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3D Passive Tag Localization Schemes for Indoor RFID Applications

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***Abstract*—Accurate and efficient localization of tags are of utmost importance for numerous existing and forthcoming RFID applications. In this paper, we introduce two novel methods for three dimensional localization of the passive RFID tags. In the first approach, namely Adaptive Power Multilateration (APM), using four RFID readers, distance estimations parameters are processed based on the minimal interrogation power and multilateration. Whereas in the second approach, namely Adaptive Power with Antenna Array (APAA), a single RFID reader equipped with horizontal and vertical smart antennas alongside with the reader's adaptive power levels are used for the tags distance estimations. The APM scheme localizes the tags with comparatively finer granularity whereas the APAA scheme supports reader's mobility and facilitates highly dense tag environments. Simulation results show that our proposed schemes provide more accurate localization than other indoor localization schemes.**

***Keywords*—localization, RFID, Angle-of-Arrival (AoA), smart antennas, power control, multilateration**

I. INTRODUCTION

Object localization, in both two and three dimensions, is a well studied problem. Numerous solutions with varying techniques have been proposed in this context. For outdoor environments, Global Positioning System (GPS) technology is an efficient solution when it comes to localization of people, equipments, vehicles, etc. However, despite the huge advancements in the indoor signal sensing, the GPS technology because of its line of sight requirements with the orbiting satellites will not be feasible for many of the indoor applications [1]. As remedy, other wireless technologies such as WLAN and ZigBee, have been investigated as possible solutions. However, these technologies are not reliable due to high error margins and do not scale to facilitate item-level tagging. Furthermore, the monetary cost of localization, using the aforementioned solutions, exceeds the actual cost of the object being tracked hence, are economically unfeasible.

Radio Frequency IDentification (RFID) is an emerging technology and is widely seen as a promising solution with ability to turn objects into a network of mobile nodes, which can then be used to track objects and trigger events, hence, instigates new applications [11]. Tag localization is the key requirement for many existing and forthcoming applications. For instance, item-level tracking on conveyor belts , localizing lost inventory in apparel industry and so forth. Numerous RFID based localization schemes, for indoor applications, have been proposed [2]–[4]. The existing schemes measure the signal strength from multiple readers [5] to calculate the tag's position. However, these schemes demand active and/or customized tags and require extensive pre-installation planning of the interrogating readers.

In this paper, we propose and evaluate two deterministic location estimation schemes for passive and active RFID tags. In the first scheme, Adaptive Power Multilateration (APM), the RFID readers dynamically adjusts their transmission power to estimate tags' location using the multilateration approach. The APM scheme localizes tags with high accuracy however, requires minimal of three and four standard RFID readers for 2D and 3D environments, respectively. In the second scheme, Adaptive Power with Antenna Array (APAA), the reader is equipped with a smart antennas systems [6]. The smart antennas system, using its horizontal and vertical antennas, estimates the Angle-of-Arrival (AoA) of the received RF signal, while also varying the transmission power levels. Unlike the APM scheme, the APAA scheme can localize the RFID tags, in both 2D and 3D settings, using a single reader, however with lesser accuracy. Furthermore, the APAA scheme facilitates mobility and dense item-level localization. The RFID localization system is implemented using MATLAB. Simulation results validate the effectiveness of both schemes in localizing passive and active tags under mobile and dense tags environment.

The remainder of the paper is organized as follows. Section II surveys the existing literature in the context of RFID localization. Section III describes the two proposed localization schemes and explains the adopted error model and multiple reader's placement scenarios. Section IV presents simulated experiments conducted using MATLAB and analyzes the obtained results under multiple scenarios. Finally, section V concludes our work and highlights future direction.

