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A NOVEL POSITIONING SYSTEM UTILIZING ZIGZAG MOBILITY PATTERN

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Abstract—This paper proposes a new positioning system utilizing mobile readers that are programmed to move in a zigzag pattern to locate the tags. The proposed zigzag mobility pattern is able to cover an area completely within a given period, determine optimal number of required mobile readers, and find out reader placement and movement pattern. The received signal strength (RSS) model is used to exchange the information over a short range by estimating the position of the tag by means of distance information between the reader and the tag. The results obtained from this study point out that the proposed method is able to provide near exact tag position. The proposed method can achieve average error as low as 0.6 m. With this proposed method, the scanning of large areas, such as warehouses, libraries, and storage areas can be done very quickly. Mobile reader is proposed because it is cost-effective, fast, and is able to provide relatively accurate results.

1. INTRODUCTION

High-speed contactless identification ability without line-of-sight (LOS) is a major advantage of the RFID (radio frequency identification) technology, which in turn makes object tracking a very

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important electromagnetic application [1–4]. Positioning analysis [2–14] is essentially important in locating the objects of interest in a certain enterprise. The knowledge of the placement, movement, and coverage of a reader is fundamental in locating the objects smoothly and efficiently. Everyone from dealers, distributors, and manufacturers to all kinds of other ventures are enhancing the use of RFID technology to amplify the visibility of their goods on site. Mobile readers [12, 15–17] are cost-effective for certain applications, such as inventory tracking, where tags only need to be read every few seconds. For example, an area needs to be covered by τ seconds (s). Nevertheless, it is crucial to find out: (i) the number of mobile readers required to provide full coverage, (ii) position of the mobile readers, (iii) velocity (v) of the mobile reader, and (iv) the number of mobile readers that is necessary when τ is varied. Therefore, a given area has to be covered within a certain amount of time τ by a number of mobile readers with the best possible placement and movement pattern.

To fulfil the main purpose, the pattern proposed for this study is a zigzag mobility pattern [15]. The zigzag pattern can be useful and efficient in certain supermarkets, libraries, warehouses, and other sort of places for storing and locating items. The proposed method can be a good choice, because it is collision free. This means, there is no possibility to collide between the readers. The proposed method is able to determine the optimal number of mobile readers within a specified time τ to ensure the total coverage by: (i) using a zigzag pattern that will be used to find out movement pattern and placement position of the mobile reader, (ii) employing the received signal strength (RSS) model to estimate the position of the tag by comparing the estimate location to the actual location of the tag from which the accuracy of the readings can be determined, and (iii) varying the interrogation range and velocity of the mobile reader. Considering a warehouse inventory tracking application, whereby RFID tags are affixed on the objects that are probably stacked up on the shelves, which are split in aisles in the warehouse. At a given time, the system can be turned on and the mobile readers will move amongst the aisles in a zigzag pattern to locate the position of the tags as it moves along them.

In this paper, a new positioning analysis with mobile readers is proposed, where readers can be mobilized by attaching a reader to a robot [11, 12, 16] that can move around the premise in a zigzag pattern and the position of the item is calculated by means of RSS model. The number of mobile readers required is devised from the proposed zigzag pattern while the velocity, interrogation range, and time needed for the reader will be recorded for complete scanning of the whole area. With the zigzag pattern, the estimated position of a tag is relatively accurate compared to other methods as explained later. In the proposed method, the maximum time required to find all the available tags in the premise is set to 5 s (to ensure a short period of time), which can be seen as an advantage compared to other mobile reader based positioning systems [11, 12, 15, 16]. The proposed method is studied thoroughly by scattering a number of tags in different scenarios. The scope of this study will benefit many customers as deployment cost will be reduced. With the mobile readers, only a couple or a few readers are needed to do the job as opposed to fixed readers [2–4] that would need many readers to be deployed to obtain the acceptable results. Mobile readers promote faster deployment of application and decrease the hassle of wiring, like fixed reader. The details of the coverage for mobile readers, the mobility pattern, and the RSS model together with the analysis and results are discussed in the subsequent sections. Finally, concluding remarks will be included at the end of this paper.

2. PROPOSED METHODOLOGY

Fundamentally, the whole point of this study is to locate particular tags. Hence, the first thing is to switch on the reader (or readers) whenever it needs to find the location of a large number of tags (or a tag) within the given premise. Beforehand, the premise will be divided into sub-areas according to the number of mobile readers needed for the particular area, the interrogation range, and the speed of the readers. For instance, if the optimal number of mobile readers is only 8, then the whole area will be divided into 8 sub-areas accordingly. A common switch can be given for all 8 readers. When the switch is turned on, all 8 readers will simultaneously move with same zigzag pattern as well as velocity to look for the tags. The information of the tags are on first come first serve basis, whereby the information of the tags will be read by the mobile reader instantaneously once it passes a tag within its range. Thus, when the required information has been obtained, the user can switch off the readers or perform another request. In this way, the reader does not have to be activated whole time. Therefore, the proposed system can conserve energy. The system can be also set with a timer to work periodically.

