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Improved Distance Estimation using a Constellation of RFID Tags

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Abstract— In this paper, we present a new approach using a group or a constellation of RFID tags in place of a single tag for distance estimation in order to improve it. We study the performance of a single active UHF-RFID tag operating at 433 MHz band compared to the constellation of four similar tags as its replacement. Distance estimations are performed using One-Slope Model (OSM). The improvements in distance estimations with constellations are based on averaging algorithm which helps to tolerate the noisy power measurements observed for a single tag. We also compare the performance of the constellations with different sizes to find the optimal size of a constellation.

Experimental validations demonstrate the performance improvements while using constellations for distance estimation. For the best constellation the average estimation error was below 0.35 m and remaining below 0.84 m for more than 90% of the times with maximum error of 1.23 m.

Keywords— UHF-RFID; constellations of tags; One-Slope Model; distance estimation.

I. INTRODUCTION

In a typical Received Signal Strength (RSS) based indoor localization system, distance estimation is based on the RSS between transmitter and receiver. As the distance becomes longer, RSS at the receiver becomes weaker. In free space, RSS is inversely proportional to the square of the distance, and it is easy to convert it into the distance using a known radio propagation model. However, in indoor environments, it is difficult to estimate distance accurately using Received Signal Strength Indicator (RSSI) due to multi-path, near-far effect phenomenon added to the path loss. In these cases, generally a system calibration is made [1], where values of RSSI and corresponding distances are evaluated in advance in a controlled environment. The most considerable advantage of this method is its low cost. The disadvantage is that its performance is affected by noise and interference and this leads to inaccurate distance estimation. That is why distance estimation using RSSI in real-world applications is still questionable [2]. However, RSSI could become the most used technology for distance estimation, considering its low cost.

In order to translate RSS into an estimated distance, several theoretical and empirical propagation models are used [3]–[6]. The classical One-Slope Model (OSM) [7, 8] is a simple propagation model that can be used for the distance estimation, but the drawback of this model is that it doesn't take into account shadowing and fading in such environments. Filtering is one of the solution to suppress the effect of fast fading on the performance of OSM. But to improve the distance estimation further, we must find another solution. In this paper, we discuss the new approach for further improvements based on the idea of using a group of RFID tags instead of a single tag for distance estimation.

The rest of the paper is organized as follows. The proposed technical solution with the new approach of distance estimation using constellation is detailed in Section II and III. The details about the experimental setup, environment and equipment are given in Section IV. Illustrative results are discussed in Section

V. Section VI gives some hints about our future work on this topic and in Section VII we give some concluding remarks.

II. CONSTELLATION APPROACH

From our previous studies related to tag placement [9], it is observed that localization accuracy is better if the tags involved in tri/multilateration are closer to each other. This may be because the radio propagation channels for the tags which are closer, are more similar to each other. Conversely, in order to cover the whole volume of an environment, tags should be placed as far apart as possible as the error in the distance estimation increases when the distance increases as well.

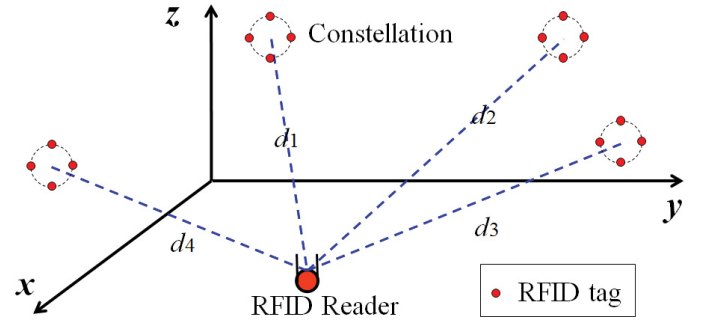


Fig. 1. Constellation approach for localization using multilateration.

To overcome these two opposite requirements in tag placement, we present a layout (Fig. 1) for a better estimation of distance, made of a constellation of tags, placing them closer to each other in a group in order to have nearly the same propagation channels for all tags. This group or constellation can be used in place of a single tag that we previously used for distance estimation and if we somehow manage to obtain a combined propagation channel model for this constellation, its performance can be better compared to the propagation model of a single tag. This new layout will allow us to improve the performance of propagation model.

III. DISTANCE ESTIMATION

For each tag in a constellation we have two different sets of RSSI values, each corresponding to two receiver antennas on RFID reader, antenna 1 and antenna 2 respectively. In the following sections we refer them as Antenna 1 data and Antenna 2 data respectively. For distance estimation we process these RSSI values. Steps involved in processing are filtering, averaging and obtaining a propagation model for distance estimation (Fig. 3).

