An Optimized Indoor RFID Positioning System Using 3D Mobility Pattern

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Abstract—**Radio frequency identification (RFID) is the widely used identification system that uses radio frequency for the detection of object position. A new RFID technique for the localization of tags in a 3D space is presented in this study. According to this technique, the optimized number of mobile readers is needed to afford full coverage within a given period of time. The mobile readers are programmed in such a way that they move in a zigzag pattern for detecting the tags. The received signal strength (RSS) model is used for determining the tag positions. From the obtained results, it can be observed that the proposed model can achieve an average error distance as low as 0.27 m for a given scenario and if the obstacles are placed in the test environment, the average error distance has only increased to 0.38 m. In order to evaluate the accuracy of the proposed technique, a comparison between the existing and proposed model is presented.**

Index Terms—**radio frequency identification, RFID tags.**

I. INTRODUCTION

Nowadays, object tracking generally is a challenging problem. Tracking is usually performed for the higher-level of applications where the requirement is the exact location [1-7] and/or shape of the objects. Because of the high speed contactless identification ability, radio frequency identification (RFID) becomes one of the highly used technologies, which can be used for more smooth and efficient object tracking applications [2, 8-15]. At present, RFID system is substituting the barcode system and is widely used in various types of commercial applications, such as in the retail industry, toll payment, supply chain management, libraries, shopping, e-passports, and many other areas as the main object tracking system [16-20]. One of the biggest challenges in RFID large scale deployment is the positioning of RFID reader antennas, which is necessary for efficient tracing of all the tagged objects inside the RFID reader environment.

The use of mobile readers [8, 21, 22] eliminates the requirement of a large number of fixed reader antennas and thus becomes cost effective. It needs only a few seconds to read the tags by using a few mobile reader antennas [23]. Though there are existing RFID systems for mobile reader, but there is still no solution to locate the position of the tags with mobile readers in the 3D space, where the positioning in 3D is more precise than the 2D space. The user can identify the positions of tags more accurately, if the *X, Y,* and especially *Z* coordinates of the tags are known. It helps the user to find out the tagged objects easily and precisely. With this motivation, a new technique is introduced in this paper, which is able to determine the optimized number of mobile reader antennas required for providing 100%

coverage in a 3D space. The antenna coverage pattern of mobile reader is assumed to be circularly polarized, with the network system connectivity radius equals to the coverage radius. The passive tags, which operate at high frequency of 13.56 MHz, are used in the development of the tracking technique [23]. Each of the mobile readers is attached to a robot [21, 24, 25], which is programmed to move in a specific zigzag pattern. The robots are located both on the rooftop and the floor of the test area and move in a zigzag pattern to cover the whole area. In the proposed method, there is no chance of collision between the mobile readers. The maximum time required to find all the available tags is set to 8 seconds and it is advantageous compared to other same type of positioning systems [8, 21, 25]. In this study, the result shows that the proposed method offers lower error distance than the existing 2D zigzag method [23].

II. PROPOSED METHODOLOGY

The main objective of this study is to localize the positions of the tags in the 3D space. Before switching on the mobile readers to locate those tags in a given time, the calculation for the number of mobile readers is needed in different types of test environment. According to the optimal number of mobile readers, the test environment will be divided into sub-areas. For tag tracking, each sub-area contains two mobile readers: one mobile reader is placed at the top of the test area and another is placed at the bottom of the test area. After that, the mobile readers are attached into robots, which are programmed to move in the same sized zigzag pattern with the same velocity, so that the readers can cover the whole area. First come first serve (FCFS) is the basis to get the information from the tags. The mobile reader moves within its selected area, if any tag comes within the reading area at that time then the information will be read by the particular mobile reader.

