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A Novel Method to Evaluate the Dynamic Performance of RFID Positioning System

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Abstract. This paper regards the dynamic performance of radio frequency identification (RFID) positioning system as the analysis target. In this paper, the transmission from the static performance evaluation of RFID positioning system to the dynamic one is done. The Fisher information matrix and identification value are introduced to evaluate the dynamic positioning performance of RFID system. The positioning performance at the case of different paths, motion rates and number of reference tags could be evaluated by calculating the Fisher information matrix and identification value. The numerical simulation shows that motion paths and rate of target and the number of reference tags, could directly affect the positioning performance of RFID system. The findings also indicate that the selected motion path and rate of the target have a direct impact on the positioning performance. Furthermore, adjusting motion path of target close to the geometric center of reference tags and reducing motion rate and acceleration appropriately could optimize the dynamic identification performance of RFID positioning system. This method provides a reference for improving the positioning performance and reducing the measurement error of RFID system.

Keywords: fisher information matrix, geometric pattern, motion path, multiple tags, RFID

1 Introduction

Radio frequency identification (RFID) technology, with its features such as non-contact, high precision and low cost, is becoming an attractive technology in the field of indoor positioning [1-3]. In RFID sensor networks, the complete information of the tested object is recorded accurately in detail, which is useful in real-time monitoring surrounding environment.

The main feature of RFID technology is its ability to identify, locate, track, and monitor people and objects, which are attached to, without a clear line of sight between the tag and the reader [4]. Three basic components of an RFID system are a tag, a reader and a host computer. The tag and the reader communicate information between one another via radio waves. When a tagged object enters the read zone of a reader, the reader signals the tag to transmit its stored data. Once the reader has received the tag's data, the information is relayed back to the computer via a standard network interface. The computer can then use the information for a variety of purpose. With its wide application in the automobile assembly industry, warehouse management and the supply chain network, RFID has been recognized as the next promising technology in serving the positioning purpose.

According to the moving situation of target, positioning problems are divided into static positioning and dynamic positioning [5]. Through using physical and geographical constraints and geometric

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relationships in static positioning, reference point and pending point could be fixed to range and positioning. Combining with the real-time information of the reference point, the target position could be estimated in dynamic positioning.

In the test of moving target, the performance for a selected path has a direct impact on algorithm, such as accuracy, identification efficiency, energy consumption, and so on. DiGiampaolo presented a global localization system for an indoor autonomous vehicle equipped with odometry sensors and a radio frequency identification (RFID) reader to interrogate tags located on the ceiling of the environment [6]. Huang presented a real-time RFID indoor positioning system based on Kalman-filter drift removal and Heron-bilateration location estimation [7]. Shi proposed an indoor positioning system algorithm based on RFID by comparing angle of arrival (AOA) and time difference of arrival (TDOA) [8]. Wang used a particle swarm optimization (PSO)-based back propagation (BP) neural network (PSO-BP) to determine the relationship between the RFID signals and the position of a tag for an RFID-based positioning system [9]. The above researches focus on the use of RFID technology to realizing the indoor positioning and pay little attention to the influence factors on the reading and positioning performance of the presented system.

In recent years, scholars have carried out extensive research on dynamic path planning, and put forward many kinds of algorithm, such as the Dijkstra algorithm, A* algorithm, genetic algorithm, and ant colony algorithm [10-14]. Our previous work optimized the tags' distribution to improve the reading performance of RFID system in static state [15-16]. However, the influence of tags' distribution on the RFID system's reading performance changes in dynamic state due to the paths and the motion rates of RFID tags. In different multiple tags' geometric pattern in dynamic internet of things (IOT) environment, adjusting the paths and the motion rates timely to achieve the best effect of positioning is the key to our work. Firstly, increasing the number of tags appropriately is an effective measure to improve the RFID system performance. Meanwhile, our findings also indicate that the selected motion path and rate of the target have a direct impact on the positioning performance. Therefore, adjusting motion path of target close to the geometric center of reference tags and reducing motion rate and acceleration appropriately could optimize the dynamic identification performance of RFID positioning system.

The structure of the paper is organized as follows. In Section 2, the Fisher information matrix is applied to analyze the geometry pattern of a target and multiple reference tags in RFID system. In Section 3, the geometry pattern of the target and multiple reference tags is simulated at the case of target in motion and motionless respectively. In Section 4, the efficiency of the target at different rate along different paths is obtained via the simulation analysis. The main results of this paper are discussed and concluded in Section 5. This method provides a reference for improving the positioning performance of RFID system.

