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# PERFORMANCE EVALUATION OF ACTIVE RFID LOCATION SYSTEMS BASED ON RF POWER MEASURES

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## ABSTRACT

In this paper we provide a general and repeatable experimental evaluation campaign of location algorithms based on RSSI measures for active RFID systems. We start from the well-known LANDMARC approach and conduct a thorough investigation aiming at evaluating its actual potentials and limitations under different environmental conditions. For the sake of completeness, we compare its behavior with the one of a further technique, named RSSI Spatial Interpolation (RSI), which is taken as a representative of a wider family of solutions which also LANDMARC belongs to. Experimental results show that by even introducing some modifications, still both algorithms get poor performance in indoor scenarios; location errors lower than $2m$ are only attainable in limited size outdoor environments in 90% of the experiments.

## I. INTRODUCTION

Although the issue of the determination of object locations in limited size areas, such as indoor environments or small outdoor spaces, has gained large attention in the last few years, a definitive solution is still lacking. Classical location technologies, like Global Positioning System (GPS), are either unfeasible, in indoor scenarios, or too expensive. Ultrasound [1] and RF solutions (such as WLAN [2, 3], Bluetooth [4] and Radio Frequency Identification (RFID) [5]) are well-known examples of technologies proposed to face the objects' location issue. In this paper our attention focuses on the latter solutions. One of the most common location metrics exploited by RF location approaches is the power of the RF signals exchanged among devices and antennas for their operation, commonly referred to as Received Signal Strength Indication (RSSI). RFID systems are currently experiencing a fast growing interest in many application fields, like logistics, health care, pharmacy [6]. In future scenarios, RFID technology will become a key player in the view of deploying always more pervasive and ubiquitous communications; this also attracting a higher attention to the deployment of RFID-based applications, such as location sensing.

This work aims at assessing the performance of RFID location systems based on RF power, under *repeatable and general* experimental configurations. A careful and systematic assessment study is still lacking even for those techniques, such as LANDMARC [5] for example, which are commonly referred to in the literature. The matter seems not to be the demonstration that mechanisms like the cited one correctly work; this is out of doubt. Rather, we aim at evaluating how careful the adoption of active RFID systems for location determination has to be considered, since the achievable accuracy can result scarce in comparison with the deployment and operation efforts actually required.

The present paper in structured as follows. In Section II. we provide a general description of algorithms using RSSI measures for location determination, and derive from them the RSSI Space Interpolation (RSI) approach for location through active RFID systems. In Section III. we describe the experimental setup considered to assess location performance of LANDMARC and RSI algorithms, along with the project parameters we focused on. Further, we show and discuss achievable results in both indoor and outdoor scenarios. Finally, in Section IV., we draw conclusions of this work.

## II. PROBLEM FORMULATION AND ALGORITHMS DESCRIPTION

In this section we first provide a general formulation to describe the family of deterministic location algorithms based on measures collected at fixed, known locations. Subsequently, we are going to describe two location algorithms we focus our attention on, i.e. LANDMARC [5] and RSSI Spatial Interpolation (RSI), a novel approach we are proposing. For the sake of simplicity, although we could refer to different location metrics as well, we are going to specialize the terms in the following to RSSI measures.