(1) Mobility Pattern

The zigzag mobility pattern for the proposed method shown in Fig. 1(a) and Fig. 1(b) describes about the movements of the mobile readers in a test environment. If the test environment is very large, then the whole area is needed to be divided into few sub-areas to decrease the time for locating the tags. The obtained mobile readers are divided in two groups. This is because, in 3D space, some readers are needed for the top position of the selected area and some are needed for the bottom side to cover the *Z*-axis. For example, if the number of mobile readers is 6, then the number of sub-area will be 3, as shown in Fig. 1(a). In this

Figure, it can be seen that, the readers move in a zigzag pattern in all sub-areas. Hence, the entire area is read through in one shot, which means, if time required for each reader to cover the sub-area is 8 seconds then the whole area can be covered in 8 seconds too.
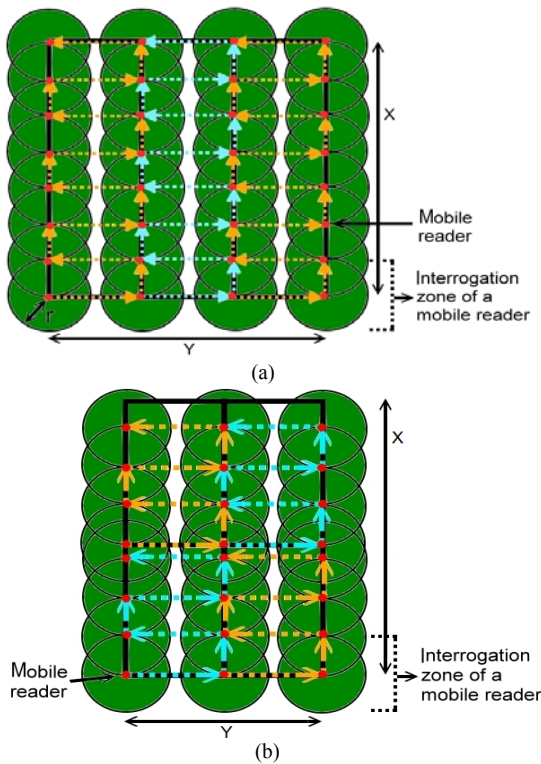

(a)

(b)

Figure 1. Zigzag movement pattern of mobile readers in X-Y view (a) X=Y area (b) X>Y area.

There are two ways to split the entire test environment according to the length of X and Y coordinates of the test environment. For $X = Y$, the test area can be divided into a few sub-areas, as shown in Fig. 1(a), where the Y coordinate is divided into some sub-areas without dividing the X coordinate. Referring to Fig. 1 (a), green circles represent the interrogation zone of the mobile reader. Rectangle or square box with black color line is the test area in X-Y view. Circles marked by the red color are the mobile readers, while zigzag pattern line and arrows marked by yellow and blue colored line represents the movement of each mobile reader inside the test environment.

In the case of $X>Y$, the test area X and Y will be divided according to the length of X and Y coordinates into two or more parts if necessary. In this way, we can minimize the distance needed to be travelled by the mobile reader. If the less number of mobile readers is needed to cover the entire test area, just divide Y into some sub-areas without dividing X. Fig. 1(b) shows that the pattern of the entire area is divided into 4 sub-areas for the case of $X>Y$.

(2) Coverage Area

The proposed movement pattern of the mobile reader is shown in Fig. 2. Interrogation zone of the mobile reader is assumed as a sphere (Fig. 2). Green and blue spheres are the reading zone of the mobile readers for the top and bottom of the coverage area. Circles marked by the red color are mobile readers. Dotted lines with an arrow in orange and purple color are the movement path of each mobile reader.