II. LITERATURE SURVEY

Numerous location estimation algorithms have been proposed to localize RFID tags; active and passive. Active tag localization includes many techniques such as SpotOn [2] and LANDMARC [3]. The SpotON [2] uses the aggregation algorithm for 3D location sensing using Received Signal Strength Indication (RSSI). The tags in this system are customized to use radio signal attenuation in order to estimate the inter-tag distance. The system requires unacceptable computational and processing time, in tens of seconds, hence, yields low localization and tracking accuracy. The LocAlizatioN iDentification based on dynaMic Active Rfid Calibration (LANDMARC) technique [3], is an active tag based localization system. The readers in the LANDMARC scheme estimate the tag location based on the sub-region that it may be in. When the tags enter each sub-region, the distance between the tag and the reader will be computed and calibrated. Furthermore, the reference tags are also placed at well-known locations in order to determine the 'power fingerprints' for such locations. The reference tags serve as landmarks to the system. Despite the effectiveness in LANDMARC localization system, it requires pre-deployment planning, pre-installation of anchor tags and customized active RFID tags.

Passive tag localization schemes include probabilistic, multi-frequency, and repository-based solutions. In the probabilistic scheme [4], a pre-deployment probabilistic estimation of the passive tags localization is performed. The passive tags, once interrogated, inform only about its presence within an angular sector. The angular sectors are created by the reader with rotating angular antenna. The rotating antenna snaps the environment in different angular sections with different transmitting powers to fine grain the angular space. However, in such a system, the localization accuracy significantly depends on pre-deployment estimation and the readers enumeration and their deployment patterns. In the multi-frequency scheme [5], the field generators expand the reader signal range (act as a repeater for the reader) and use frequency range of 433 MHz for signalling the tags whereas the tags communicate with the reader using UHF frequency of 916 MHz. However, the use of field generators normally increases the location error. Therefore, are not feasible for localization of passive tags in 3D environments. In the repository-based scheme [7], an RFID-based Library Information Management (R-LIM) system is maintained to localize and track the tagged library books. The R-LIM maintains a repository of the IDs of the RFID tags affix on each book along with the book residing shelf ID. The reader scans multiple shelves by moving along each shelve. The R-LIM scheme effectively localize the book however, only within its shelved area.

All the aforementioned schemes, however, require pre-deployment scanning and book-keeping, optimal readers deployment, custom tags, economical inefficient and/or are tailored for a given application.

III. Proposed Localization Schemes

In this paper, we propose two 3D indoor localization schemes for passive RFID tags using the range-based and bearing-based approaches. In the range-based scheme, namely Adaptive Power Multilateration (APM), a modified multilateration technique is used to calculate the expected tags location. Multilateration [8] is a deterministic estimation method; the statistical parameters such as mean or median are used for robust estimation. This is shown in Fig. 1, wherein the expected location of the tag will be the average of the intersection points

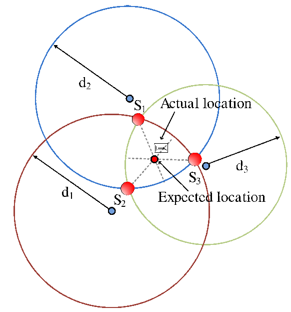


Fig. 1. Multilateration technique

S_1, S_2, and S_3. In APM, the reader's antenna power level is dynamically adjusted for fine-grained distance resolutions. In this context, a modified multilateration method is proposed, since the existing variants of multilateration do not employ the adaptive power levels approach nor exploit the RFID specific characteristics. In the context of RFID localization, the use of adaptive power level is a novel approach which has been adopted from our earlier work to resolve tag collisions [10]. The unique feature, implicit to RFID tags (i.e. reader's triggering of tag to send its serial number is embedded with the RSSI) is used to simplify the range calculations. The APM scheme achieves high localization accuracy using off-the-shelf RFID readers. In the bearing-based scheme, namely Adaptive Power Antenna Array (APAA), the adaptive power levels is adopted beside two smart antennas. The smart antennas estimate the horizontal and vertical angle of tag relative to the reader. The estimated angles and power levels are then used in the estimation of the tag location.

