An Accurate Passive RFID Indoor Localization System Based on Sense-a-Tag and Zoning Algorithm

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Abstract. Localization and tracking of objects (e.g. objects or people) in indoor environment will facilitate many location dependent or context-aware applications. Localization of passive ultra high frequency (UHF) radio-frequency identification (RFID) tags attached to objects or people is of special interest because of the low cost of the tags and backscatter communication that is power efficient. An augmented RFID system for localization based on a new tag called Sense-a-Tag (ST) that communicates with the RFID reader as a passive tags and can detect and record communication of other passive tags in its proximity was introduced several years ago. In ST-based localization system, a large set of passive landmark tags are placed at the known locations. The system localizes ST based on the aggregation of binary detection measurements according to localization algorithm, such as weighted centroid localization (WCL). However, the aforementioned method is easily affected by the outlier detection of distant landmark tags by ST. To improve localization accuracy, this paper propose to iteratively refine the interrogation area of the reader so that it includes only the most relevant landmark tags. The performance of the proposed method is demonstrated by extensive computer simulation and realistic experiments.

Keywords: Internet of Things · Ultra High Frequency (UHF) Radio Frequency Identification (RFID) · Weighted centroid · Zoning algorithm

1 Introduction

In recent years, the concept of the Internet of Things (IoT) has been gaining popularity. The basic premise of the concept is that "things" are interconnected and have unique identifiers. One of the potential technologies for the IoT is radio frequency identification (RFID). However, coarse-grain location of a tag obtained by current RFID systems is not suitable for the context-awareness of identifiable objects in IoT. The objective of this paper is to analyse and improve the functionality of a novel semi-passive tag called "Sense-a-Tag (ST)" introduced in [1]. The ST can be used for accurate indoor localization based on

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proximity detection. The ST is based on the idea of tag to tag communication that has been introduced earlier [2]. ST is able to capture both UHF RFID reader and tag signals and it is fully compatible with EPCGlobal Class 1 Generation 2 RFID protocol (we will refer to it as Gen2 protocol). The ST can also act as a Gen2 tag and send the information to the reader. The ST can overcome existing limitations of RFID systems including cost and localization accuracy. The existing systems for proximity detection and localization are mainly based on active RFID and run on specialized platforms. Since ST can be added as a new hardware to any current Gen2 UHF RFID system without any modification in hardware or firmware of off-the-shelf tags and readers, it can be considered as a realistic solution for proximity detection and localization applications.

The ST-based localization system requires that RFID readers are installed and a network of passive landmark tags is placed. The landmark tags are placed at known locations. Since the ST can detect communication of the RFID reader and the landmark tags in its proximity and send detected landmark tags' IDs to the reader. The host software estimates the position of the ST based on the position of the detected landmark tags. In [3], we investigated the "weighted-centroid" method of localization and activity tracking system based on proximity detection using ST and RFID passive tags. In [3], the RFID reader reads all landmark tags in each query round. Due to RF propagation characteristics, as well as relative orientation among the reader, ST and landmark tag's antennas, it is possible that sometimes the ST detects some distant landmark tags while missing to detect nearby landmark tags. This effect causes comparatively large estimation error. In this paper, we propose a method where we iteratively refine the interrogation area of the reader so that it includes only relevant landmark tags in order to improve the ST localization accuracy. A combination of weighted centroid localization method and the method of iteratively reducing the zone that the ST detects is called the zoning algorithm in this paper.

We have calibrated our newly developed UHF RFID simulation framework PASS based on the data obtained from the field experiment [4,5]. Using this simulator we could simulate behaviour of all components of the system including the reader, tags and ST in a given environment. The zoning algorithm is evaluated in both PASS simulator and real office environment.

The paper is organized as follows. Section 2 introduces the background and related work. In Sect. 3, based on the brief description about ST-based localization system, we present combined localization method that includes the zoning algorithm and Weighted Centroid Localization(WCL). Section 4 describes the PASS simulator. The simulation and experimental results are shown in Sect. 5. We conclude the paper with future discussion in Sect. 6.