A. Filtering

Before averaging and estimating the distance, we filtered the RSSI values corresponding to deep fading with the help of a simple Low-Pass Filter (LPF) [10]. The equation for the LPF that we used is given in (1). Where T_i is the RSSI value received at the receiver at a measurement position number i . P_i is the RSSI value after filtering. The constant α can have a value between 0 and 1 which controls the extent of filtering needed.

$$P_i = \alpha P_{i-1} + (1 - \alpha) T_i \quad (1)$$

When the LPF is used, the abnormal values of RSSI are eliminated as seen in Fig. 2, where the value of α is taken as 0.6. The filtering helped us to eliminate occasional very large distance estimation errors and to improve overall performance.

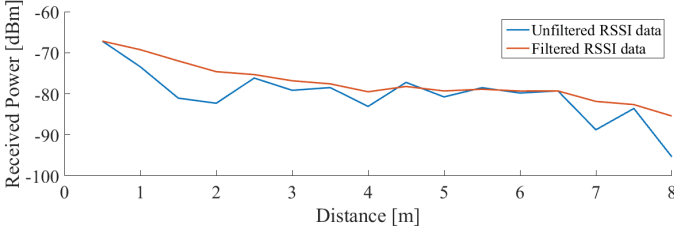


Fig. 2. Received power by a tag before and after filtering.

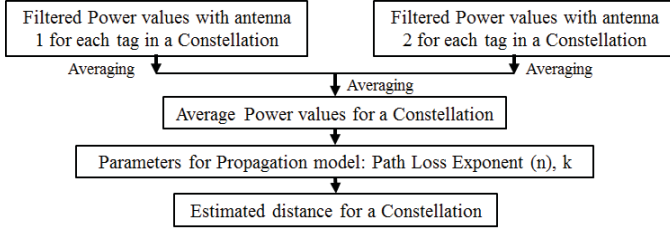


Fig. 3. Steps for averaging and distance estimation.

B. Averaging for Constellations

In order to obtain a combined result for a constellation we performed averaging of filtered power values obtained by all the tags in the constellation. Once we got the average power values for a constellation for each antenna we once again averaged it combining the powers of both antennas. The final averaged powers are then used to obtain the propagation model for single virtual tag constituted by all the tags in the constellation. This combined propagation model eventually used for the distance estimation.

C. One-Slope Propagation Model

When we consider the radio propagation scenario in free space, the received power P_r by an antenna at a distance d separated from its transmitter can be represented according to the Friis free space equation (2) [11].

$$P_r(d) = P_t \cdot G_t \cdot G_r \cdot \left(\frac{\lambda}{4\pi d} \right)^2 \quad (2)$$

Where P_t is the transmitted power, G_t is gain of transmitter antenna, G_r is gain of receiver antenna and λ is the wavelength. This theoretical channel model is comparable to the experimental propagation channel model used below for each tag. We need to choose the propagation model of the environment in order to estimate the reader-to-tag distance from the received power. One-Slope model [12, 13] is a bijective relation between power $P_{received}$ and distance d (3). Where n is the path loss exponent.

$$P_{received} = \frac{k}{d^n} \quad (3)$$

If we consider the logarithmic scale, the received power in dBm P_{dBm} can be expressed linearly (4).

$$P_{dBm} = ax + b \quad (4)$$

The coefficients a , b are found using 'polyfit' function in Matlab which finds the fitting polynomial curve for the RSSI data with path loss exponent n (5).

$$n = -\frac{a}{10} \quad (5)$$

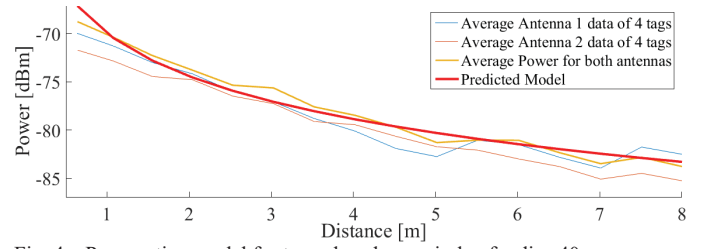


Fig. 4. Propagation model for tags placed on a circle of radius 40 cm.