Let us consider $n$ receiving antennas and $N$ reference points spread over the area of interest at coordinates $(x_i, y_i)$, with $X = \{x_i\}_{i=1,\dots,N}$ and $Y = \{y_i\}_{i=1,\dots,N}$. We can build up vectors with the RSSI measures collected by the $n$ antennas, respectively belonging to each reference point $\Theta_i = \{\theta_{ip}\}_{p=1,\dots,n}, i = 1,\dots,N$ and to the target object we want to locate in the observed area $S = \{s_p\}_{p=1,\dots,n}$. Thus, a *distance* can be defined in the RSSI space, between the measures pertaining to the target object and to each reference point, $e_i = d(S, \Theta_i)$, $E = \{e_i\}_{i=1,\dots,N}$. The vector $E$ of distances is used to apply the *k-nearest neighbors* algorithm, that is to select the $k$ reference points $i_1,\dots,i_k$ with the minimum RSSI distance $d$, namely $e_{i_1},\dots,e_{i_k}$, from the target object to be located. Differently, in order to build a denser two-dimensional map for the RSSI distances, we suggest to interpolate the vector of distances $E$, defined at the spatial coordinates $X$ and $Y$ of the reference points, over denser spatial sets $\tilde{X} = \{\tilde{x_i}\}_{i=1,\dots,\tilde{N}}$ and $\tilde{Y} = \{\tilde{y_i}\}_{i=1,\dots,\tilde{N}}$, with $X \subseteq \tilde{X}, Y \subseteq \tilde{Y}$, thus obtaining the interpolated vector of distances $\tilde{E} = \mathscr{I}(X, Y, E, \tilde{X}, \tilde{Y})$. Similarly to the computation of the *k-nearest-neighbors* of vector $E$, we evaluate the local minima of the two-dimensional function $\tilde{E} = \tilde{E}(\tilde{x}, \tilde{y})$, $\tilde{x} \in \tilde{X}$, $\tilde{y} \in \tilde{Y}$ and take the lowest $k$ among them $\tilde{e}_{i_1},\dots,\tilde{e}_{i_k}$. In both cases, the unknown position $(\tilde{x}_{es}, \tilde{y}_{es})$ is estimated as a suitable linear combina-

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tion of the coordinates of the $k$ selected reference points. That is, the position of the object to be located is computed as $\tilde{x}_{es} = \sum_{m=1}^{k} \tilde{x}_{i_m} w(\tilde{e}_{i_m})$, $\tilde{y}_{es} = \sum_{m=1}^{k} \tilde{y}_{i_m} w(\tilde{e}_{i_m})$. In such expression, weights $w$ are introduced as functions of the RSSI distances $\tilde{e}_{i_m}$ between the target tag and the selected reference points.

The description reported above is both *general* and *technology independent*. As a consequence: (i) to define actual location algorithms we must specify the parameters we left free, e.g. the distance $d$ in the space of RSSI measures and the definition of the the weights $w$; (ii) such description doesn't refer to a specific radio-frequency technology and could fit for WLAN, Bluetooth or RFID systems as well.

In Table 1 we show how two popular indoor location algorithms, namely RADAR [2] and LANDMARC, can be seen as particular implementations of this description. RADAR is a significant research work addressing the issue of location through RSSI measures, developed with reference to WLAN technology. RADAR formulation asks for an operator, equipped with a WLAN device, to perform an *off-line* detection phase, which consists in moving over the selected reference points and picking the RSSI values of frames exchanged with WLAN Access Points (AP). Subsequently, *real-time* location estimates can be computed for WLAN users in the area of interest, by calculating the nearest reference points and averaging among them, according to parameters detailed in Table 1. LANDMARC, which exploits active RFID technology, has a similar behavior, except for the presence of active RFID tags at the reference points. Such *reference tags* allow to eliminate the off-line phase, since RSSI measures are continuously updated following each interrogation from RFID readers.

For the sake of completeness, in this paper, we also design and analyze a new proposal, named *RSSI Spatial Interpolation* (RSI), which aims at assessing if the spatial interpolation of the collected RSSI measures over denser reference grids can lead to better location performance, when compared to approaches based on sparser spatial sets of information. As reported in Table 1, RSI utilizes Spline functions to spatially interpolate the distances $e_i$, $i = 1, \ldots, N$, relevant to tags put at each reference point. In such a way we build up spatially-enhanced distance maps, that increase the number of candidate positions for the reference points. More specifically, we thicken the spatial grids up to $1cm$ distances between two adjacent interpolated points. We admit two possible definitions for the weights $w$ used to average the positions of the selected reference points, namely the center of mass, proposed in RADAR, and the expression proposed in LANDMARC (see Table 1), which favors reference points with a lower RSSI-distance from the object to be located. Through the study of RSI behavior we propose to evaluate if the use of both canonical interpolation strategies and different weighting functions help to improve location accuracy, with respect to former solutions.

| *Algorithm* | *RF technology* | $d$ | $\mathscr{I}$ | $w$ |
|---|---|---|---|---|
| RADAR | WLAN | $\sum_{ith\,AP}(.)^2$ | Identity | $1/k$ |
| LANDMARC | active RFID | $\sqrt{\sum_{ith\,Ant}(.)^2}$ | Identity | $\frac{1/\tilde{e}^2_{i_m}}{\sum_{m=1}^{k} \tilde{e}^2_{i_m}}$ |
| RSI | active RFID | $\sqrt{\sum_{ith\,Ant}(.)^2}$ | Spline | $\frac{1/\tilde{e}^2_{i_m}}{\sum_{m=1}^{k} \tilde{e}^2_{i_m}}$ (default) or $1/k$ |