2 State of the Art

Generally, we can divide any RF-based indoor positioning systems to two main categories: range-based and range-free. In range-based localization, methods are dependent on accurate measurement of the RF signal that we can get RFID tags or readers. Previous designs based on this methodology such as Cricket [6], Radar [7], SpinLoc [8], all required information extracted from wireless propagation such as RSSI, angle of arrival, relative velocity measurement or fine-grained point-to-point distance information. However, the propagation parameters of wireless signal is vulnerable to the non-line-of-sight situations, severe multipath fading effects and dynamic temporal changes of indoor environment. Therefore, the accuracy and robustness of range-based localization methods are relatively low.

The main idea of range free localization depends on discriminating the presence of reference nodes within the target's proximity [9,10]. The most encouraging reason for using range-free localization systems is that they are less vulnerable to the effects of complex indoor environment. Centroid method is an example of a range free localization algorithm. Centroid method is based on finding the position of the unknown object based on the avarage of the coordinates of the coordinates of positions of the landmark nodes. LANDMARC [11] and WCL [12] improved centroid design by assigning weights to the different reference nodes. In weighted WCL the node, which is closer to the target node, would be assigned larger weight in the location estimation algorithm.

Later, several methods have been introduced to improve proximity based localization. APIT [10] segmented the area into a large number of triangular regions with different sets of landmark nodes. The target node receives the messages from those landmark nodes that have common coverage with its location. The overlapping area from all received data can be used to estimate the location of a target node.

P. Bahl et al. [7] offered a localization method with two phases based on RSSI and proximity respectively to increase the localization accuracy. They proposed concepts named Environment Independent Positioning (EIP) and Environment Dependent Positioning (EDP). In the initiation phase, the EIP provides a coarse location. Based on this information, a model determination module produces updated and appropriate signal propagation parameters. In the second phase, EDP generates refined position according to the acquired environmental parameters.

Vire is also a classical algorithm for indoor positioning which based on Landmarc solution [13]. Vire algorithm needs RFID readers that can get precise RSSI of each reference tags or detected tags. Vire present the concept of virtual tags. The advantage of Vire is the fact that it can rely on a smaller number of reference tags. The disadvantage is the need to calculate the position of virtual tags and the need to obtain signal strength information. Hence, the algorithm represents a trade-off between real-time performance and accuracy.

CY Cheng [14] introduced a localization algorithm using clustering on signal and coordination patterns. With this algorithm such technique increased the accuracy of LANDMARC and Vire. The localization algorithm combines the advantages of two models, applying the concepts of virtual tags and two-step clustering analysis. Augmented RFID Receiver (ARR) introduced in [15] uses a method called synchronous detection to be able to overcome frequency offset challenges associated with intercepting tag signals using a non-envelope detection scheme. This system captures the data by an off-the-shelf UHF RFID reader IC and then sends and processes the data using an FPGA hardware and soft processor core. Since ARR has high power consumption and it communicates with the host through Ethernet, it cannot be used for portable applications.

A. Atalye et al. in [1] introduced a device called Sense-a-tag that improves localization in UHF-RFID systems. A localization system based on ST and WCL algorithm has been investigated in [3]. The localization accuracy is directly dependent on the density of deployed landmark tags, speed of the movement of the ST and the distance between the ST and landmark tag on one side and the reader antennas on the other side. In these papers, the localization accuracy is studies for several different deployment scenarios. The accuracy achieved using WCL method when the landmark tags are 1 m apart in the direction of y-axis and 0.5 m apart in the direction of x-axis is about 32 cm.

3 Structure of the System

3.1 ST Structure

The ST is a semipassive device and can operate as a standard passive RFID tag that communicates with RFID reader via backscattering communication. However, it has an important additional functionality: it can detect the backscattered response from the tags to the reader.

