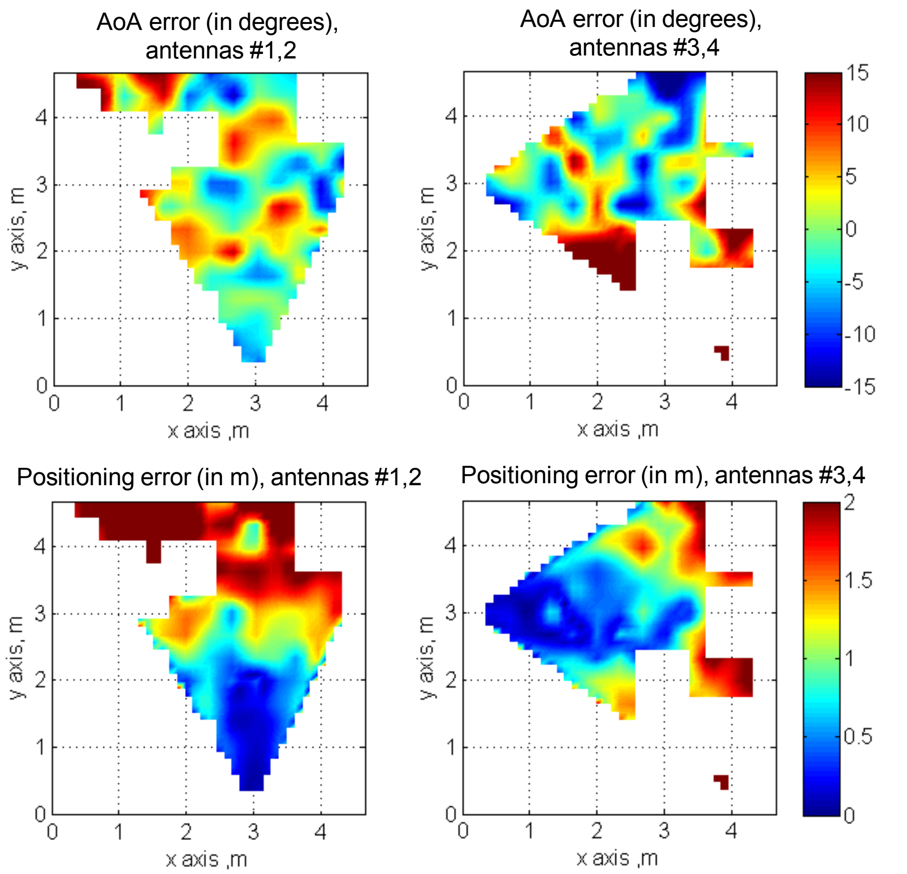


Figure 17. Upper row: AoA estimation error, in degrees. Lower row: positioning error, in m. Estimated position is calculated by by combining AoA and distance information. Errors are calculated only in the coverage area for each set of two antennas: antennas #1,2 (left column), antennas #3,4 (right column).