A. Adaptive Power with Multilateration (APM)

In this method, the adaptive power level technique [10] is applied to any pre-installed readers and the tag position is then estimated using multilateration calculations. For each reader, two power levels are evaluated and logged for each tag laying within its interrogation zone. The first level is the maximum power, P_{i-1}, at which tag did not respond to the reader queries. The second is the minimum power level, P_i, at which the tag responded. The two power levels, along with the singulated tags serial-numbers are used along with the multilateration based tag's location calculation.

For the multilateration based calculation, the center point between the two power levels is assumed to be the radius (P) of the spheres that centred at the reader. The radius of the sphere is used to determine the intersection points with the other readers' spheres (i.e., radios P from other readers) for a particular tag. Therefore, the center point of two power levels is

$$P = \frac{P_i + P_{i+1}}{2} = P_{i-1} + \frac{l}{2} \quad (1)$$

where l is the power level step, i.e., the incremental value between two sequential power levels. The APM scheme, beside being a variant of multilateration approach, requires predetermined readers placement due to the adaptive power level approach. The reason is that the power levels may introduce some cases where it is impossible to have intersection amongst the required number of readers. An example of such a case is when one reader's range fits inside another reader's range (no intersection points). Such cases are further discussed in Section IV. To this end, we introduce the tetrahedron-based readers placement (Fig. 3-a), where maximum non-collinearity between the readers is achieved when they are placed at the vertices of the tetrahedron. Outside the tetrahedron region, the localization accuracy of the tag drops as the probability of having no intersections between the power spheres increases.

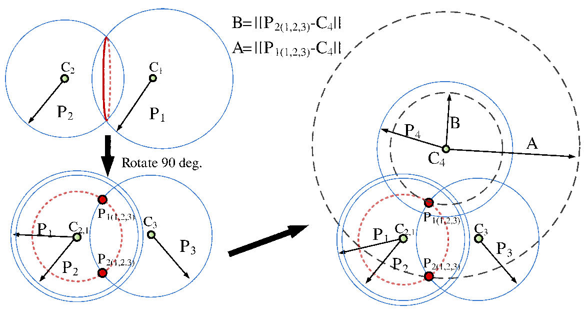


Fig. 2. Clustering of the centre point for 3 readers

To estimate the location of a particular tag m in the x,y, and z coordinates requires determination of unique intersecting point of the four readers radius, as shown in Fig. 2. Two points $P_{1(1,2,3)}$ and $P_{2(1,2,3)}$ are calculated from the centre point of power level P, an intersection of power levels, from eq. (1), of the three readers R_1,R_2, and R_3 [9]. Furthermore, the distances between the fourth reader and the two points P_1 P_2 are calculated. The point which has the closest distance to P_4 is selected as the expected point from R_4 and is denoted E_4.

$$E_4 = \begin{cases} P_{1(1,2,3)}, & \text{if } ((\|P_{1(1,2,3)} - C_4\| - P_4) \\ & \quad < (\|P_{2(1,2,3)} - C_4\| - \overline{P_4})) \\ P_{2(1,2,3)}, & \text{otherwise} \end{cases} \tag{2}$$

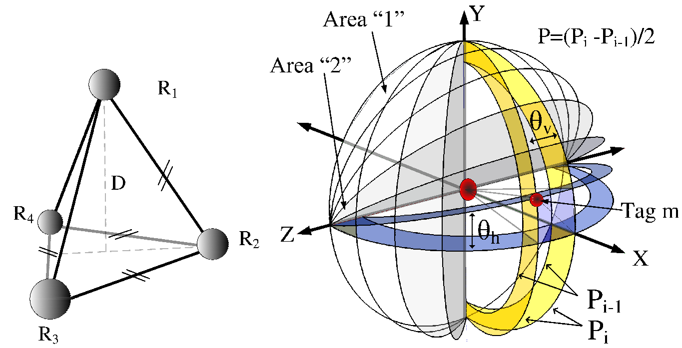
The expected point from other readers, E_1, E_2, and E_3, are also calculated in similar manner. An average of all the intersection points ($E_average$) is used to determine the estimated location of the tag m,

$$E_{average} = \frac{\sum_{k=1}^{K} E_k}{K} \tag{3}$$

where K is the number of readers covering the space (in Fig. 2, K = 4). APM scheme requires pre-deployment planning and is suitable for a fixed-reader mobile-tag applications. Potential applications of the APM scheme may include patient monitoring, museum artifacts monitoring and context-aware applications, where readers mobility is not crucial.