TABLE I. EFFECTIVE PATH LOSS EXPONENT AND STANDARD DEVIATION FOR DIFFERENT CONTELLATIONS

Constellation Radius (cm)	Effective Path Loss Exponent (n)	Standard Deviation (n)
10	1.36	0.60
20	1.43	0.36
30	1.55	0.42
40	1.47	0.42
50	1.40	0.55
60	1.30	0.55
70	1.32	0.31

Finally the estimated distance can be found using (6). We used this model to estimate the distance between the centers of the constellation to the measurement position.

$$d = 10^{\left(\frac{P_{dBm} - b}{a} \right)} \quad (6)$$

Fig. 4 shows the propagation model for constellation with radius 40 cm. This figure also shows the average powers obtained from the filtered power values of all four tags in the constellation with individual antenna and the final averaged value in the background. Table I shows the values of effective path loss exponents for different constellations after averaging procedure and also the standard deviation.

IV. EXPERIMENTAL SETUP

A. Environment

The experiment is performed in a classroom environment of dimensions 8.5 m x 7.5 m x 2.51 m, which can be seen in Fig. 5. In order to eliminate the interferences and the reflections caused by the objects in the classroom, all the chairs, tables and other objects were removed. There were still some metallic objects such as big heater, writing board and metallic grid on the ceiling.

B. RFID equipment

For this work, four active UHF-RFID tags at 433 MHz band are used. The tags can be detected from as far as 20 meters in an indoor environment. A bidirectional traffic detection RFID reader, having two $\frac{1}{4}$ wave antennas is considered for the experiment. RS232 connector is used to connect the reader to the computer. The tag model "Coin ID" and reader model "UTP Diff 2", used for this work are from RFID manufacturer Ela Innovation [14].

C. Setup

Constellations of tags were placed on a wooden board hanging vertically on the wall. Tags in different constellations were placed over the concentric circles with radius varying every 10 cm, from 10 cm to 70 cm as shown in Fig. 6 (a). The center of the circles is at 1.26 m height from the floor. The RFID reader is aligned in front of the wooden board such that

the center of the circle is at the same height as the middle / half length of the reader antennas. The reader is placed over cardboard boxes in order to avoid reflection of received signal.

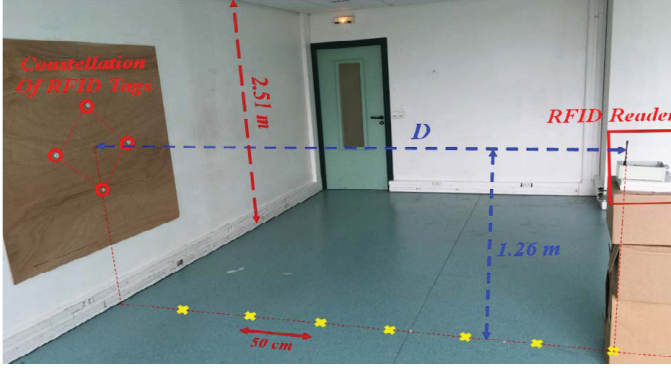


Fig. 5. Measurement scenario showing the setup of RFID tags in constellation and RFID reader.

D. Measurements

Two different measurement campaigns were realized following a straight line in front of the center of wooden board. Starting from 0.5 m from the center of wooden board, RSSI values are recorded at every 0.5 m up to 8 m as seen in Fig. 6 (b). At each measurement position one thousand sets of RSSI values were recorded for each tag, with each set containing the RSSI values for antenna 1 and antenna 2 of the reader. For further processing, we averaged these one thousand RSSI values in order to take into consideration the variation of signal strength over time. The first measurement campaign recorded the RSSI data for a single RFID tag. In this case measurements were taken for all four tags separately, by placing each tag at the center of wooden board. During the second measurement campaign RSSI measurements are taken for the 4 tags one constellation at a time for the 7 radii (from 10 cm to 70 cm).