2.1. Coverage for Mobile Readers

Firstly, to locate the specific tags, the mobile readers are activated. Once they are switched on, the mobile readers will then move according to a zigzag pattern to locate the tags. Once all the tags required are

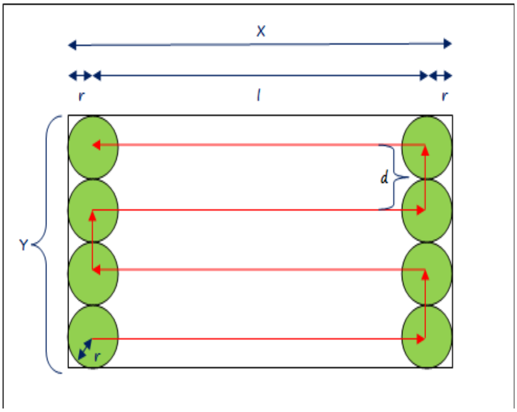


Figure 1. General mobility pattern.

read by the mobile readers, they will return to their original position to wait for the next instruction. Figure 1 shows the movement pattern of the mobile readers, where X and Y is the horizontal and vertical portion, respectively at which the mobile reader will travel, l is the horizontal distance, d is the vertical distance, and r is the interrogation range.

The majority of researches have considered two dimensions positioning analysis [2–4, 11, 12, 15, 16] and assumed the interrogation zone of a reader as a two dimensional circle. Detailed report on circular radio coverage is also provided in [18, 19]. Moreover, circular radio coverage is perfect for the applications whenever tag orientation is unpredictable [1]. The figure above shows the zigzag pattern of the mobile reader and the range it will cover. From Figure 1, the following equation can be formed as follows.

$$X = 2r + l \tag{1}$$

By rearranging Equation (1), the following can be obtained.

$$l = X - 2r \tag{2}$$

An important note is that, the horizontal and the vertical distance of the mobile reader is calculated as $X - 2r$ and $Y - 2r$, respectively, since the circle does not travel end to end. Also, the following equation can be found from Figure 1,

$$d = 2r \tag{3}$$

Let d_{no} is the number of d's needed and l_{no} be the number of l's needed in a given area. Hence, the number of d's needed for the vertical part of the area is,

$$d_{no} = \frac{Y - 2r}{2r} \tag{4}$$

As for the horizontal path, the number of l's is,

$$l_{no} = d_{no} + 1 = int(d_{no}) + 1 \tag{5}$$

where *int* denotes an integer operation.

Combining both the number of vertical and horizontal paths needed, the distance traveled by a mobile reader can be formulated as below.

$$Distance\ traveled = (l_{no})(l) + (d_{no})(d) \tag{6}$$

Then, to obtain the number of mobile readers M, the following is obtained:

$$M = \frac{Distance\ traveled}{Time * Velocity} \tag{7}$$

Equation (6) is substituted into Equation (7), producing:

$$M = \frac{(l_{no})(l) + (d_{no})(d)}{\tau * v} \tag{8}$$

Equations (2)–(5) are then substituted into Equation (8) to obtain the following:

$$M = \frac{(d_{no} + 1)(X - 2r) + \left(\frac{Y-2r}{2r}\right)(2r)}{\tau * v} \tag{9}$$

After working through all equations from (1) to (9), the following equation is obtained.

$$M = \frac{\left(\frac{Y-2r}{2r}+1\right)(X-2r)+(Y-2r)}{\tau * v} = \frac{\left(\frac{Y}{2r}\right)(X-2r)+(Y-2r)}{\tau * v} \tag{10}$$

Finally,

$$M = \frac{XY - 4r^2}{2 * r * \tau * v} \tag{11}$$

The Equation (11) indicates that, τ and v is inversely proportional to $M(\tau \propto \frac{1}{M}$ and $v \propto \frac{1}{M})$ while M is proportional to the inverse of r only approximately.