B. Adaptive Power with Antenna Array(APAA)

Tag localization in the APAA scheme is based on two techniques. First technique, similar to the APM scheme, is based on the adaptive power levels. The reader reconfigures the transmission power to deterministically estimate the tag's location. Second technique is based on AoA measurements. The AoA measurements are calculated using the phase differences at the smart antenna. The reader is affixed with two smart antennas, vertical and horizontal, with an angle step of θ_s. The AoA information is also associated with the tag serial-number and is stored in reader's repository. Both information, the AoA measurement and the power-level are then used to estimate the location of the tag, as illustrated in Fig. 3-b.



(a) 3D tetrahedron (b) AoA and power-level

Fig. 3. Reader's placement along with its AoA and power-level measurements

The tag expected location in the APAA scheme is defined by the power-levels (P_{i-1}, P_i) and the AoA measurement, θ_v from the vertical antenna array and θ_h from the horizontal antenna array and range of the two angles, is

$$x_m(P,\theta_v,\theta_h) = \frac{\sin(\theta_h)}{|\sin(\theta_h)|} * \sqrt{\frac{P^2}{\left(1 + \frac{\cos^2(\theta_v)}{1-\cos^2(\theta_v)} + \frac{\cos^2(\theta_h)}{1-\cos^2(\theta_h)}\right)}} \tag{4}$$

$$y_m(P,\theta_v,\theta_h) = \frac{\cos(\theta_h)}{|\cos(\theta_h)|} * \sqrt{x_m(P,\theta_v,\theta_h)^2 * \frac{\cos^2(\theta_v)}{1-\cos^2(\theta_v)}} \tag{5}$$

$$z_m(P,\theta_v,\theta_h) = \frac{\cos(\theta_v)}{|\cos(\theta_v)|} * \sqrt{x_m(P,\theta_v,\theta_h)^2 * \frac{\cos^2(\theta_h)}{1-\cos^2(\theta_h)}} \tag{6}$$

For accurate estimation, the smaller the angle step (θ_s), which is based on the beamforming resolution of the smart antenna, the better the estimation of the vertical angle (θ_v) and horizontal angle (θ_h) would be. The effect of the power step l is embedded within P in the above equations. The effects of θ_s and l on the accuracy of the proposed scheme are studied in the following section. Unlike APM, where cases of no intersection points amongst all readers are possible, every

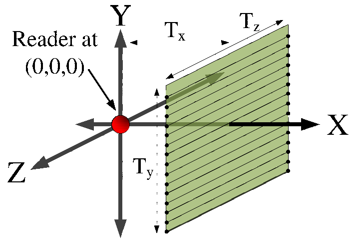


Fig. 4. Testing methodology

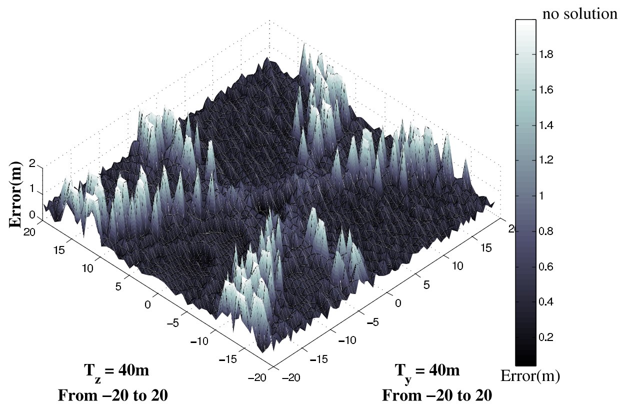


Fig. 5. Average error in APM in a tetrahedron with a depth of 10m. T_x =[1:1:10], T_y= 40m, T_z=40m, l= 0.5m

location in APAA scheme will fit in some angle and power level which guarantees a solution.