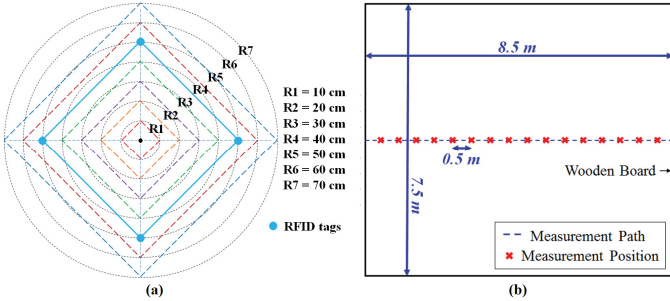


Fig. 6. (a) Placement of tags in a constellation of radius 50 cm and positions of other constellations. (b) Measurement scenario

V. PERFORMANCE EVALUATION

A. Optimal size of Constellation

As explained in section II, to make distance estimation more reliable, even with a very simple channel model a constellation must fulfill a trade-off, bringing enough diversity and keeping almost the same propagation conditions. This raises the question about the constellation size. To obtain the optimal size of constellations we compared performance of all the constellations together. Fig. 7 shows the variation of error in distance estimation for constellations with different radii as a function of the distance. For all the constellations it can be noticed that, the error increases when distance increases. This is the case beyond 6 meters. When the measurement position is closer to the tags, the power received by the reader is mostly due to the Line-of-Sight (LOS) path. As the distance increases, because of the multipath effects, the OSM doesn't perform well and the error tends to increase.

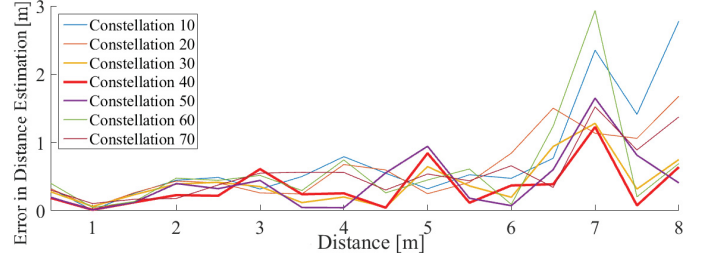


Fig. 7. Variation of Error in Distance Estimation for different constellations as a function of the distance.

TABLE II. MEAN DISTANCE ESTIMATION ERROR AND STANDARD DEVIATION FOR DIFFERENT CONTELLATIONS

Constellation Radius (cm)	Mean Distance Estimation Error (m)	Standard Deviation (m)
10	0.77	0.77
20	0.63	0.48
30	0.41	0.34
40	0.35	0.33
50	0.43	0.43
60	0.60	0.69
70	0.55	0.40

The mean distance estimation error and standard deviation for this error, for each constellation, is shown in Table II. The mean error as well as the standard deviation is computed with all the errors in the straight line from the wooden board until the end of the room (8 meters).

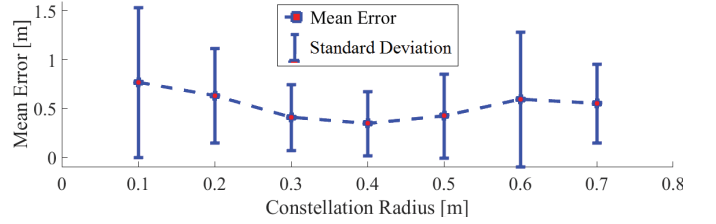


Fig. 8. Variation of mean Distance Estimation Error for different constellations as a function of constellation radius.

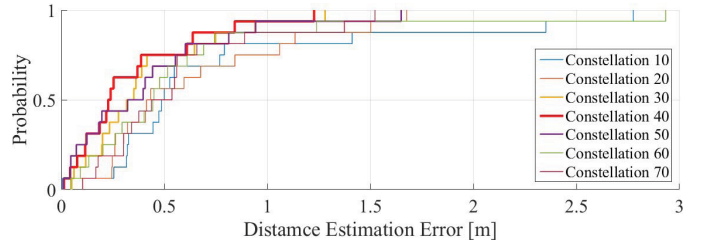


Fig. 9. Comparison between error performance (CDF) of constellations with different radii.

Best results are achieved at 40 cm radius where mean error is 0.35 m and the standard deviation is 0.33 m. The cumulative distribution function (CDF) for all the constellations is compared in Fig. 9. Once again the best results can be seen for constellation with radius 40 cm. The error for this radius remains below 0.84 m for more than 90% of the cases with maximum error of 1.23 m. It can be seen that the constellations with radius 30 and 50 cm also give good results.

B. Constellation vs. Single tag

In order to compare the distance estimation performance of constellations with a single tag we analyzed the performance of single tags based on the first measurement campaign. The RSSI data obtained from this measurement campaign is also filtered using the same LPF used for the campaign 2. After filtering,

we followed the similar procedure to obtain estimated distance for 3 different cases when each tag is placed alone at the center of the wooden board. For the first two cases we performed distance estimation for each tag with both antennas separately. In the third case we averaged the powers with both antennas for each tag before distance estimation. In all three cases we find a tag which has the best error performance (Fig. 10).