2 Fisher Information Matrix of RFID Positioning System

2.1 Geometric Parameters of RFID Positioning System

A positioning system is mainly composed by a target and some reference tags. The geometric parameters of reference tags and the target are shown in Fig. 1. The location of a single pending target is indicated as $P=[x_p, y_p]^T$ and the location of i^{th} reference tag is indicated as $T_i=[x_i, y_i]^T$. Therefore, the distance between the i^{th} reference tag and the target could be expressed as $r_i=\|P-T_i\|$. Afterward, the true azimuth bearing $\varphi_i(P)$ from i^{th} reference tag to the target is written as [17].

$$\varphi_i(P)=\arctan\left(\frac{x_P-x_i}{y_P-y_i}\right) \tag{1}$$

where arctan (*x/y*) is the four-quadrant inverse tangent of *x/y*. If the target is in motion, at each point in moving path, the angular relationship between the reference tag and target can be calculated by Equation (1).

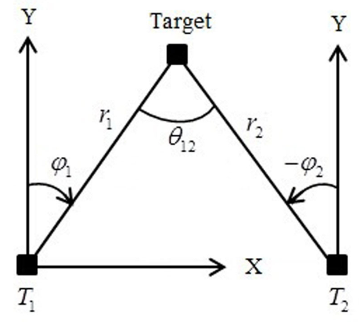


Fig. 1. Geometric parameters of reference tags and a target

2.2 A Metric for Optimal Location of Multi-tags

A metric is defined for a general measurement vector $\overline{Z} = Z(W) + n$ and a general parameter vector $W \in R^M$ which is to be estimated from the observable measurements $\overline{Z} \in R^N$ with $N \geq M$. Meanwhile, $n \in R^N$ is a vector of Gaussian random variables with zero mean and a constant covariance matrix Σ, that is to say $\overline{Z} \sim N(Z(W), \Sigma)$ [16].

On the premise that the errors are random errors submitting Gaussian distribution, the likelihood function W of given the vector $\overline{Z} \sim N(Z(W), \Sigma)$ is given by

$$f_{\overline{Z}}(\overline{Z};W) = \frac{1}{(2\pi)^{N/2}|\Sigma|^{1/2}} \exp\left(-\frac{1}{2}\left(\overline{Z} - Z(W)\right)^{\mathrm{T}} \Sigma^{-1}\left(\overline{Z} - Z(W)\right)\right) \quad \textbf{(2)}$$

where $Z(W)$ is the mean of $\overline{Z}$. The natural logarithm of $f_{\overline{Z}}(\overline{Z};W)$ is given by

$$-\ln\left(f_{\overline{Z}}(\overline{Z};W)\right) = \frac{1}{2}\left(\overline{Z} - Z(W)\right)^{\mathrm{T}} \Sigma^{-1}\left(\overline{Z} - Z(W)\right) + c \quad \textbf{(3)}$$

where c is a term independent of W .

The Cramer-Rao bound for an unbiased estimate $\overline{W}$ of W is given by

$$\mathrm{E}\left[\left(\overline{W} - W\right)\left(\overline{W} - W\right)^{\mathrm{T}}\right] \geq I(W)^{-1} = C(W) \quad \textbf{(4)}$$

Where $I(W)$ is defined the Fisher information matrix.

The $(i, j)^{th}$ element of $I(W)$ states that

$$\left(I(W)\right)_{i,j} = \mathrm{E}\left[\frac{\partial}{\partial w_i}\ln\left(f_{\overline{Z}}\left(\overline{Z};W\right)\right)\frac{\partial}{\partial w_j}\ln\left(f_{\overline{Z}}\left(\overline{Z};W\right)\right)\right] \quad \textbf{(5)}$$

On the premise that the errors are random errors submitting Gaussian distribution, the $(i, j)^{th}$ element of $I(W)$ could be rewritten as

$$\left(I(W)\right)_{i,j} = \frac{\partial Z(W)^{\mathrm{T}}}{\partial w_i}\Sigma^{-1}\frac{\partial Z(W)}{\partial w_j} + \frac{1}{2}tr\left(\Sigma^{-1}\frac{\partial \Sigma}{\partial w_i}\Sigma^{-1}\frac{\partial \Sigma}{\partial w_j}\right) \quad \textbf{(6)}$$

where $tr(\cdot)$ is the rank of matrix. In general, the term is useful when the covariance is a function of the true parameter states W .