Cuboids with no color and black outline are the sub-areas to be tested. The mobile reader starts moving from the corner of sub-area and moves along the edge of sub-area. After reaching to the opposite corner, the reader will go up r distance at X-axis and starts moving from the left side to the right side through a line lies in the Y-axis of sub-area. The steps keep going repeatedly until the mobile reader reaches to another edge of the sub-area. In this way, the entire area will be covered by the mobile readers.
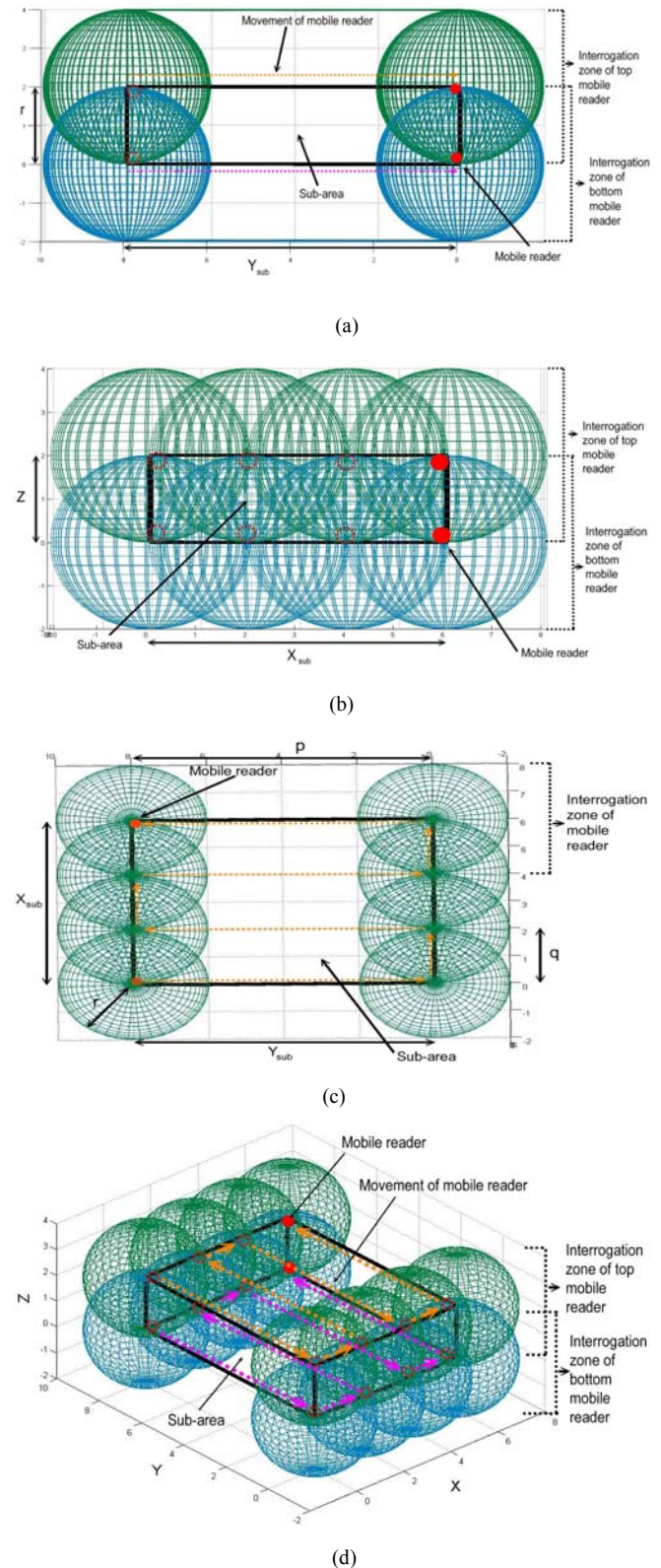

(a)

(b)

(c)

(d)

Figure 2. Mobility and placement pattern of mobile reader antennas in sub-area (a) Y-Z view (b) X-Z view (c) X-Y view (d) 3D view.