IV. Performance Evaluation

In this section, the proposed schemes are evaluated for its accuracy and efficiency compared to other schemes in liteature. The accuracy of the two schemes is tested using identical random movement patterns. Fig. 4 illustrates the testing methodology for the two schemes. The random movement patterns are lines with a fixed X coordinate (T_x in Fig. 4) and values of Y and Z coordinates are fluctuating randomly around the lines pattern. T_x determines the distance, from the reader, at which the schemes are tested. T_y is the hight of the testing sheet with array of lines, which will create a sheet of random movements at T_x meters from the reader. The random movements lengths are also bounded by T_z on the Z-coordinate. By changing the value of T_x, the 3D space will be covered in the evaluation of both schemes. The reader model and power stepping are simulated in MATLAB simulation tool.

A. APM Scheme

As discussed earlier, the accuracy of APM scheme is dictated mainly by the collinearity between the readers and the power stepping. In the testing of the APM scheme four non collinear readers are placed, as in Fig. 3-a, to maximize the accuracy. However, the power step is the main determining factor in the accuracy of the scheme since it defines the intersection points and therefore, making the desired solution as either valid or, if possible, invalid.

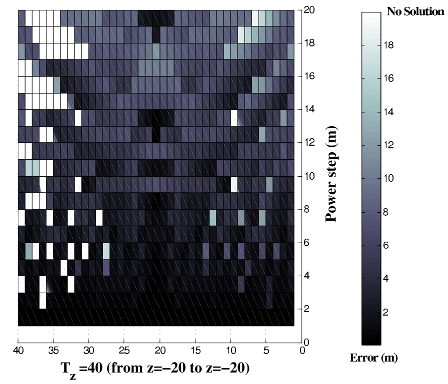


Fig. 6. Power step effect on the overall error the tetrahedron of $10m$ depth, T_x=[1:10], T_y= 40m, T_z=40m, l =[0.1:1:10.1]

A tetrahedron with a depth (D), as is shown in Fig. 3-a, of 10m is tested for APM scheme error calculation. The average error is calculated at power step (l) of 0.5m as is measured using the configurable output power of the Skyetek-M9 UHF RFID reader [1]. The average error of the different patterns are shown in Fig. 5. As evident, most of the calculated errors are below $l/2$. Despite low errors, there are certain locations (outside the tetrahedron space) that are affected by a non-intersecting spheres. This results into an invalid solution, i.e., unable to estimate its location. In Fig. 5, the error values of more than $2m$ are not shown because the error values are either less than $2m$ or are the location points with invalid solution. the number of unestimated location is affected directly by the power step. Fig. 6 shows the effect of the powering stepping value on the overall error estimation of a randomly moving tag in an area of $40m$x$40m$. The value of l is increased from $0.1m$ to $10.1m$ with a step of 1m at a time. The bright rectangles in Fig. 6 are the locations where no estimation is possible.

B. APAA Scheme

APAA scheme is also evaluated using the random movement illustrated in Fig. 4. The same values of the random paths that are used in testing the APM scheme are used to test the APAA scheme. In this scheme, The main parameters affecting the accuracy are defined by the angle step $\theta_s$and the power step l. The scheme is evaluated for l=$0.5m$ [1], and smart antennas with resolution of θ_s=10° [6].

As is depicted in Fig. 7, the overall accuracy of the APAA scheme is high and is void of any invalid solutions. However, for $|\theta_v|$ and $|\theta_h|$ angles greater than $45°$ the accuracy starts to drop since the area covered in between θ_v and θ_h increases dramatically, (Area labeled 1 in Fig. 3-b has $\theta_h > 45°$, whereas Area labeled 2 has $\theta_h < 45°$).