However, in all the cases it is assumed that is in dependent of the parameter to be estimated. In this case the last equation simplifies to

$$\left(I\left(W\right)\right)_{i,j}=\frac{\partial Z(W)^{\mathrm{T}}}{\partial w_i}\Sigma^{-1}\frac{\partial Z(W)}{\partial w_j} \tag{7}$$

If the value of $\left(I\left(W\right)\right)_{i,j}$ is 0, w_i and w_j are orthogonal and their maximum likelihood estimates are independent. The entire Fisher information matrix is then given by

$$I(W)=\nabla_W Z(W)^{\mathrm{T}}\Sigma^{-1}\nabla_W Z(W) \tag{8}$$

where is the Jacobian of the measurement vector with respect to W . The matrix $C(W)=\Gamma(W)^{-1}$ is symmetric positive define and defines a so-called uncertainty ellipsoid.

2.3 Fisher Information Matrix of RFID Positioning System

Supposing P is the state parameter of target and $r(p)$ is the measurement vector, we could obtain the Fisher information matrix of the positioning system, which is indicated as:

$$I_r(P)=\nabla_P r(P)^T R_r^{-1}\nabla_P r(P) \tag{2}$$

where $R_r=\sigma_r^2 I_N$, σ_r^2 is the common variance of measurement and $\nabla_P r(P)$ is the Jacobian expressed as [17]:

$$\nabla_P r(P)=\begin{bmatrix}\sin(\varphi_1) & \cos(\varphi_1)\\ \vdots & \vdots\\ \sin(\varphi_N) & \cos(\varphi_N)\end{bmatrix} \tag{3}$$

If the number of reference tags is N , the Fisher information matrix could be written as:

$$I_r(P)=\frac{1}{\sigma_r^2}\sum_{i=1}^{N}\begin{bmatrix}\sin^2(\varphi_i) & \dfrac{\sin(2\varphi_i)}{2}\\ \dfrac{\sin(2\varphi_i)}{2} & \cos^2(\varphi_i)\end{bmatrix} \tag{4}$$

In multiple tags system, at least $N\geq 2$ tags are required to estimate the value of P. The determinant $\left|I_r(P)\right|$ is used as a scalar measure of positioning performance since it is implicitly a function of the reader-tag geometry. Thus, the determinant $\left|I_r(P)\right|$ provides an explicit means of relating the localization geometry to the location performance. If the state parameter of target P is an effective unbiased estimator and the spatial error is very small, the determinant of the Fisher information matrix $\left|I_r(P)\right|$ is given by:

$$\left|I_r(P)\right|=\frac{1}{4\sigma_r^4}\left[N^2-\left(\sum_{i=1}^{N}\cos(2\varphi_i)\right)^2-\left(\sum_{i=1}^{N}\sin(2\varphi_i)\right)^2\right]=\frac{1}{\sigma_r^4}\sum_K\sin^2(\varphi_j-\varphi_i)\qquad j>i \tag{5}$$

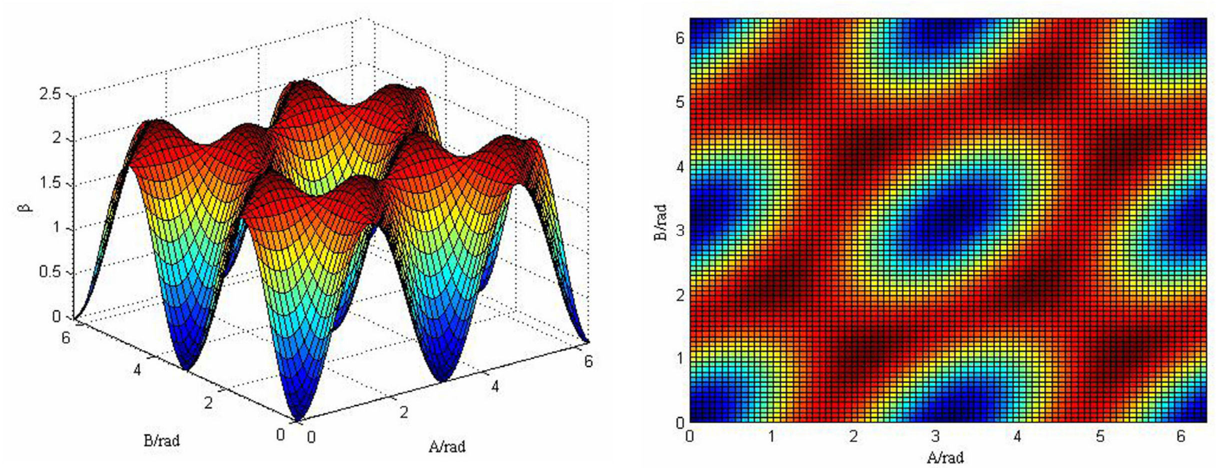
where $K=\{\{i,j\}\}$ is defined as the set of all combinations of i and j with $i,j\in\{1,2\cdots,N\}$ and $j>i$. Given an arbitrary number N of reference tags, the maximum value of the determinant is $N^2/(4\sigma_r^4)$. Since the determinant can be used to judge the effect of positioning, here the determinant is defined as the identification value of the positioning system, $\beta=\left|I_r(P)\right|$.