The ST waits for the particular enquiry commands of the reader for landmark tags. Subsequently, if the ST captures the tag's response and the reader's corresponding acknowledgement, it is considered that tag is detected by ST. The proximity detection information about the detected tag is stored in the memory of the ST. When the reader singulates the ST, the ST transfers the information about the detected tag(s) to the reader.

Figure 1 presents the main operations of software executed on the host computer. The software is used to control the reader and to read tag information from the reader. However, in the figure we show only the part of the software that is needed to process ST. In order to incorporate STs into existing RFID systems, the readers treat the STs as standard tags. Since the readers are not aware of the STs and they treat them as ordinary tags, the host has to specify the procedure of reading the tags and the STs. Also, the host understands the STs operations and it controls the reader using standardized commands. Hence, the host is responsible for intelligent control of the system. The first task of the host is to make sure that the reader first reads tags and then STs. Thus, the reader has to be able to read tags rather than STs in the first reading cycle. During this cycle, the STs listen to the tags responses and store the detected tags information. In the second round, the reader reads only STs.

After initialization, the host initiates the query cycle. The tags' ID numbers and ST information are obtained by the reader and transferred to the host. Next, the host has to analyse the ST information and to relate the tags with the particular STs.

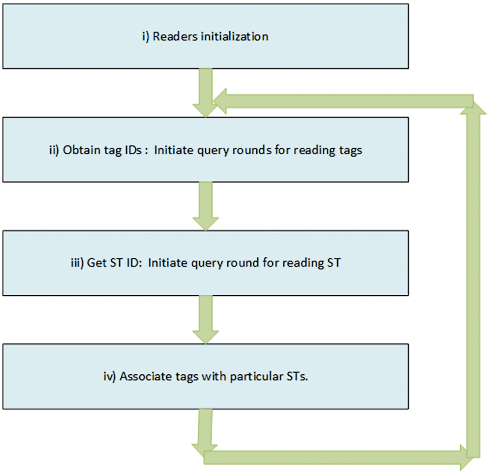


Fig. 1. Steps implemented by the host for obtaining information from STs.

3.2 Zoning and WCL

The method used for localization is *"Weighted Centroid"*. In the centroid method, the target calculates its position at the center of the detected reference tags, as shown in Fig. 2(a). To increase the accuracy of the localization, *weights* are introduced into this system. Weights are used to calculate the distance of the target from each respective landmark tag, as shown in Fig. 2(b). Depending on the system, weights can be a function of RSSI value or other factors that can reflect the distance from each tag. In our case, number of reads by the ST was used for weight factors.

The algorithm which can be performed on each unknown location of ST is shown in Eq. (1). In this formula, $P_i(x, y)$ indicates the position of unknown ST i. The known position of tag j is given by $B_j(x, y)$. The number of tags which are within the communication range of the unknown ST is indicated by m where w_{ij} describes the weight value for landmark tag j used by the ST i.

$$P_i(x, y) = \frac{\sum_{j=1}^{m} w_{ij} \cdot B_j(x, y)}{\sum_{j=1}^{m} w_{ij}} \tag{1}$$

where w_{ij} is the number of times the tag is read by the ST in each report.

There are a couple of limitations in the centroid method. The localization accuracy is dependent on the density of the landmark tags. On the other hand, the power strength of the backscattered signal from passive tags varies in time. That might cause ST to detect some landmark tags that are farther than some other landmark tags that are not detected. This will cause significant localization error.