(3) Calculation of Mobile Reader Antennas

This calculation is based on the 3D positioning analysis. The interrogation zone of a reader is assumed as a 3D sphere. Hence, the area of test space A is,

$$A = X \times Y \times Z \qquad (1)$$

where X, Y, and Z are the dimensions in meter for X-axis, Y-axis, and Z-axis of the test space. The zigzag pattern of the mobile reader for a sub-area with different views is shown in Fig. 2. In Fig. 2(c), p is the travelling distance of a mobile reader at Y-axis, q is the travelling distance at X-axis, and r is the interrogation range of the mobile reader. The Z is assumed to be the same as interrogation range r of the mobile reader. Here, two mobile readers are needed (one at top and another one at bottom of Z-axis) for each sub-area of the test environment. From Fig. 2(c), we have,

$$Y_{sub} = p \qquad (2)$$

Here, Y_{sub} is the length at Y-axis of sub-area of the test area and the travel distance q in X-axis is-

$$q = r \qquad (3)$$

Let q_{no} is the number of q's needed and p_{no} is the number of p's needed for a given area. Therefore, q_{no} can be calculated from Fig. 2(c), that is-

$$q_{no} = \frac{X}{r} \qquad (4)$$

where r is the reading range of the mobile reader. Similarly, p_{no} can be calculated from Fig. 3(a), that is-

$$p_{no} = q_{no} + 1 \qquad (5)$$

As we mentioned earlier, two mobile readers are needed for covering each sub-area. The time needed for each mobile reader is S_{no} that will cover the assigned sub-area M, that becomes,

$$S_{no} = \frac{M}{2} \qquad (6)$$

For determining the number of mobile readers, calculations are done in two different cases. First, for the case $X = Y$ and second, for the case $X > Y$. Hence, the equation to obtain M will be different according to two different cases.

For the Case $X = Y$:

From Fig. 3(a), the length of the sub-area at X-axis is, $X_{sub} = Y_{sub}$, because the length of Y is equal to the length of X. Therefore, if the time needed for each mobile reader is S_{no}, then the equation for Y will be formulated as follows-

$$Y = Y_{sub} \times S_{no} \qquad (7)$$

The total distance travelled by the mobile readers in the whole test area can be calculated by summing the distance travelled at Y-axis (p_{no} time with the distance of Y) and X-axis (S_{no} time with the distance of X). Thus, it can be formulated as below.

$$\text{Distance travelled, } D = (p_{no})Y + (S_{no})X \qquad (8)$$

Therefore, the number of mobile readers M can be obtained by the formula,

$$M = \frac{D}{\tau \times v} \times 2 \qquad (9)$$

where τ is for time and v is for velocity. If the value of (8) is substituted into (9), it becomes,

$$M = \frac{(p_{no})Y + (S_{no})X}{\tau \times v} \times 2 \qquad (10)$$

where τ is the time required to detect all the tags, and v is the velocity of the mobile reader, which operates in the sub-area. Substituting the value of (4), (5), and (6) into (10), we get the number of mobile readers needed to detect the tags in a particular area as

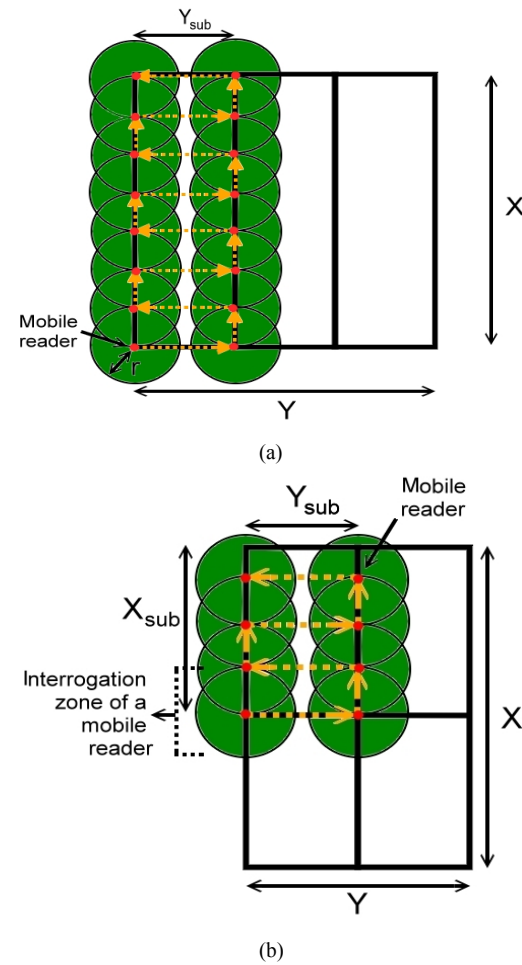$$M = \frac{\left(\dfrac{X}{r} + 1\right)(2Y)}{(\tau v - X)} \qquad (11)$$

(a)

(b)

Figure 3. One of the sub-areas of test area with (a) $X=Y$ (b) $X>Y$.