3 Simulation of Fisher Information Matrix

For the number of reference tags $N=3$ and the common variance $\sigma_r^2=1$, if the target is in motionless, the identification value β could be restated as:

$$\beta = \left| I_r(P) \right| = \sin^2(A) + \sin^2(A - B) + \sin^2(B) \quad \textbf{(6)}$$

where $A = \phi_3(P) - \phi_1(P),\ B = \phi_2(P) - \phi_1(P),\ A, B \in [0, 2\pi)$. The surface and cross-sections of the identification value's three-dimensional diagram are given in Fig. 2.

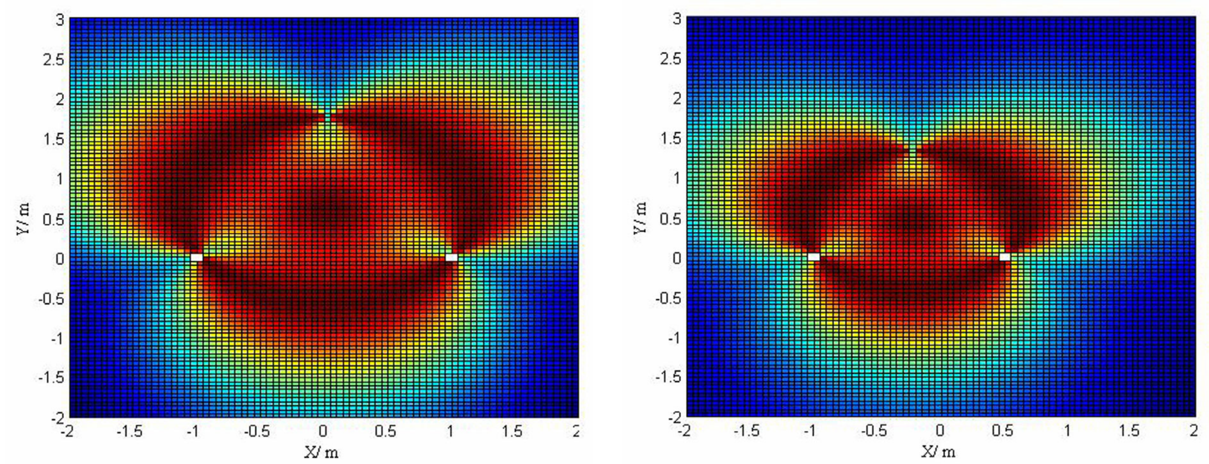


(a) (b)

Fig. 2. Vertical views of identification value at the case of three tags

Form Fig. 2, we calculate that the determinant value is maximum at eight points and minimum at nine points. The maximum determinant value is given by $N^2 / (4\sigma_r^4) = 9/4$. When the reference tags are placed according to these maximum points, the target could be read easily.

Once the target is in motion, the motion time t, acceleration a and motion rate need to be introduced into the identification value. The maximum and minimum points could have a shift, as shown in Fig. 3. Taking regular triangle distribution for example, Fig. 3(a) presents the maximum determinant value of three tags at the case of static target while Fig. 3(b) presents the maximum determinant value at the case of moving target. We could see that there is a shift of maximum points when the target moves.