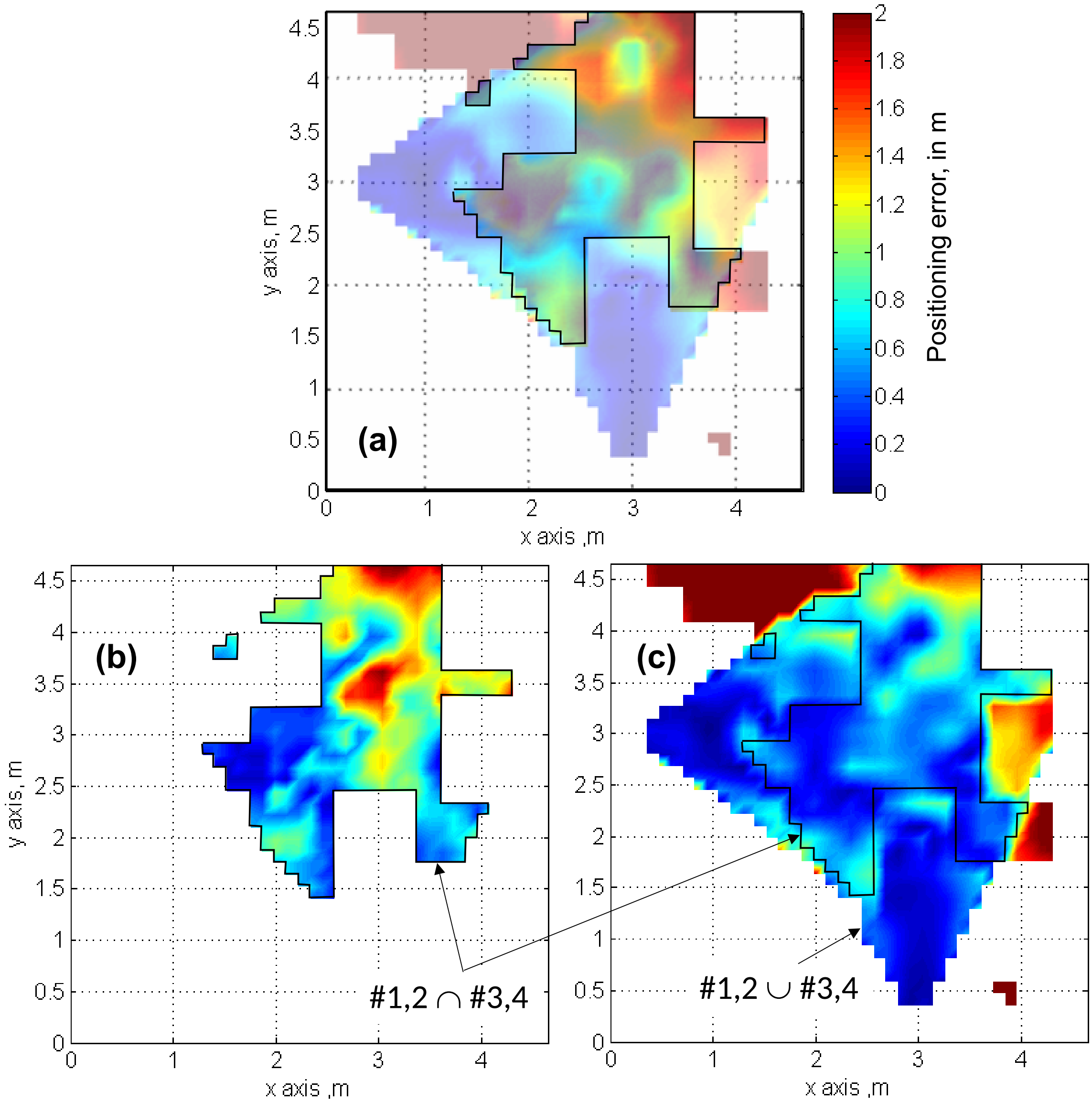


Figure 18. (a) Overlapping of coverage areas of antennas #1,2 and antennas #3,4, showing the positioning error, in m. (b) Area covered by the four antennas simultaneously. Positioning error with conventional RSS technique based on cost function minimization [20]. (c) Area covered by the four antennas simultaneously and by each set of two antennas. Positioning error with the hybrid AoA-RSS technique.