In Fig. 8, the angle stepping from $1°$ to $45°$ shows a linear trend with the error estimation when the RFID tags are sensed within $-45°$ and $45°$ of the horizontal and vertical smart antennas. For the case when $|\theta_v|$ and $|\theta_h|$ angles are greater

[1] http://www.skyetek.com/ProductsServices/EmbeddedRFIDReaders/SkyeModuleM9/tabid/208/Default.aspx

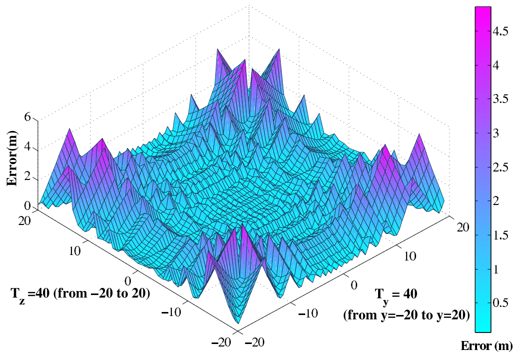


Fig. 7. Average error in the APAA. With T_x=[1:1:10], T_y= 40m, T_z=40m, l= 0.5m

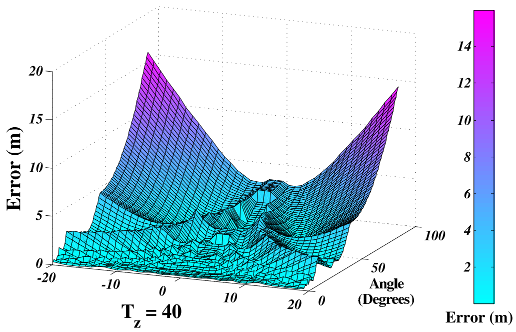


Fig. 8. Error trend for angle steps between 1° to 90°. with T_x=[1:1:10], T_y= 40m, T_z=40m, l=0.5m.

than 45°, the quadratic increase in the area dominates the error estimation in the scheme. This is because the contribution of power stepping, in the total error, is no longer comparable to the area increase (i.e. no matter how small the power step is, the area is the main factor in the error calculation).

A comparison between APM, APAA and other schemes from the literature are summarized in Table I. Due to space limitation, only a few metrics are used for comparison. The existing localization schemes has very coarse localization accuracy, only support 2D tag localization or are not designed for passive tag locations. On the other hand, both APM and APAA schemes support 3D passive RFID tag localization.

The APAA scheme support reader and tag mobility with an acceptable localization error. The APM scheme shows the highest accuracy in comparison to [2]–[4] making it an efficient localization solution for certain applications such as patient monitoring, warehouse containers localization, and so forth. Whereas, mobility support along with relatively high accuracy makes the APAA scheme a suitable solution for item level localization and tracking, tunnel and mine operations, and dense environments.

V. Conclusion

Two indoor localization schemes using two different approaches have been proposed to localize objects, with an attached RFID tag, in 3D space. The schemes benefit from RFID tag's passive replies in order to estimate the power levels at which the tag is responsive. The first scheme, namely adaptive power multilateration, provides a high accuracy when at least four non-collinear readers are available with their intersecting interrogation range. The second scheme, namely adaptive power with antenna array, utilizes the AoA measurement and adaptive power levels to estimate the location of passive RFID tags in 3D. Our simulation results show that the proposed schemes provides accurate localization services hence, making them suitable for diverse RFID application, e.g. supply chain management, robotic guidance systems, apparel industry and many others.

[2]calculated at $l = 0.5m$ using Skyetek M9 RFID reader

Scheme	System accuracy	Advantages / Disadvantages
Alippi [4]	$0.6m$	passive tags / 2D
APM	0.32m [3]	3D / deploy sensitive
APAA	0.48m [3]	3D / antenna resolution
LANDMARC [3]	$1.81m$	active tags only / 2D
SpotOn [2]	cluster size	3D / dual. freq tags

TABLE I
Comparison of various localization schemes

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