(a) (b)

Fig. 3. Identification value of three tags is in static and motion

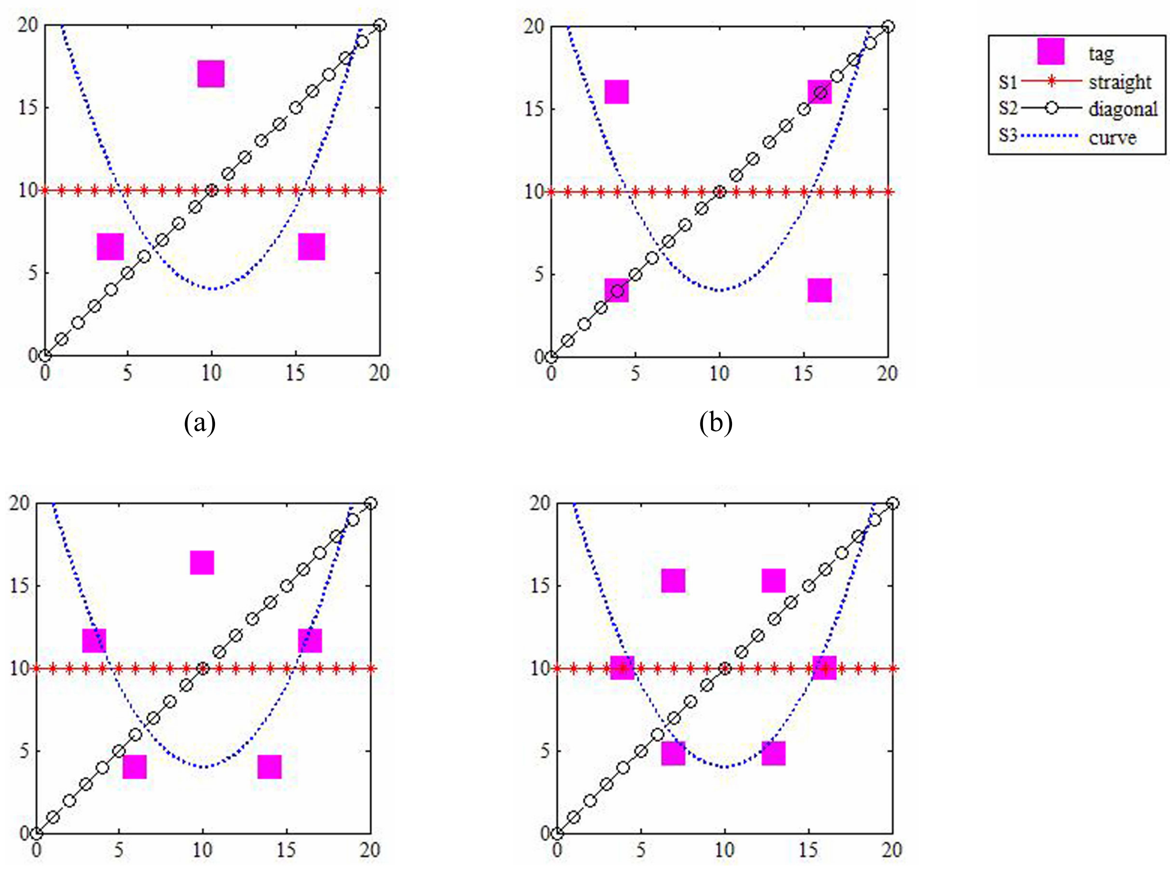
Substituting the coordinate function $x_p = f_1(a,t), y_p = f_2(a,t)$ into Equation (1) and Equation (5), the identification value β displays timely at any point of a path:

$$\beta = |I_r(P)| = \frac{1}{\sigma_r^4}\sum_s \sin^2(\arctan(\frac{f_1(a,t)-x_i}{f_2(a,t)-y_i}) - \arctan(\frac{f_1(a,t)-x_j}{f_2(a,t)-y_j})) \tag{7}$$

In Equation (7), the number of reference tags is arbitrary. For different paths and motion rates of target, we can obtain the different expressions of x_P and y_P.

4 Simulation of the Positioning System

In order to evaluate the validity of the above positioning performance, the relevant results are compared when the target move at different motion rates along different paths. Three, four, five and six tags are closed to be reference tags respectively while the target moving along three kinds of paths in selected areas ([0 20], [0 20]), as shown in Fig. 4. X-Y plane presents the region of the positional distribution of the reference tags and the movement paths of the target. Fig. 4(a) represents the triangle distribution of three reference tags and three kinds of paths of the corresponding target, Fig. 4(b) denotes the square distribution of four reference tags and three kinds of paths of the corresponding target, Fig. 4(c) expresses the regular pentagon distribution of five reference tags and three kinds of paths of the corresponding target and Fig. 4(d) states the regular hexagon distribution of six reference tags and three kinds of paths of the corresponding target. Three lines (S1, S2, and S3) show three different movement paths of the target.