2.2. RSS Model

The RSS model is used to determine the mobile reader to tag distance. The general basic formula for the RSS model is given as the ratio of the received power to the transmitted power for the given mobile reader gains, reading range and wavelength under perfect circumstances. The following relationship between the received power P_r and the transmitted power P_t can be obtained [2, 3]:

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4\pi}\right)^2 \left(\frac{1}{d}\right)^n \tag{12}$$

where G_t and G_r are the gains of the tag and the mobile reader, respectively, λ is the wavelength, d is the distance between tag and mobile reader, and n is the signal strength exponent, which depicts the influence of the transmission medium. From Equation (12), the RSS between the reader and the tag antennas can be revised as below [2]:

$$RSS(d) = 32.4\,(\mathrm{dB}) + 20\log\left(\frac{f}{1\,\mathrm{GHz}}\right) - 10 * n * \log\left(\frac{d}{1\,\mathrm{m}}\right) \quad (13)$$

where f is the carrier frequency. The d can be determined by rearranging Equation (13) as below.

$$d = 10^{\frac{RSS(d) - 32.4\,(\mathrm{dB}) - 20\log\left(\frac{f}{1000}\right)}{-10*n}} \quad (14)$$

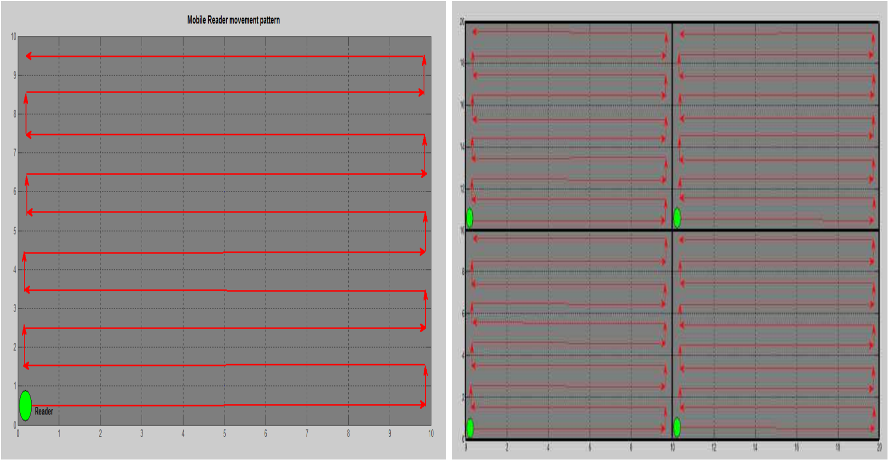
Free space propagation is implied between the reader and the tag, thus n is equal to 2 (i.e., equal power distribution in transmission medium as reported in [2] and does not take in consideration of path obstruction, reflection, absorption, and other attenuation effects). Then, the general equation to estimate the tag position can be obtained in the following [2, 3].

$$(x[\text{estimate}], y[\text{estimate}]) = \frac{\sum_{i=1}^{k}\left[\left(\frac{1}{d_i}\right)^2 R_i(x, y)\right]}{\sum_{i=1}^{k}\left(\frac{1}{d_i}\right)^2} \quad (15)$$

where $R_i(x, y)$ denotes the coordinates of mobile readers that move in a zigzag pattern and k denotes the number of mobile readers involved in tracking process. In Equation (15), k is always equal to 1 as there is only one mobile reader involved in each sub-area to locate a tag.

2.3. Mobility Pattern

The zigzag mobility pattern as shown in Figures 2(a) and 2(b) explains on how the reader will move around a specified area. The zigzag pattern is an ideal solution that has many aisles of items to look for. Theoretically, this pattern will cause the reader to stop when it reaches the tag. This fundamental unit is shown in Figure 2(a), is replicated as many times as needed according to the number of mobile readers obtained from Equation (11). Therefore, Figure 2(a) is just a part of the whole premise. In this sub-area, the specified reader will sweep through the given sub-area for tags. To provide coverage to the whole area, this fundamental unit is multiplexed accordingly. For example, if $M = 4$, then the mobility pattern would look like Figure 2(b). From the proposed pattern in Figure 2(b), it can be seen that the mobile



(a) (b)

Figure 2. (a) Fundamental unit with one mobile reader and the zigzag pattern. (b) Replicating the fundamental unit for complete coverage of the whole area with 4 mobile readers and the zigzag movement pattern.

readers move in a zigzag pattern in all sub-areas. The readers will be able to go through all the aisles.