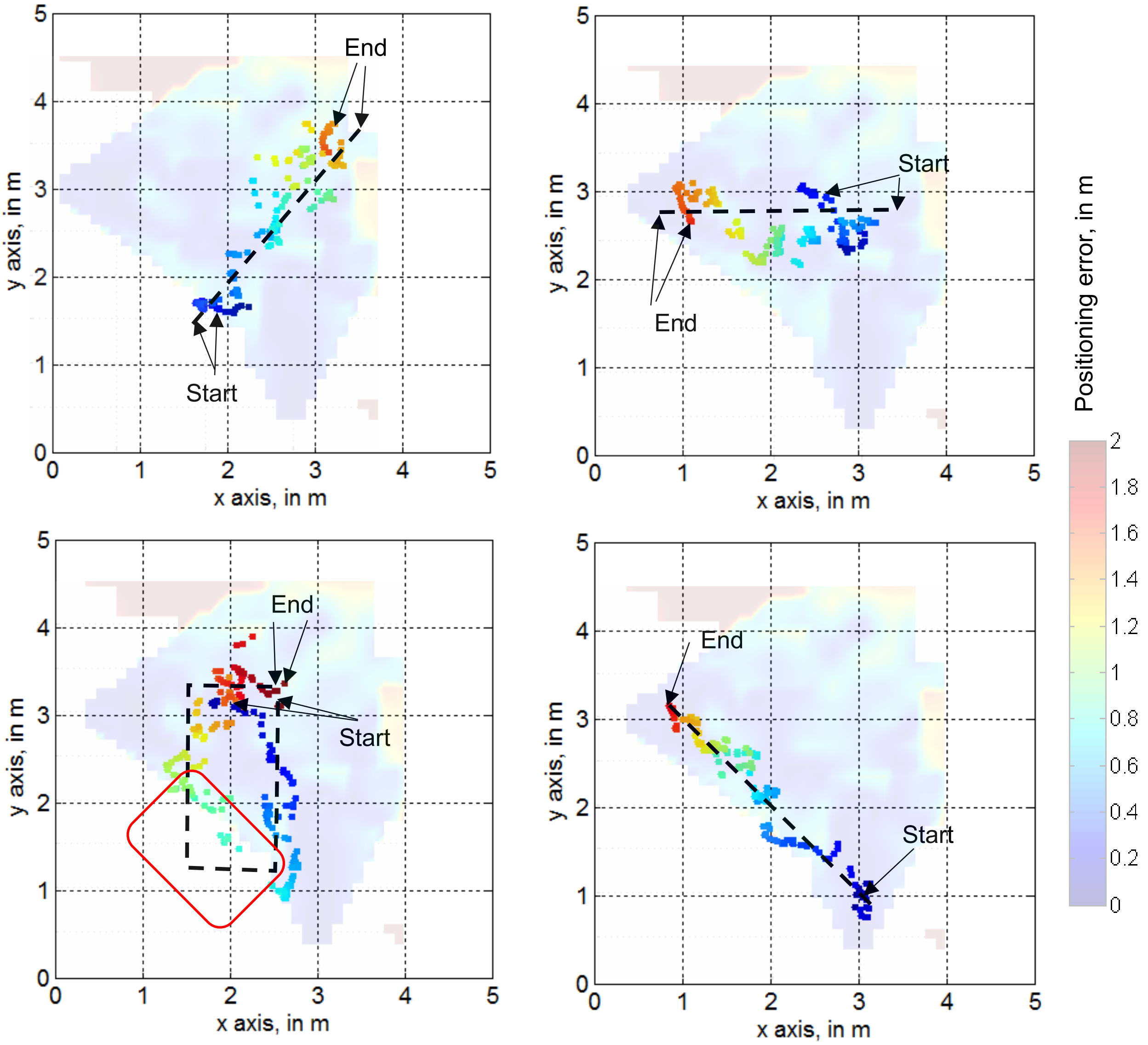


Figure 19. Examples of asset tracking for different paths. Positioning error is underimposed with light shading. The area depicted with a red circle in (c) denotes the part of the path outside the coverage area.