For the Case $X > Y$:

From the test area $X > Y$ (Fig. 3(b)), X and Y are needed to be divided into more than one sub-areas, so that the travelled distance of the mobile readers decreases. Therefore, for this case, the mobile reader for each sub-area can be calculated using (11) by substituting X by X_{sub} as follows:

$$M_{sub} = \frac{\left(\dfrac{X_{sub}}{r} + 1\right)(2Y)}{(\tau v - X_{sub})} \qquad (12)$$

The entire area contains two sub-areas. Hence, if we want to calculate the number of mobile readers for covering the entire area, then M has to be multiplied by 2. Therefore, the

total number of mobile readers M becomes

$$M = M_{sub} \times 2 \tag{13}$$

Thus, by putting the value of (12) into (13), we obtain the number of mobile readers for the test area $X > Y$

$$M = \frac{\left(\frac{X_{sub}}{r} + 1\right)(2Y)}{(\tau v - X_{sub})} \times 2 \tag{14}$$

(4) Distance Calculation

The distance between the mobile reader and the tag can be determined by using the RSS model. The distance between the tag and the mobile reader can be calculated by using the Friis equation as below [10],

$$P_r = P_t G_t G_r \left(\frac{\lambda}{4 \times \pi}\right)^2 \left(\frac{1}{d}\right)^n \tag{15}$$

where P_t and P_r are the transmitted and received powers, respectively, 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 describes the influence of the transmission medium.

From (15), the relationship between the RSS and the distance of the tag and mobile reader antennas can be [10],

$$RSS(d) = 32.4(dB) + 20\log\left(\frac{f}{1(GHz)}\right) - 10n\log\left(\frac{d}{1(m)}\right) \tag{16}$$

where f is the carrier frequency. Therefore, d can be determined by rearranging (16) and we obtain,

$$d = 10^{\frac{RSS(d) - 32.4(dB) - 20\log\left(\frac{f}{1000}\right)}{-10n}} \tag{17}$$

Free space propagation is assumed between the tag and reader, thus, n is equal to 2, according to [26]. For calculating the coordinate of tag, the weighting factor w_i is introduced and is given by

$$w_i = \frac{1}{d_i^2} \tag{18}$$

The tag position can be calculated using a general equation as given below

$$\left(x_{est}, y_{est}, z_{est}\right) = \frac{\sum_{i=1}^{k} \left(\frac{1}{d_i}\right)^2 R_i(x, y, z)}{\sum_{i=1}^{k} \left(\frac{1}{d_i}\right)^2} \tag{19}$$

where $R_i(x, y, z)$ denotes the coordinates of mobile readers, which move in a zigzag pattern, while k denotes the number of mobile readers involved in tracking process.