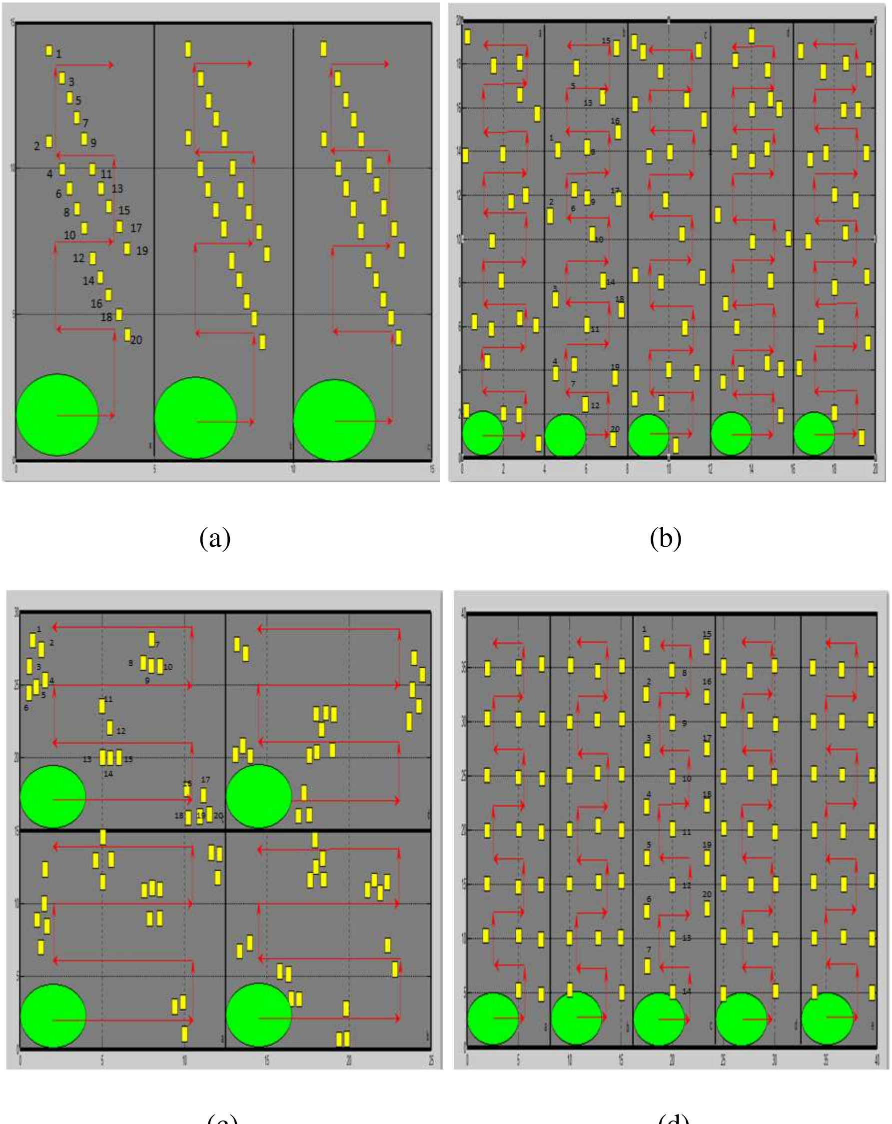
After calculating the number of mobile readers needed (for example, $M = 4$, like Figure 2(b)), the premise is then divided into 4 sub-areas, a mobile reader is allocated at the starting point in each of the sub-areas. All the readers will move simultaneously to find the required tags. Thus, the whole area is swept through in one shot. For instance, if the time taken for one reader to go through its area is about 4 s to 5 s; this means, within 4 s to 5 s, the whole area would have been covered as well due to the fact that all other three mobile readers have gone through their designated areas at the same time.

3. RESULTS AND PERFORMANCE EVALUATION

For better understanding, a few scenarios have been chosen, where the number of mobile readers, area, velocity, and the interrogation range are varied. In each scenario, the time of the mobile reader to locate the tags is recorded. In this study, the number of tags that are to be investigated is bounded to 20. From our study [20], it is found that, for I.Code 1 tags, it takes approximately 3 s to detect all 20 tags for a standard mode. Therefore, to read each tag in the vicinity, it takes about 0.12 s to 0.15 s. For the convenience, the maximum time for the mobile reader to complete its task, τ is set to 5 s for all the scenarios.