Since ST can just detect the tags that complete communication with the reader, if we confine reader's interrogation zone to the landmark tags in proximity

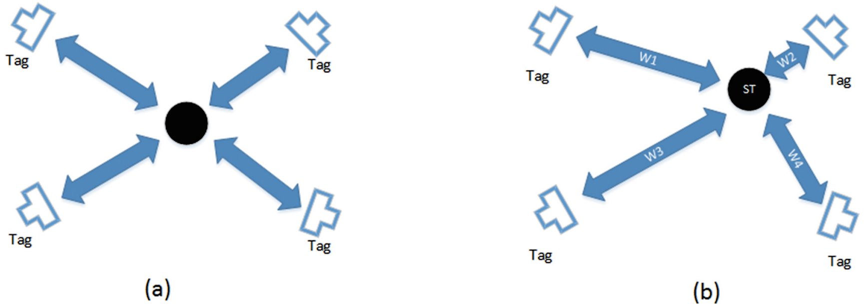


Fig. 2. (a) Centroid localization method. (b) Weighted-centroid localization method

of the ST, then the error will be smaller. In Gen 2 systems the reader can send a command to select particular tags that will be read in the next query round. During system setup, it is possible to assign the ID numbers to the landmark tags so that the only landmark tags in particular zones can be selected. The designer of the system has full freedom on how to assign the ID numbers and what kinds of zones to select. In this paper we assign the ID numbers so that we can divide the whole area into symmetric rectangular zones.

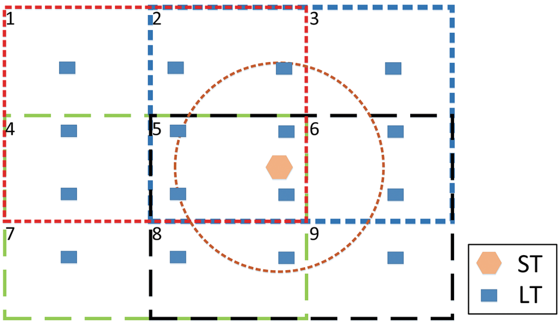


Fig. 3. Virtual zones with landmark tags (Color figure online)

Figure 3 shows an example configuration that consists of 16 landmark tags and one ST that needs to be located. One reader that interrogates the landmark tags and ST, is not presented in the figure. The 4 zones have been shown using four different color rectangles containing 9 tags each. For example, zone A with brown color covers landmark tags placed in rectangles 2, 3, 5 and 6. Zone B with dark green color covers landmark tags placed in 5, 6, 8 and 9. To avoid error in zone boundaries, there should be some overlapping area between the zones. In our example we have rectangles 5 and 6 as an overlap area between zones A and B.

First, the reader interrogates the whole area. There are 8 different landmark tags (LTs) in the detection range of the ST. As we mentioned before, there is not a linear relationship between the distance and number of detections by the ST. This will cause that in some situations, the landmark tags in rectangles 2 or 9 are detected more times by the ST compared to tags in the rectangles 5 or 8 and the estimated location error will be higher accordingly. In the second round, the reader just interrogates two zones (just the landmark tags in rectangles 2, 3, 5, 6, 8 and 9) by adding a mask in the query. In the third round, the reader will just interrogate one zone (landmark tags in 5, 6, 8 and 9). In this round we can see that the landmark tags in 2 will be filtered from our equations.

4 Simulator Core

The augmented RFID system is modelled in our newly developed Proximity-detection-based augmented RFID system simulator (PASS) framework. PASS is a time-domain system-level simulator, which is based on position aware RFID system (PARIS) simulation framework. The development environment is MATLAB 2012a on Windows 8.1 (64bits). From PARIS simulation framework, PASS inherits the behaviour model of a NXP UCODE G2XM based passive UHF RFID tag and wireless propagation channel, as well as a core framework to perform simple control and logging. While PARIS mainly focuses on ranging rather than the system behavior, we completed the functionality of generic reader and tag so that the simulator behaves according to ISO 18000-6C protocol [4,5]. The sensatag model is designed to emulate the specific sensatag device. Following the modular and hierarchical design pattern, the levels of PASS hierarchy are separated, and different models for reader, tag, sensatag, and wireless channel are also strictly divided.

5 Simulation and Experimental Results

We present the results of the simulation and the corresponding experiment in the office environment. To characterize parameters of the simulator, noise level, reader's transmitting power and other parameters are obtained based on the measurement data from the field experiment.