Table 1: Comparison between RF location algorithms

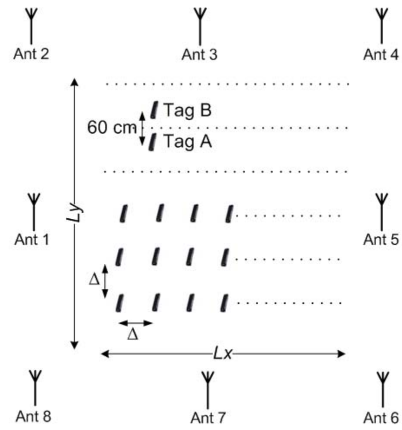


Figure 1: Experimental setup with active RFID tags placed as reference points in a rectangular grid and eight RFID antennas

## III. EXPERIMENTAL SETUP AND LOCATION RESULTS

In this section we describe the experimental campaign conducted to assess the performance of the cited LANDMARC and RSI solutions. Our objective is to build a more general and reproducible experimental setup than that described in [5], and to quantify the impact of the different parameters affecting the location procedures. We provide improved test configurations by considering more regular reference scenarios and up-to-date RFID technologies, capable of collecting direct RSSI measures. Thus, we can both achieve more in-depth analysis of LANDMARC performance and propose a general comparison with the RSI approach. More specifically, we considered both indoor and outdoor scenarios deployed in the configuration shown in Fig. 1. It consists of 8 RFID antennas placed around a rectangular grid of active RFID tags, evenly spread over the floor of a large room (indoor case) or of a square (outdoor case) $\Delta$ cm far from each other. In the following, we will specify all the notable project parameters.

We used active RFID devices produced by Identec Solutions [7] which operate at 868 MHz: two I-Port III RFID readers drive the 8 available antennas by periodically broadcasting scan requests addressed to all of the present RFID tags, of type i-Q, which are capable of up to 100m response ranges. After performing a scan procedure, we collect at each antenna the RSSI measures of the response signals emitted by tags. Such RSSI values are strongly affected by many different factors, related to complex propagation phenomena, that pose very challenging issues about general analytical descriptions [8]. In Fig. 2 we show the histogram of the RSSI measurements, expressed in $dbm$ units, collected in 30 consecutive scan operations at one of the antennas from two tags (named $A$ and $B$ in Fig.1) put in the indoor scenario $60cm$ far from each other. We can see that (i) the absolute RSSI measures can be quite different even

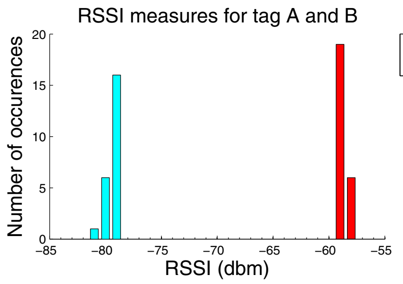


Figure 2: RSSI measures collected at Antenna 1 after 30 scan operations for tags A and B (see Fig.1), 60 cm far from each other

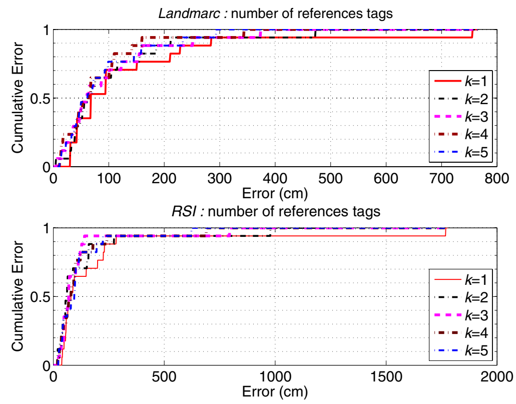


Figure 3: Location error in outdoor scenario when varying the number of reference points $k$ from 1 to 5

for spatially close tags and (ii) the time-dependence is weak in a static environment, since the values collected for each tag differ at most for $2dbm$ over consecutive scans.