3.1. Scenario 1: Tags are in a Non-uniform Pattern

For scenario 1, an area of $15\,\mathrm{m} \times 15\,\mathrm{m}$ is investigated as shown in Figure 3(a). The velocity of the reader is $5\,\mathrm{m/s}$ [15] while the



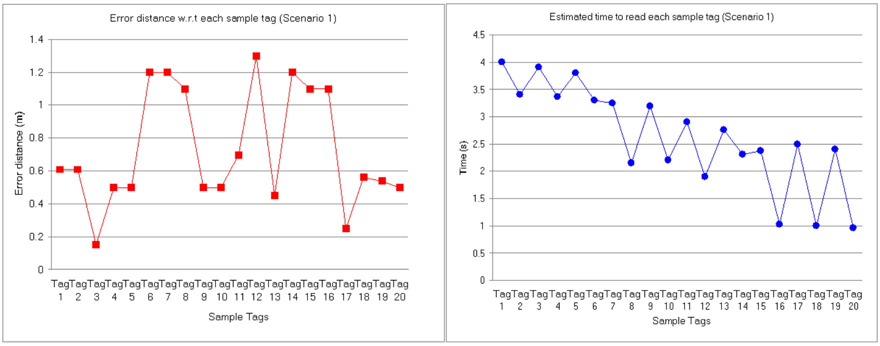
(a) (b)

(c) (d)

Figure 3. Mobility pattern for readers while tags are arranged in (a) non-uniform pattern, (b) scattered randomly, (c) cluster, (d) uniform pattern.

interrogation range r is 1.5 m. The time for the reader to sweep through all the tags is set to a maximum of 5 s as mentioned above. The number of mobile readers needed for this space can be calculated using Equation (11). It is found, the number of mobile readers required is 3. Hence, the 15 m $\times$ 15 m area is divided into 3 parts (parts a, b, and c) to accommodate the number of readers required. All of the 3 readers will move simultaneously in a zigzag pattern as presented in the figure to locate the tags in the given area. After 5 s, all the readers will then go back to its original position and wait for the next instructions. Within those 5 s, all the 20 tags in each sub-area are located by the mobile readers. From Equation (11), it can be seen that the number of readers needed depends on a few variables. Therefore, it is actually up to the user to set the number of readers for a premise with such an area size.

The error distance or deviation between the actual tag and the estimated tag recorded by the mobile reader is calculated and the results are as in Figure 4(a). The reason of the large deviation in some cases is due to the location of the tag, which is far from the movement path of the mobile reader. From Figure 3(a), there are about 7 tags, which are placed far from the reader's path. The obtained worst error is 1.3 m while the lowest error is 0.15 m. The obtained average error is 0.7 m (< 1 m error) for this scenario. With the data obtained, the time graph is also acquired as presented in Figure 4(b). The distance traveled is divided by the velocity to obtain the time required to reach a particular tag. It can be seen that the proposed system takes maximum 4 s to complete part a of Figure 3(a). It can be also seen that Tag 20 is the first tag or the closest tag to the mobile reader's original position; therefore, it merely takes about 0.9 s to locate that tag.

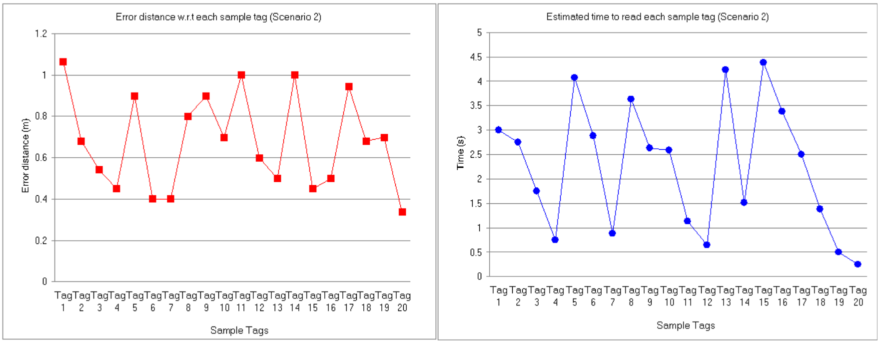


(a) (b)

Figure 4. Scenario 1: (a) Error distance for sample tags. (b) Time required for the mobile reader to read the tags.

3.2. Scenario 2: Tags are Scattered Randomly

In scenario 2, the tags are randomly scattered about a 20 m by 20 m premise. The interrogation range is set to 1 m while the velocity of the mobile reader is 8 m/s. For simplicity sake, τ is set to 5 s. Thus, using Equation (11), the number of mobile readers required is 5. Since, there are 5 mobile readers, the 400 m^2 area is divided into 5 parts (parts *a, b, c, d,* and *e*) as in Figure 3(b). All 5 mobile readers behave similarly and will start moving in a zigzag pattern and finish sweeping the whole area synchronously. For example, part *b* in Figure 3(b) is chosen to analysis the error distance and time of each tag. Tag 1 in Figure 5(a) shows the largest error of 1.06 m, since the tag is far from the mobile reader. The errors are mostly caused by either the vertical distance or the horizontal distance. When both of the horizontal and vertical distances increase, the error distance becomes larger. The smallest error is 0.3 m while the average error distance for this scenario is 0.67 m. From Figure 3(b) and the time graph of Figure 5(b), Tag 20 is the first detected tag while Tag 15 is the last detected tag. The last tag takes 4.38 s to be detected. The closest tag to the mobile reader is Tag 20, which takes only 0.25 s to locate by the mobile reader. Although the tags are scattered randomly in this scenario, the time to locate each of the tags does not increase. Thus, the arrangement of the tags does not cause an impact to the time for each tag location.