III. RESULTS AND PERFORMANCE EVALUATION

For performance evaluation, four different scenarios have been used and all of them are shown in Fig. 4. Each scenario has two different conditions: one is the free space condition and another is the obstacles condition. Here, in Fig. 4, only the obstacles condition is shown. Table I shows the list of all detail characteristics of all scenarios.
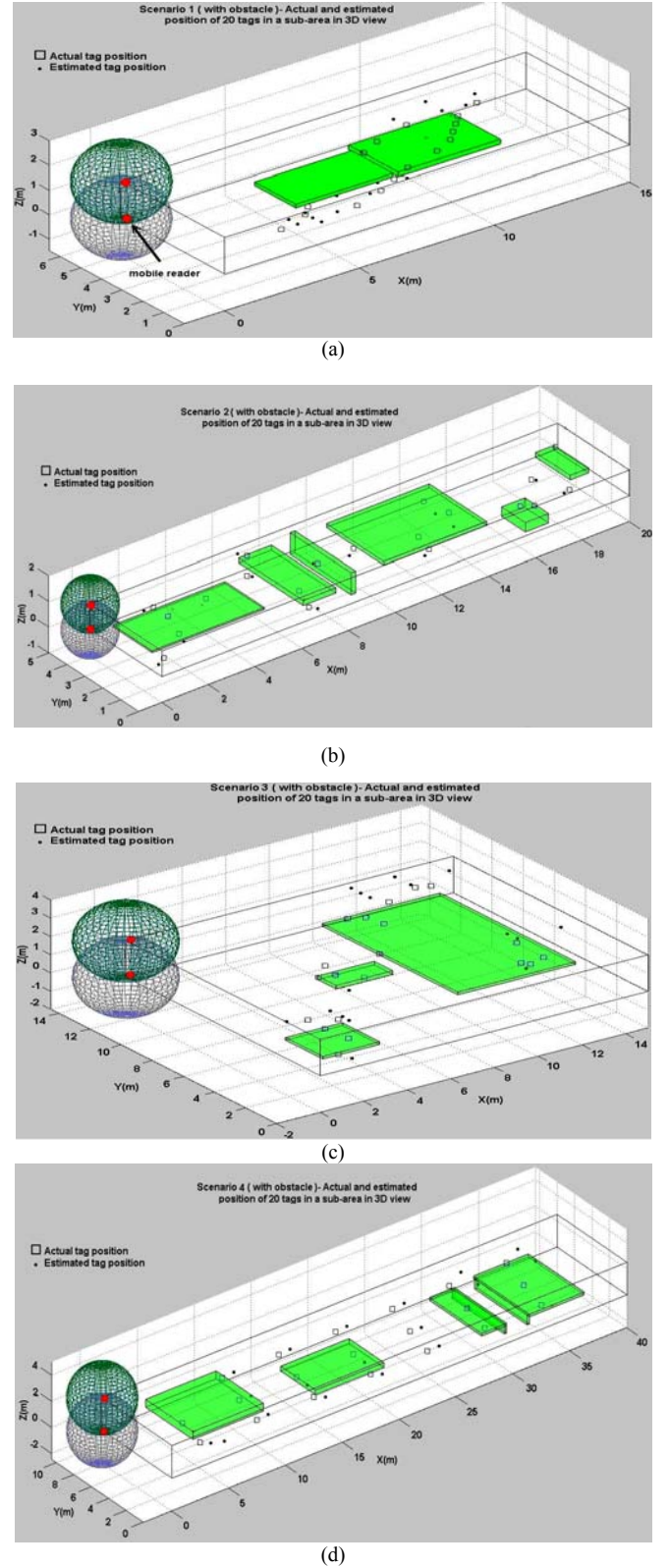

(a)

(b)

(c)

(d)

Figure 4. Mobility pattern of readers (with obstacle) in a sub-area (a) Tags are in a Non-uniform pattern (b) Tags are Scattered Randomly (c) Tags are placed in a Cluster (d) Tags are Uniformly placed in 3D space.

TABLE I. CHARACTERISTICS OF ALL SCENARIOS.