We use such observations to build up the tag grids of Fig.1 by using a limited number of tags, namely 30. If we consider an unperturbed environment, that is if macroscopic conditions of our site remain unchanged during the scan operations, the collected RSSI values remain almost time-invariant, as shown in Fig.2. Thus, we build our two-dimensional grid of reference tags and collect the relevant measures incrementally, by filling some rows of the grid with the tags we own, and then shifting the tags rows ahead on the grid. This way, we simulate with a good degree of confidence the contemporary presence of all of the required reference tags on the grid.

From Fig.2 we can also notice that valid RSSI samples collected are less than the number of scan operations. This is mainly due to *collisions* generated by simultaneous responses emitted on air by different tags. Our RFID system implements a proprietary anti-collision algorithm, that tries to minimize the occurrence of collisions, though not eliminating them at all. Anti-collision is not the focus of this research, therefore we do not stress such feature any more in the following.

Many parameters pertaining the location algorithms and the experimental setup affect the location performance. In our trials, we choose to evaluate the impact of each of them, while keeping the others fixed at their default values (we use the notation introduced in Section II. and in Fig. 1):

- **Number of reference points** $k$, determines the polygon containing the estimated location. We varied $k$ from 1, i.e. locating the object at the point of the grid with the minimum RSSI distance from it, to 5, i.e. computing the assessed position within the pentagon with vertexes falling at the $k$ selected reference points. The default choice we used is $k = 4$.

- **Weighting function** $w$ to compute the relevance of each reference point. We considered two solutions, namely (1) the simple selection of the center of mass or (2) the weighting formula proposed in LANDMARC (as reported in Table 1) that assigns higher weights to reference points with lower RSSI distances. The default choices we used are those reported in Table 1.

- **Spacing between reference points** $\Delta$, i.e. the distance between tags in the grid. We ran location procedures with, respectively, $\Delta = 60, 120$ and $180cm$ in order to recognize suitable trade-offs between location accuracy and operational costs. The default value we used is $\Delta = 60cm$.

- **Antenna configuration** i.e. number and disposition of the antennas in the area of interest. We considered two configurations, with (1) all the 8 antennas or (2) the 4 antennas in the middle of the grid's edges working. As a default we used 8 antennas.

In the following sections we will show the location results obtained in outdoor and indoor environments by varying the project parameters detailed above for both LANDMARC and RSI algorithms. As a performance metric we choose the *location error* $err$, defined as the euclidean distance between the true position of the RFID tag we want to locate and the one computed by the location algorithm. We collected 25 location estimates, by moving the locating tag along the main diagonal of the grid, and reported into the following graphs the cumulative location errors we registered.

### A. Outdoor scenario

The outdoor configuration we refer to consists of a rectangular square of $19.8 * 7.2m^2$, with reference tags put at $\Delta cm$ from each other (see Fig.1). The first parameter we vary is the number $k$ of reference points used to average the estimated position. In Fig.3 we report the cumulative distribution of location errors $err$ for LANDMARC and RSI when considering $k = 1, \ldots, 5$. If we focus on the location error registered for 90% of measures, a reasonable confidence level on the expected results, we can notice that the worst results are achieved with $k = 1$, i.e. when the estimated position coincides with the reference point with the shortest distance from the locating object; while we get the best performance when $k = 4$, with a 90% error of about $1.5m$. By looking at the RSI approach, we confirm that trusting on 1 or 2 reference points leads to poorer average and worst case errors, while the best performance is fulfilled by us-

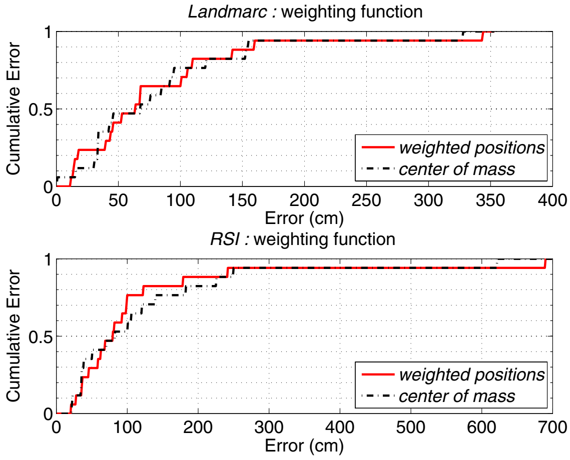


Figure 4: Location error in outdoor scenario when varying the weights $w$ used for the selected reference points