(a) (b)

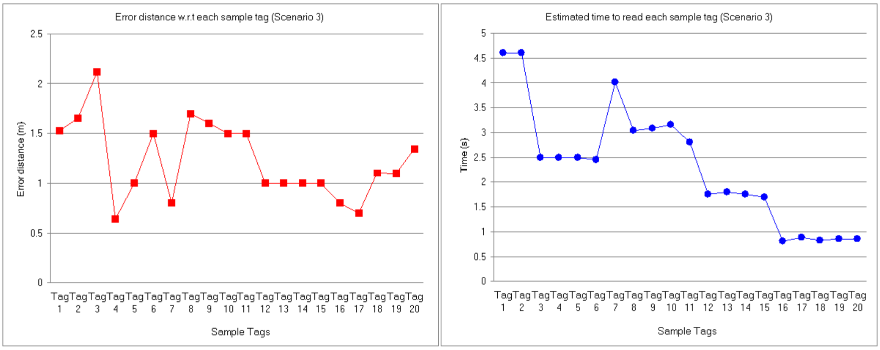
Figure 5. Scenario 2: (a) Error distance for sample tags. (b) Time required for the mobile reader to read the tags.

3.3. Scenario 3: Tags are Placed in a Cluster

The third scenario is for a 25 m $\times$ 30 m area as shown in Figure 3(c). The interrogation range is 2 m while the velocity is increased to 10 m/s. The time allocated to detect all the 20 allocated tags remains at 5 s. Using the same Equation (11), the number of required mobile readers is 4. Since, there are 4 mobile readers, the total area is divided into 4 parts (parts *a, b, c,* and *d*) as presented in Figure 3(c). For this example, the tags in part *c* of Figure 3(c) are to be investigated for error distance and time computations. Most of the tags offer error distances much lower than 1.5 m as shown in Figure 6(a), except Tag 3 that is giving the worst error of about 2.1 m. The average error for this scenario is 1.2 m and the nearest tag (Tag 4) is located with an error distance of 0.64 m. Since the tags are placed in a cluster for this scenario, the obtained error deviation appears to be in a group as well. This is because the tags in the same cluster are around the vicinity of the mobile reader's path. From Figure 3(c), Tag 1 is the last tag to be located while Tag 16 is the first to be located. It is easy to see from Figure 6(b), Tag 1 and Tag 16 are located within 4.6 s and 0.81 s, respectively. At this point, the time graph mimics the pattern of the tags in a way. The time between the tags, which are close together, are located by the mobile reader within a close range of time.

3.4. Scenario 4: Tags are Uniformly Placed

This example explores the scenario 4, where the tags are placed in an order. The premise investigated is a 40 m by 40 m with mobile readers



(a) (b)

Figure 6. Scenario 3: (a) Error distance for sample tags. (b) Time required for the mobile reader to read the tags.

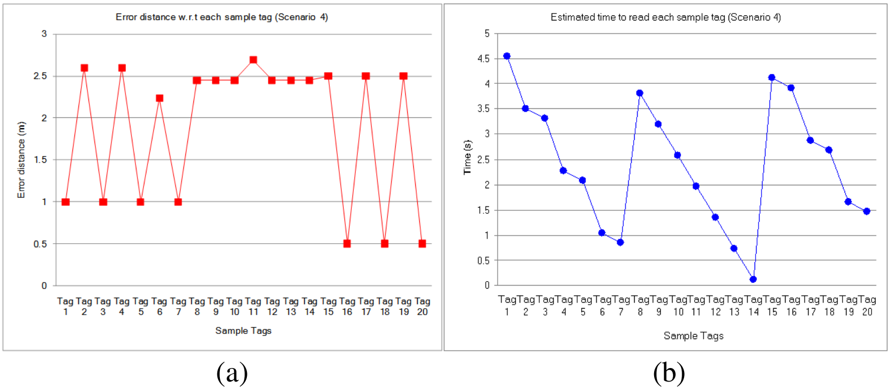


Figure 7. Scenario 4: (a) Error distance for sample tags. (b) Time required for the mobile reader to read the tags.