X×Y×Z (m×m×m)	Tag pattern	r (m)	M	v (m/s)	τ (s)
15×15×1.5	Non-uniform	1.5	6	8.75	8
20×20×1	Scattered Randomly	1	10	13	8
30×25×2	Cluster	2	8	14.25	8
40×40×2.5	Uniformly	2.5	10	22	8

The error distances are recorded by the mobile reader and a comparison is made between the free space and obstacle condition for the proposed model, which is shown in Fig. 5. In both conditions, the error distance between the actual tag position and the estimated tag position is calculated. From Fig. 5, it can be observed that the error distance for the obstacle condition is much higher than the error distance for free space condition. That means, the accuracy of tag positioning for the free space condition is much better than the obstacle condition. This is because, each of the tags in free space condition can be read by both readers (top and bottom mobile reader) simultaneously. Therefore, the weighting factor w_i of (18) also increases, which estimates more accurate position of the tag and decreases the error distance. Alternatively, when obstacles appear in scenarios, it may block any mobile reader to read the tags and for that reason, the error distance increases.

mobile reader in 2D method moves forward to a distance of $2r$ on the X-axis path each time after a complete move on Y-axis, while the mobile reader in 3D method (proposed method) moves forward only a distance of r. In the proposed method, the movement path of the mobile reader is denser, thus, the distance between the tag and mobile reader will be very low. As a result, the error distance is lower for the proposed 3D method. Some of the tags have the same E for both 2D and 3D methods, because the distances between the tag and mobile reader are the same. A summary of the performance for all scenarios is shown in Table II.

Figure 6. Mobility pattern of the mobile reader (scenario 1) (a) Existing method (b) Proposed method.
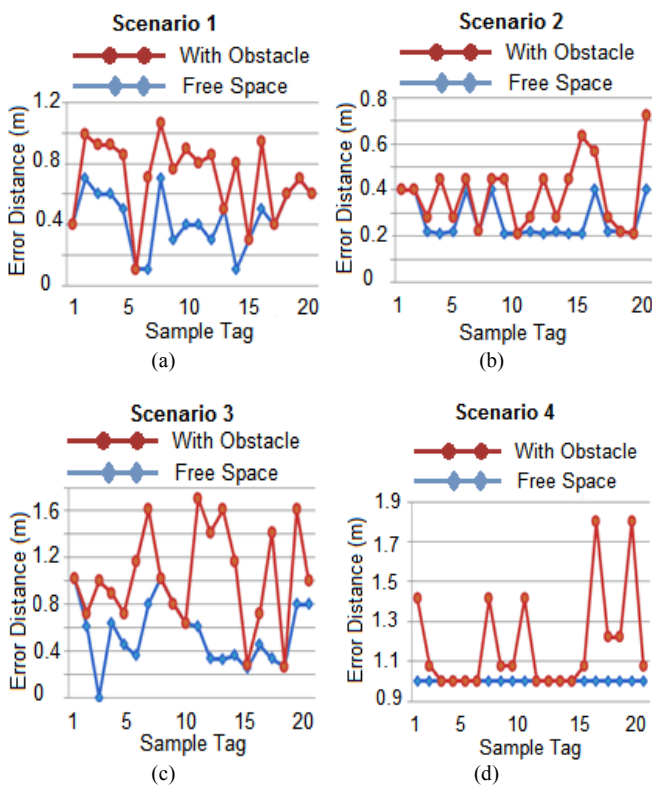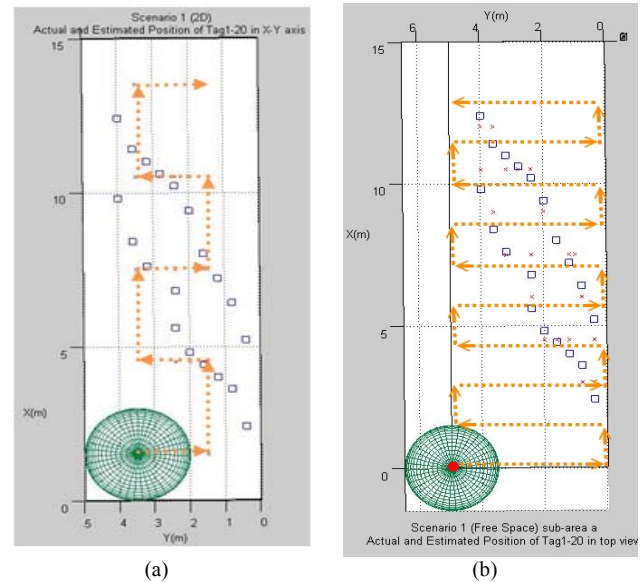

Figure 5. Comparisons of error distance with free space and obstacle conditions for (a) Scenario 1 (b) Scenario 2 (c) Scenario 3 (d) Scenario 4.