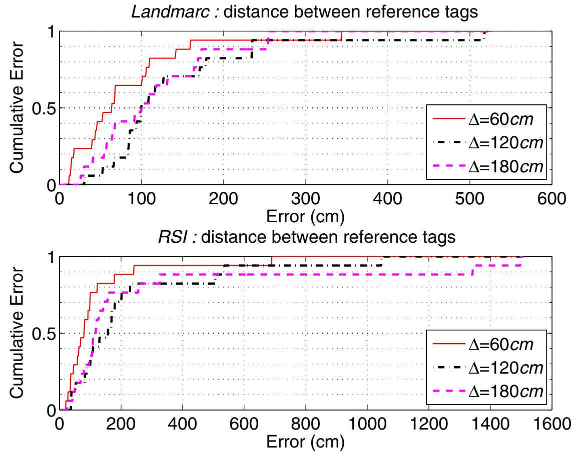


Figure 5: Location error in outdoor scenario when varying the spacing $\Delta$ between reference tags

ing 3 reference points, with an error lower than 1.5m for 90% of trials. For both algorithms, we can state that selecting a single reference point leads to poor accuracy. Further, choosing 5 reference points is not suitable as well, since there is the risk to average over too many, possibly very distant, positions.

As for the weighting function $w$, we compared the simple choice of the center of mass, i.e. choosing the same weight $w = 1/k$ for all the $k$ selected reference points, with the expression proposed in [5] (see Table 1). Looking at Fig.4, we cannot distinguish a clear advantage coming from different expressions of $w$. We interpret this result by saying that, on the average, it is more important to correctly select the nearest reference points than to assign them different weights based on their RSSI distance from the target object.

In Fig.5 we show that, as we could expect, by increasing the spacing $\Delta$ between reference tags we incur in lower accuracy levels, both on average and worst cases. In fact, denser grids of reference tags lead to a higher reliability level for the RSSI spatial description and, consequently, to a more qualitative set of informations available to location algorithms. Further, if we look at RSI, we observe that the performance degradation due to increasing values of $\Delta$ is not particularly mitigated by the use of spline interpolation of the RSSI distances.

Finally, we assess the impact of the number of antennas, with results shown in Fig.6. We observe that using of 8 antennas performs better than using 4, in the majority of the considered tests. This result is intuitive, since a larger number of antennas allows to gather more data, thus allowing to discriminate better among different points in the RSSI distances space.

### *B. Indoor scenario*

We conducted the same analysis as above in an indoor space of $9.6 * 4.8m^2$, consisting of a room with different kinds of furniture (e.g. chairs, cabinets, etc). As a general consideration, we can say that indoor operation introduces much more complexity on propagation, eventually taking to greater location errors and less predictable results. In Fig.7 we compare the cumu-

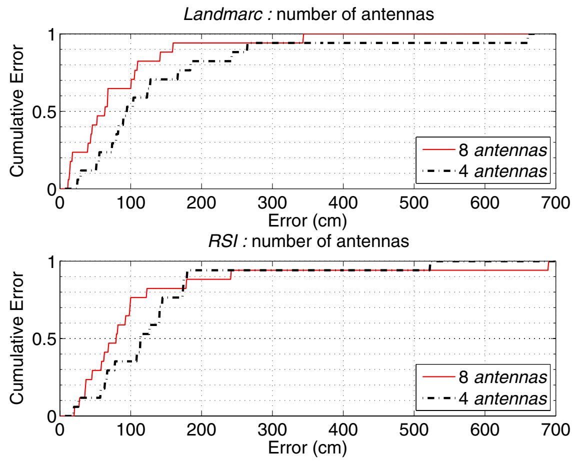


Figure 6: Location error in outdoor scenario when varying the number of antennas

lative location errors, obtained by fixing the algorithm parameters to the default values reported above in this section. We can see that LANDMARC and RSI algorithms get similar performance on both average case, with errors lower than 1.5m, and on 90% of the trials, with errors of about 2.5m. The experiment we deployed and the results we attained are consistent with those reported in [5].