5.1 Simulation Results

To evaluate the idea of zoning-WCL based localization, first we establish the experimental scenario in the simulator. The area $4\,\mathrm{m} \times 2\,\mathrm{m}$ was covered with passive UHF RFID landmark tags. Landmark tags are placed in the simulator 0.5 m from one another in the direction of X axis in 3 different rows that are at the distance of 1 m from one another. A virtual robot that was tagged with an ST was moving along a trajectory defined in the simulator. The simulator ran 3 different scenarios: (a) pure WCL, (b) WCL + half-division zoning, (c) WCL + quarter division.

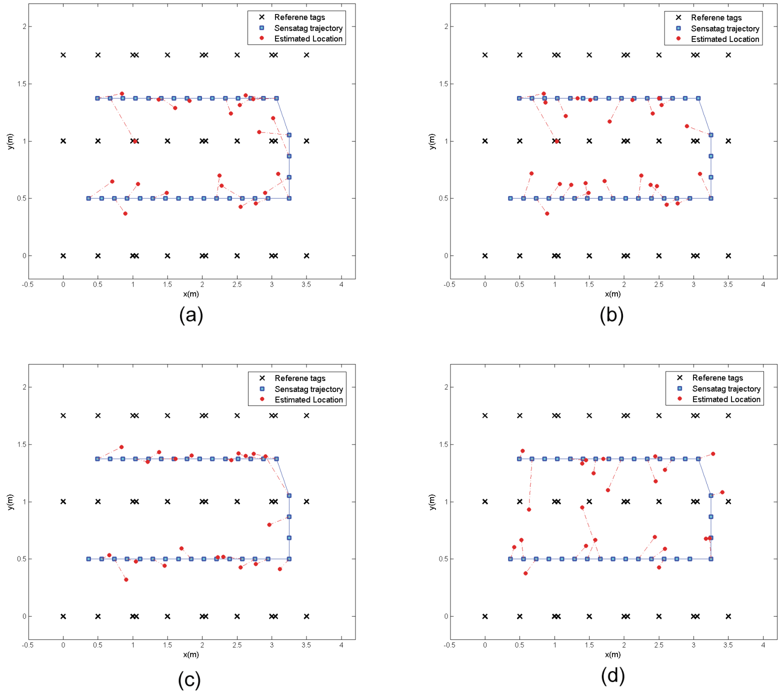


Fig. 4. Localizing the ST in landmarked area. (a) WCL method. (b) WCL + dividing zone to half in X direction. (c) WCL + dividing zone to half in Y direction. (d) WCL + dividing zone to quarters in X direction. (Color figure online)

Figure 4 shows the simulation results for the described scenarios. The blue path is the path that virtual robot moves on. The red dots are the location estimation of the ST at each time instance. Figure 4(a) illustrates the localization based on WCL. The error in Y direction is expected to be larger than the error in X direction due to more asymmetric deployment of landmarks in the direction of Y axis. In Fig. 4(b) the landmark tags are divided into two zones in the direction of X axis. That means we have two step localization procedure where in the first step the reader reads all landmark tags and the second one it interrogates the landmark tags in the half area where the ST is located. We do not see significant improvement in location estimation because the zones are still big enough to put unnecessary landmark tags in the detection area of the ST.

The same scenario was repeated in Y axis only and the results are shown in Fig. 4(c). In this figure we can see the significant decrease in localization error in the direction of Y axis error compare to the regular WCL. In Fig. 4(d) the zone divided to 4 subzones in X axis and the localization procedure now includes three steps. The root mean square error (RMSE) for zoning in X direction is shown in Fig. 5. Based on the graph, we can observe an evident improvement in X direction by dividing the zone to smaller sections. The error in Y direction increased because of involvement of less tags in Y direction. Note that if we divide the zone in Y direction as well,this error would be much smaller like the scenario that happened for X direction.