According to the existing 2D zigzag method [23], all the investigated scenarios are in 2D condition and the reading zone of mobile reader is assumed as a circle. The mobile reader of the existing 2D zigzag method [23] moves in a zigzag pattern. However, it moves forward with a distance of $2r$ at the X-axis path each time after finishing one line of Y-axis. At the same time, the proposed method involves only with a distance of r. Fig. 6 shows the difference of the zigzag pattern of the mobile reader between the proposed method and the existing 2D method [23].

Fig. 7 shows a comparison of error distance between the existing 2D method and the proposed method for four scenarios. From these figures, it is clear that the obtained error distance for the existing 2D zigzag method [23] is higher than that of the proposed method. This is because, the
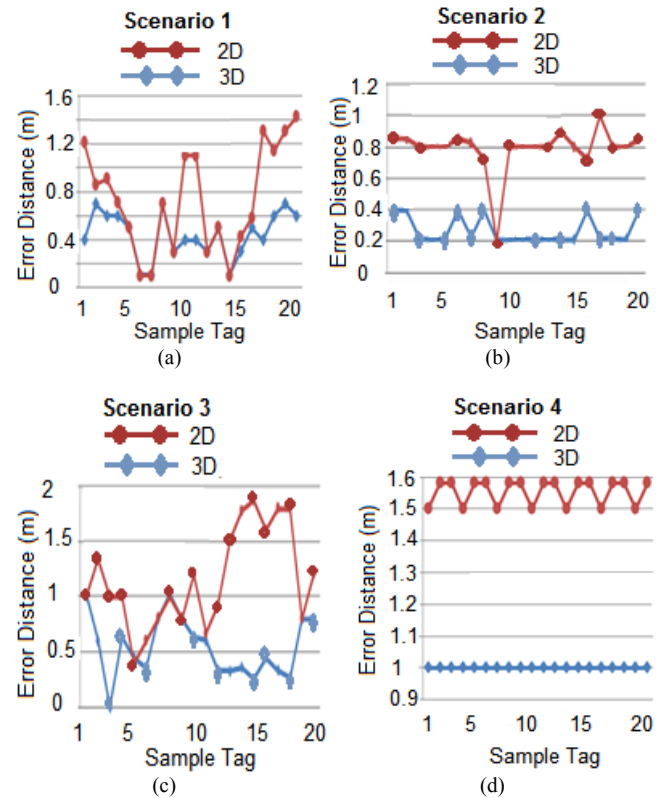

Figure 7. Comparisons of error distance by using 3D and 2D methods for (a) Scenario 1 (b) Scenario 2 (c) Scenario 3 (d) Scenario 4.

TABLE II. PERFORMANCE SUMMARY FOR ALL SCENARIOS.

Scenario	r (m)	Average error in free space by existing 2D zigzag method (m)	Average error in free space by proposed method (m)	Average error with obstacles by proposed method (m)
1	1.5	0.733	0.442	0.707
2	1	0.788	0.271	0.384
3	2	1.155	0.543	1.040
4	2.5	1.553	1.001	1.184

IV. CONCLUSION

This study presents an optimized tag localization method in 3D space within a specific time by using an optimum number of mobile readers. The mobile readers move in a zigzag pattern and RSS model is used to determine the tag's position. Theoretically, it is found that the mobile readers can successfully achieve 100% coverage inside the test environment. From the obtained results, it is obvious that the proposed system is capable to locate the tags with lower error. Even if the obstacles are placed in the test environment, the error distance does not change much and remains in acceptable level. Therefore, this method is suitable for real life implementation for identifying the location of the tags smoothly and accurately with low and desirable cost.

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