Due to space limitations, we only report comparisons about spacing $\Delta$ between reference tags in the grid and number of antennas. In Fig.8 we see that the impact of the spacing $\Delta$ on location is not as plain as expected. As for LANDMARC, grid density doesn't play a significant role. Thus, we argue that the number of reference tags can be reduced without heavy impact on location performance. Differently, RSI algorithm exhibits increasing accuracies when moving toward denser grids ($\Delta = 180, 120, 60cm$). Such a result allows us to say that the complex propagation issues involved in indoor environments are not suitably modeled with spatial interpolation through

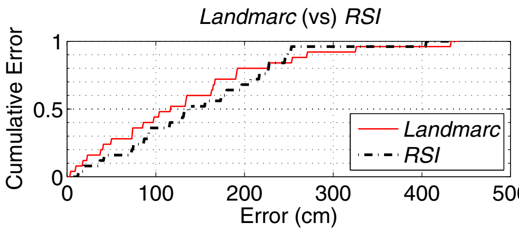


Figure 7: Performance comparison between LANDMARC and RSI in indoor scenario

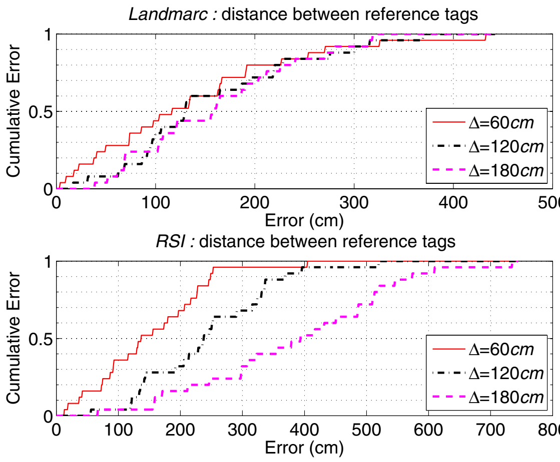


Figure 8: Location error in indoor scenario when varying the spacing $\Delta$ between reference tags

spline functions.

As for the number of antennas, we get the smoother and more predictable results reported in Fig.9. We can clearly distinguish that using 8 antennas significantly reduces location errors, with respect to the use of 4 antennas. Such behavior is intuitive, since gathering RSSI values from more antennas enhances the information retrieved by the location algorithm and allows for a better differentiation of the candidate positions in the RSSI space.

## IV. Conclusions

In this paper we assessed the performance of location algorithms based on RSSI measures in active RFID systems, namely the well-known LANDMARC approach and another solution we conceived, called RSSI Spatial Interpolation (RSI). We analyzed location errors achievable in both outdoor and indoor environments, through general and repeatable experimental configurations, by varying several parameters affecting the algorithms operation. The results provided in this paper pose some limitations to the use of such location techniques: (i) we observed that a very high number of active RFID tags need to be spread over the operating region, as reference points, if a high accuracy level is desired; (ii) similarly, a high number of antennas helps improving the location accuracy, at the cost of increasing deployment costs; (iii) the considered environments

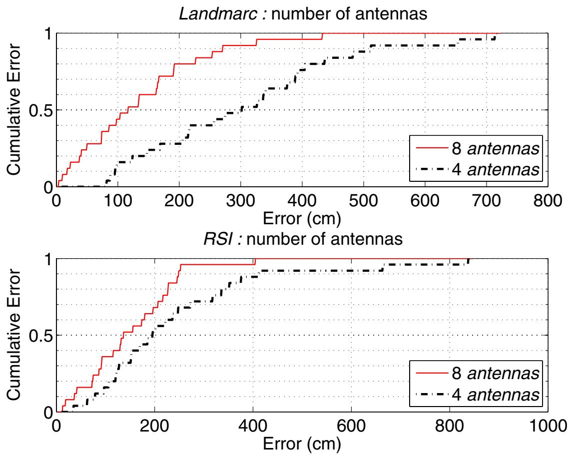


Figure 9: Location error in indoor scenario when varying the number of antennas

suffer from propagation issues that heavily affect location performance and (iv) don't allow for easy prediction of the best operational parameters for location algorithms.

To the best of authors' knowledge, this is the first performance study of location systems using active RFID developed with a wide and reproducible experimental setup. Such study hopefully helps to clarify the achievable results and the impact of many parameters on RFID location, not adequately addressed up to now.

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