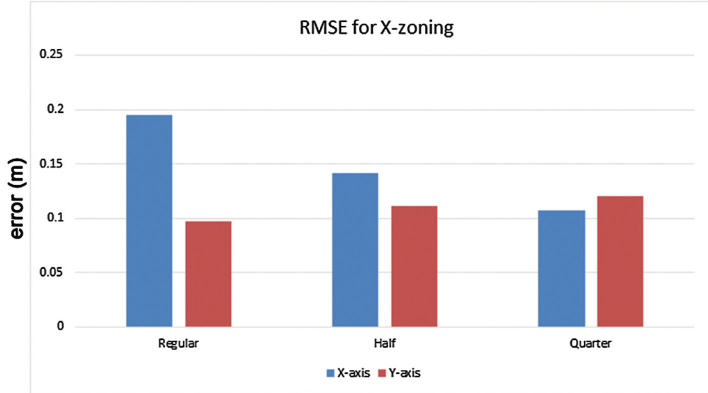


Fig. 5. RMSE for different X-axis zoning scenarios

Note that there is a non-linear relation between dividing zones and accuracy. We need also to take into consideration additional processing time required when more divisions are performed. Therefore, there is a trade-off between localization accuracy and processing time.

5.2 Real Experiments with ST

The same experimental setup has been done in a laboratory to test the assumptions in a real environment. ST was mounted on a robot that followed at a constant speed a black line path in a similar manner as in the simulator. A C# based GUI was developed to get the results from the reader, run localization algorithms and presents location of the ST on the GUI in real-time.

Stationary ST. First we placed the robot at a random location and stored 50 samples at that coordinate. We wanted to see if the zoning affects the localization accuracy. Figure 7 shows the localization results with and without quarter zoning for the random location. Real location of the ST is (175 cm, 50 cm). Each red dot is representation of 1 location estimation. Obviously the results after zoning are more precise compare to regular WCL. The average error in X direction (vertical) decreased from 33.5 cm to 18.8 cm. Figure 6 illustrates the average error and standard deviation for 50 samples on vertical direction with and without quarter zoning.

The same experiment has been run for 10 more points and the mean value of the error for all samples is bellow 21.6 cm compared to 38.1 cm for the regular WCL method.

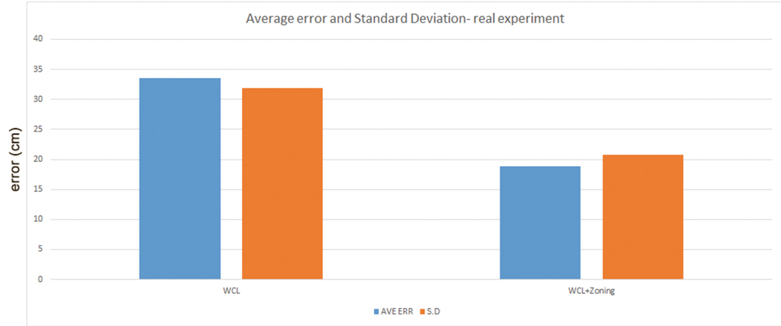


Fig. 6. Average error and standard deviation on X axis for 50 samples (real experiment).