traveling at 13 m/s and have an interrogation range of 2.5 m. For ease of calculation, the time allocated for all tags to be read is assumed to be a maximum of 5 s. The number of mobile readers required is 5, which is obtained from Equation (11). It is shown in Figure 3(d) that the whole area is to be divided into 5 parts (parts *a, b, c, d,* and *e*). In this case, part *c* of Figure 3(d) is investigated. From Figure 7(a), it is found that, the error distance is either smaller or larger. The error is smaller when the tags are close to the mobile reader and larger when those are placed far away. The obtained worst error is 2.9 m while the highest accuracy or the lowest error is 0.5 m. The average error distance is 1.9 m for this scenario. The pattern of the error graph is almost a zigzag pattern. This is because the mobile reader is moving in a zigzag pattern while reading all the tags that are placed uniformly. The readings with the same error are probably in a same line or having the same distance from the reader. The time graph in Figure 7(b) shows that the tags are placed in 3 lines, because there are almost 2 linear slopes appeared that are similar to one another and 1 perfectly linear slope. It takes about 4.54 s to complete locating Tag 1 and takes about 0.12 s to locate Tag 14, which is the first tag the mobile reader comes across. Table 1 lists the performance summary obtained from all four scenarios.

The positioning accuracy of the proposed method is also compared with BlueBot (unrefined accuracy with moving of 801.11b client device) [11], BlueBot (refined accuracy with moving of robot attached with an RFID reader) [11], and our square grid based positioning (with fixed RFID reader) [2] systems as illustrated in Table 2. To perform fair comparison, all experimental settings are kept analogous. It can be

Table 1. Performance summary.

Area Dimension ($X \times Y$)	Tag Pattern	Sub-area Length	Tag Density	Reading Range (m)	Tag Reading Speed (Min.)	Mobile Readers	Velocity of Reader (m/s)	Max. τ (s)	Avg. Error (m)
15m×15m	Non-uniform	X: 5m Y: 15m	3.7/m^2	1.5	4 tags/s for all sub-areas (for all readers) at the same time	3	5	4	0.728
20m×20m	Scattered randomly	X: 4m Y: 20m	4/m^2	1		5	8	4.38	0.677
25m×30m	Cluster	X: 12.5m Y: 15m	9.4/m^2	2		4	10	4.6	1.229
40m×40m	Uniform	X: 8m Y: 40m	16/m^2	2.5		5	13	4.54	1.934

Table 2. Performance comparison between existing methods and the proposed method.

	BlueBot (Unrefined Accuracy)	BlueBot (Refined Accuracy)	Square Grid	Proposed Method
Average Error (m)	4.092	1.483	0.355	0.655
Worst Error (m)	8.00	2.583	0.5051	1.035

seen that the proposed method outperforms both BlueBot positioning systems. It is also found that the fixed reader utilizing square grid reader network has better accuracy than that of the proposed method; however, the overall cost would be higher. Hence, the proposed system utilizing zigzag mobility pattern is definitely a better solution compared to fixed reader based positioning system in terms of cost.

4. CONCLUSION

This paper has offered a new positioning and object tracking method using one of the latest gadgets, namely, mobile reader. The study involves RFID mobile reader that moves in a zigzag pattern, thus the position of the tags is calculated through RSS model as well as complete coverage is ensured to the indoor area. The proposed system can allow multiple readers to move concurrently to locate the required tags; thus, the whole area can be swept through in one shot. The obtained results confirm that the proposed system can be a suitable alternative in terms of accuracy and cost. The proposed positioning method is able to provide tracking error with less than a meter and in some situations, the estimated position of the tags can be extremely close to the exact position. It is found that the proposed system is able to locate the tags for all four scenarios with an average time of 2.4 s and a maximum time of 5 s, which is better compared to other mobile reader based positioning systems [11, 12, 15, 16]. From the critical results and analysis, it is also found that, only Tag 1 (scenario 2), Tag 3 (scenario 3), and Tags 2, 4, and 11 (scenario 4) placed in the worst position (this is an irregularity, where tags placed almost outside the sensing range of the mobile reader), thus give the error distance marginally greater than the interrogation range of the mobile reader. However, these five tags are still successfully positioned by either vertical or horizontal scanning of the mobile reader and will be never missed completely. In future, the method proposed in this study can be implemented in some real applications, such as supermarkets and warehouses to locate all the tags smoothly and orderly.