Reference	Technology	Scenario size	Nodes, sensors (*)	Nodes / 100 m²	Absolute error	Relative error
[25]	RFID (phase measurement)	3 x 3 m	3	33.3	0.21 m avg. 2.39º AoA error, avg.	5 % avg.
[10], scenario Fig. 10 (b).	RFID	10 x 5 m	6	12	0.83 m	7.4 % avg.
This contribution	RFID, 2 DF RSS-based AoA units.	3.5 m x 3.5 m	2	16.3	0.9 m	14.5 % (90% confidence)
[20]	ZigBee	12 x 6 m	6	8.3	0.5-0.6 m 2 m max.	3.7 % avg. 15 % max.
[24] (simulations)	RFID, RSS-based AoA.	8 m x 8 m	4	6.25	0.75 m avg. 1.8 m max.	6.7 % avg. 16 % max.
[23] (section 5.2)	Hybrid RFID (HF, UHF) and WLAN	10 x 12 m	12: 5 WSN, 4 RFID antennas, 3 HF badge readers	10	2.44 m avg.	15.6 % avg.
[15]	WLAN + fingerprinting (radiomap)	7.4 x 14 m	3	2.9	2.5 m max.	16 % (80% confidence)
This contribution	RFID, 4 antennas	3.5 m x 3.5 m	2 (2 groups of 2 ant.)	16.3	1.15 m	18.5 % (90% confidence)
[14]	WLAN, Bluetooth + fingerprinting	23 x 23 m	4 (with 62 training points)	0.75	5 m	21 % (90% confidence)
This contribution	RFID, single-DF RSS-based AoA.	2.5 x 4.5 m	1	8.9	0.45 m avg. 1.7 m max. 5.9º AoA error, avg.	18 % avg. 26 % (85% confidence)
[21]	ZigBee	5.8 x 4 m	12	51.7	2 m	28 % (90% confidence)
[18]	Bluetooth	4.5 x 5.5 m	4	16.2	3.8 m max.	28 % max.

(*) Number of nodes, sensors placed in physically different locations.

Table 1. Comparison of RSS-based ILS, sorted by position estimation error (avg.: average error, max.: maximum error).