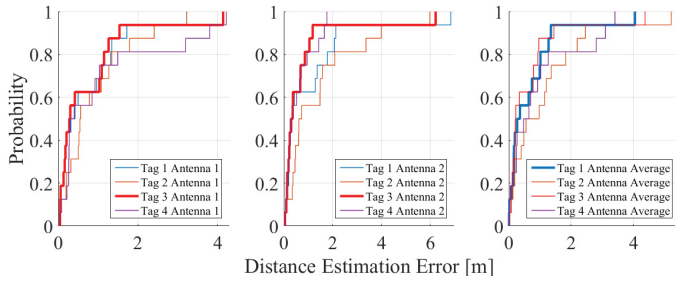


Fig. 10. Error performance (CDF) of single tags. (a) considering antenna 1 data (b) considering antenna 2 data (c) considering the average power of both antennas.

As we can see in Fig. 10, for the first two cases, Tag 3 has the best error performance while in the third case, the error performance of Tag 1 is better than the rest of the tags.

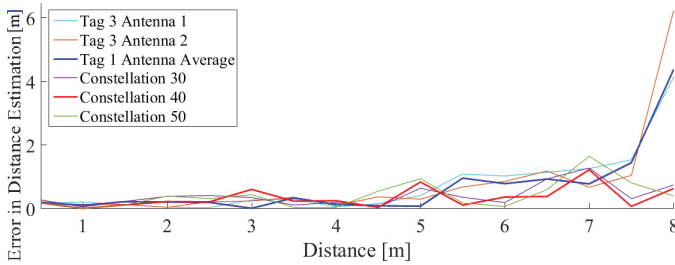


Fig. 11. Comparison between the error performance of single tag and the best constellations.

In order to compare the performance of constellations with a single tag we consider the error performance of three best constellations and compare it with the error performance of single tag in all three cases (Fig. 11). It can be seen that below 5 m distance from the tags, performance of a single tag can be better than constellations, but after 5 m it becomes worse. For a single tag error increases in an exponential way with distance. However, in the case of constellation the error increases with the distance slowly and never exceeding 1.23 m. Therefore, in the smaller indoor environments where a single tag can cover a distance of 5 m, using constellations is not much helpful, but for the large environments such as halls where the tags are needed to be placed farther, constellation approach can be useful to achieve a very accurate distance estimation.

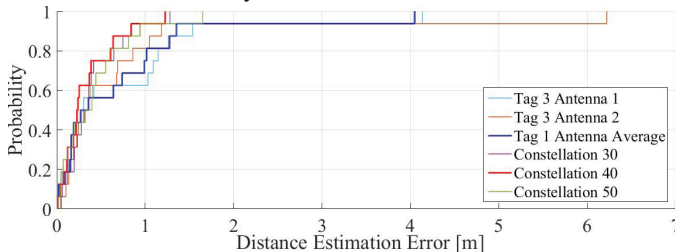


Fig. 12. Comparison between the error performance (CDF) of single tag and the best constellation.

The comparison between the CDF can be seen in Fig. 12. As seen from the CDF curves at 50% and 90% the performance of the constellation, with the help of the constellation we obtained consistently good distance estimation. From the CDF comparison, it is clear that the distance estimation results for constellations are clearly better compared to single tag when we consider distances larger than 5m.

VI. FUTURE WORK

The work presented in this paper was performed by removing all the obstacles in the classroom in order to compare the distance estimation performance of a constellation with a single tag in optimal conditions. Also to prove the concept, the study was performed only along a single line in the classroom. However, the influence of the obstacles as well as different measurement scenarios can affect the obtained results, therefore it will be interesting to study the performance of this constellation approach with presence of obstacles and also using different positions in the room. Also, it will be important to study the constellation performance for localization in different indoor environments.

VII. CONCLUSION

This paper presents a new approach to improve the distance estimation in indoor environments by replacing a single beacon with a constellation of beacons. While dealing with noisy RSSI measurements, use of constellation effectively improves the performance of the radio propagation model over distances larger than 5 m. Distances are estimated with a mean error of 0.35 m and the CDF is 0.23 m at 50% and 0.84 m at 90% in a 7.5 x 8.5 square meters empty classroom, following an 8 meters path at the center of the room. In future, it will be interesting to see how the localization performance is affected by this approach. Reliability of the constellation approach in cluttered environments is another key issue for study.

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