REFERENCES

1. Lahiri, S., *RFID Sourcebook*, IBM Press, New Jersey, 2006.
2. Tan, K. G., A. R. Wasif, and C. P. Tan, "Object tracking utilizing square grid RFID reader antenna network," *Journal of Electromagnetic Waves and Applications*, Vol. 22, No. 1, 27–38, 2008.
3. Reza, A. W. and T. K. Geok, "Objects tracking in a dense reader environment utilizing grids of RFID antenna positioning," *International Journal of Electronics*, Vol. 96, No. 12, 1281–1307, 2009.
4. Reza, A. W. and T. K. Geok, "Investigation of indoor location sensing via RFID reader network utilizing grid covering algorithm," *Wireless Personal Communications*, Vol. 49, No. 1, 67–80, 2009.
5. Mitilineos, S. A. and S. C. A. Thomopoulos, "Positioning accuracy enhancement using error modeling via a polynomial approximation approach," *Progress In Electromagnetics Research*, Vol. 102, 49–64, 2010.
6. Tayebi, A., J. Gomez, F. Saez de Adana, and O. Gutierrez, "The application of ray-tracing to mobile localization using the direction of arrival and received signal strength in multipath indoor environments," *Progress In Electromagnetics Research*, Vol. 91, 1–15, 2009.

7. Seow, C. K. and S. Y. Tan, "Localization of omni-directional mobile in multipath environments," *Progess In Electromagnetics Research*, Vol. 85, 323–348, 2008.
8. Bahillo Martinez, A., S. Mazuelas Franco, J. Prieto Tejedor, R. M. Lorenzo Toledo, P. Fernandez Reguero, and E. J. Abril, "Indoor location based on IEEE 802.11 round-trip time measurements with two-step NLOS mitigation," *Progress In Electromagnetics Research B*, Vol. 15, 285–306, 2009.
9. Mak, L. C. and T. Furukawa, "A time-of-arrival-based positioning technique with non-line-of-sight mitigation using low-frequency sound," *Journal of Electromagnetic Waves and Applications*, Vol. 22, No. 5, 507–526, 2008.
10. Prieto Tejedor, J., A. Bahillo Martinez, S. Mazuelas Franco, R. M. Lorenzo Toledo, P. Fernandez Reguero, and E. J. Abril, "Characterization and mitigation of range estimation errors for an RTT-based IEEE 802.11 indoor location system," *Progress In Electromagnetics Research B*, Vol. 15, 217–244, 2009.
11. Patil, A., J. Munson, D. Wood, and A. Cole, "BlueBot: Asset tracking via robotic location crawling," Tech. Rep. No. RC23510, IBM T. J. Watson Research Centre, Hawthorne, NY, 2005.
12. Burgard, D. W., D. Fox, K. Fishkin, D. Hahnel, and M. Philipose, "Mapping and localization with RFID technology," *IEEE International Conference on Robotics and Automation*, Vol. 1, 1015–1020, New Orleans, LA, USA, 2004.
13. Oztekin, A., F. M. Pajouh, D. Delen, and L. K. Swim, "An RFID network design methodology for asset tracking in healthcare," *Decision Support Systems*, Vol. 49, 100–109, 2010.
14. Weichert, F., D. Fiedler, J. Hegenberg, H. Muller, C. Prasse, M. Roidl, and M. ten Hompel, "Marker-based tracking in support of RFID controlled material flow systems," *Logistics Research*, Vol. 2, 3–21, 2010.
15. Anusha, S., "RFIDcover: A coverage planning tool for RFID networks with mobile readers," Dissertation paper, Indian Institute of Technology Bombay, India, 2005.
16. Ladd, A. M., K. E. Bekris, A. Rudys, G. Marceau, L. E. Kavraki, and D. S. Wallach, "Robotics-based location sensing using wireless ethernet," *Journal of Wireless Networks*, Vol. 11, 189–204, 2005.
17. Cortés, J., S. Martínez, T. Karatas, and F. Bullo, "Coverage control for mobile sensing networks," *IEEE Transactions on Robotics and Automation*, Vol. 20, No. 2, 243–255, 2004.
18. Li, L. W., C. P. Lim, and M. S. Leong, "Near field of electrically

small thin square and rectangular loop antennas," *Progress In Electromagnetics Research*, Vol. 31, 181–193, 2001.

19. Lim, C.-P., L.-W. Li, and M.-S. Leong, "Method of moments analysis of electrically large thin square and rectangular loop antennas: Near- and far-zone fields," *Progress In Electromagnetics Research*, Vol. 34, 117–141, 2001.
20. Reza, A. W., T. K. Geok, K. J. Chia, and K. Dimyati, "RFID transponder collision control algorithm," *Wireless Personal Communications*, in press, DOI: 10.1007/s11277-010-9932-8 (available online), 2010.