A Received Signal Strength RFID-based Indoor Location System

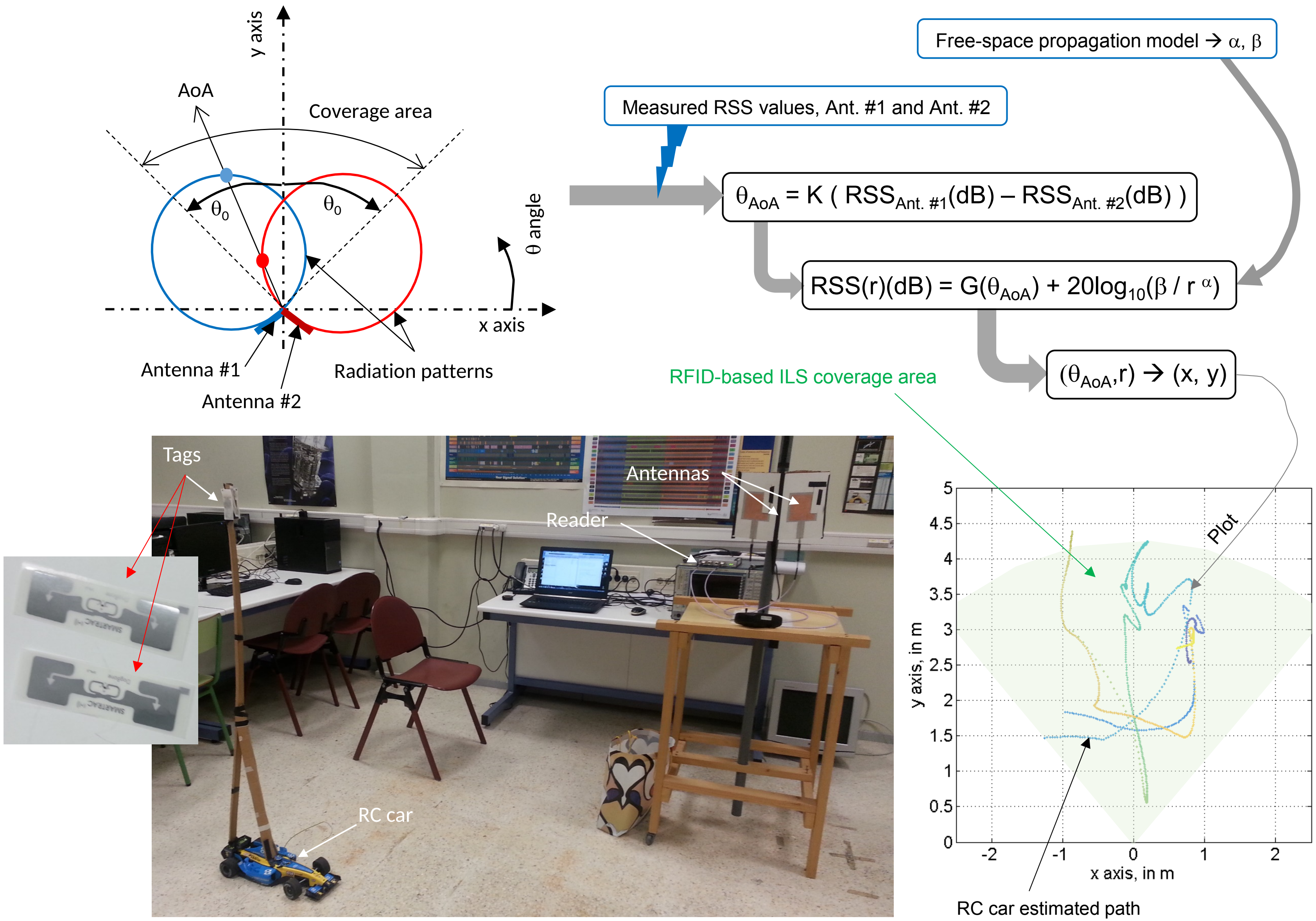
Abstract

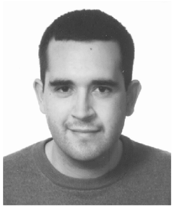
A RFID-based Indoor Location System (ILS) that makes use of Received Signal Strength (RSS) information is presented. The proposed system is derived from a simple Direction Finder (DF) consisting on two antennas tilted one to respect to the other, so that their radiation patterns partially overlap. RFID tags are attached to the person or asset to be tracked. The ratio between RSS values received on each antenna is used to estimate the Angle of Arrival (AoA) of the electromagnetic signals backscattered by RFID tags. Once the AoA is estimated, the absolute RSS values are compared against a free-space propagation model to obtain an estimate of the range or distance. Then, given the AoA and the range, the position of the RFID tags can be obtained. The proposed system, based on a single DF unit, is tested in three real indoor scenarios: the first example is devoted to evaluate the agreement between the theoretical and experimental characterization of the DF system, in terms of the radiation patterns of its antennas as well as the position estimation accuracy within the coverage area, analyzing the robustness of AoA against multipath. Second example shows simple cases of asset tracking. And the third one presents an enhanced system comprising two sets of antennas that improves positioning accuracy. A comparison with state-of-the-art ILS is also presented, in order to put the proposed RFID-based ILS into context.

Keywords:

Wireless Sensor Networks (WSN)
Indoor Location Systems (ILS)
Angle of Arrival (AoA)
Received Signal Strength (RSS)
Radio Frequency Identification (RFID)
Radiodetermination

Graphical abstract:





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Highlights:

In this contribution, the highlights are:

a) Development and testing of a simple, low-cost ILS system based on a simple Direction Finder (DF) that uses relative RSS levels for AoA estimation, and the absolute RSS levels for range estimation.

b) Capability of providing positioning information with a single sensing unit, with a relative error of 26 % (85 % confidence level). Accuracy can be improved by adding more sensing units. Accuracy is improved by adding a second sensing unit: 14.5 % relative error (90% confidence level).

c) Use of multiple RFID tags attached to the asset or person to be tracked to enhance detection, reducing RSS fluctuations due to multipath.