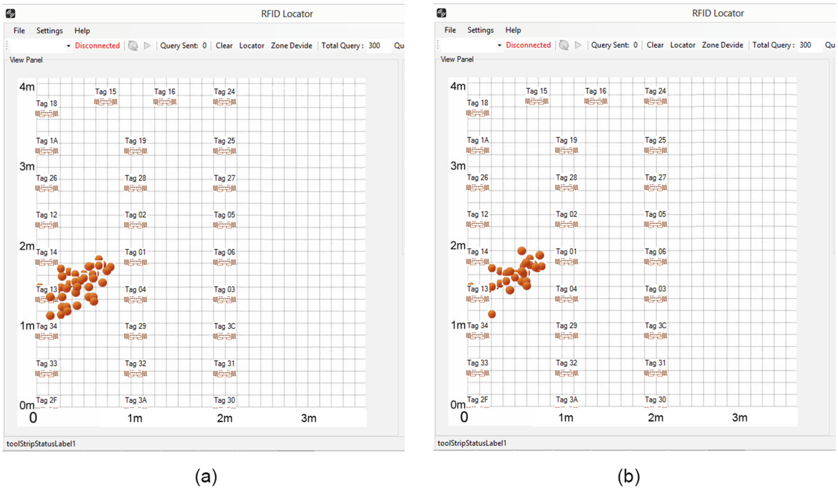
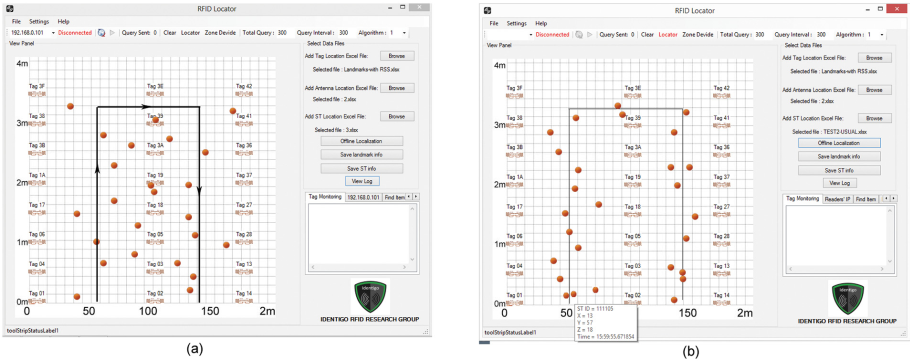


Fig. 7. GUI for real-time localization. Fifty location estimates of the ST are shown for the following cases: (a) Regular WCL, (b) WCL + quarter zoning

Mobile ST. To confirm simulation results, we repeated the same scenario of Fig. 4 but using real ST and RFID system. The ST is placed on a robot that follows the black line and move between the landmark tags. Figure 8(a) shows the location estimations during the robot movements. Considering the Y direction for example (horizontal axis), the red dots that are representation of location estimations, are mostly close to the center. That is because the farthest set of landmark tags on the right or on the left affect the estimation and we have larger error in Y direction. Figure 8(b) illustrates the same scenario but localization method is based on half zoning. We can clearly observe that the red dots converge to the path and are on both sides of the black line.



(a) (b)

Fig. 8. Real-time localization of the mobile ST when location estimation is performed using: (a) Regular WCL. (b) WCL + Half zoning (Y direction) (Color figure online)

6 Conclusion

In this paper it is demonstrated that it is possible to improve the localization accuracy of ST-based augmented RFID localization system with the combination of WCL and zoning algorithm. Based on the zoning algorithm, the outlier detection of ST towards distant reference tags is dropped, correspondingly the estimated location of target from WCL is more accurate. The performance of the proposed method is evaluated in the simulation and field experiment.

Future work includes two directions. The first direction is to improve the three steps iterative zoning procedure. Applying the Kalman filter, the prediction of ST's future position will be available [16]. Based on the prediction, the zoning algorithm would decide which zone to interrogate, which would reduce time for running localization procedure significantly. The second direction is to formulate the flexible zoning scheme. Although the current zoning algorithm is more robust to outlier detection, its potential to counter the localization heterogeneity is not developed. The heterogeneity in proximity detection-based localization solution originates from the non-uniform distribution of reference nodes within target's proximity. In flexible zoning the division of landmark tags in zones is adjustable according to the estimated position of the ST. Furthermore, the zone could be refined iteratively into smaller size. The zoning algorithm would become "zooming" algorithm. However, this method would bring about implementation challenges. Since the RFID reader interrogates a group of tags by issuing command with a specific mask, then the assignment of EPC numbers would be much more complex.

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