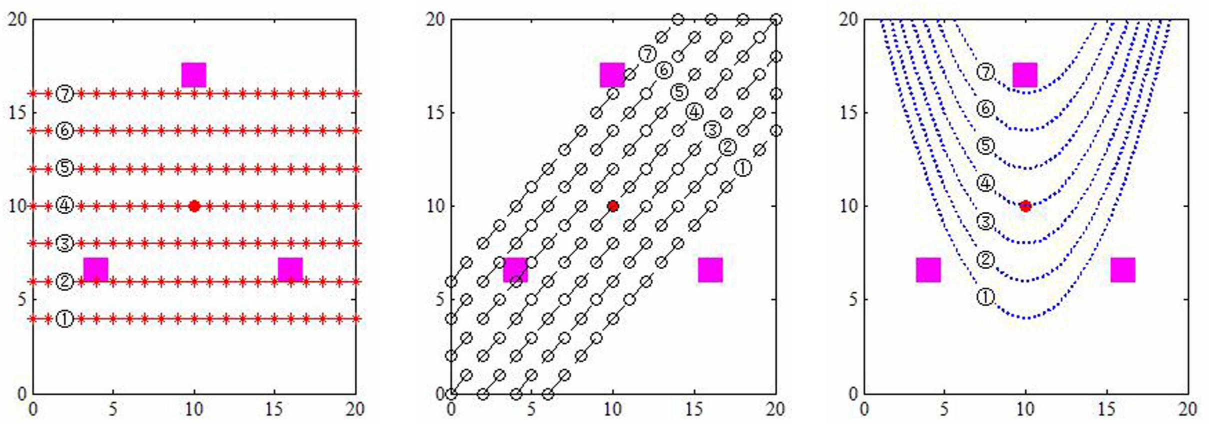
(a) (b)

(c) (d)

Fig. 4. Reference tags' distribution and target's movement paths

4.1 Target's Uniform Motion along Different Paths

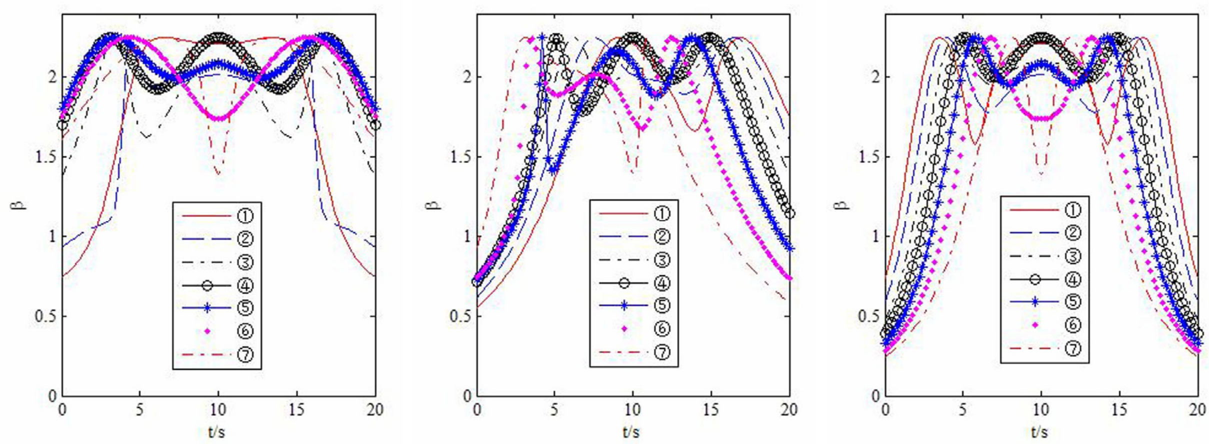
When the target moves uniformly along different three kinds of paths, the positioning system reads the target's information per 0.2s and $\sigma_r^2 = 1$. Taking three reference tags for example, seven moving paths in each kind are chosen for the target at the upper and lower sides of the reference tags' geometric center, as shown in Fig. 5. At the case of three reference tags, Fig. 5(a) represents seven straight paths of the target, Fig. 5(b) denotes the seven diagonal paths of the target and Fig. 5(c) expresses seven curve paths of the target.



(a) (b) (c)

Fig. 5. Eleven kinds of location maps in three paths

Therefore, the relationship between motion time t and the identification value β is shown in Fig. 6. At the case of three reference tags, Fig. 6(a) are the curves of motion time and the identification value when the target moves at a constant speed along straight paths, Fig. 6(b) is the case of diagonal paths and Fig. 6(c) is the case of curved paths.



(a) (b) (c)

Fig. 6. Curve of the identification value and motion time

From Fig. 6, we find that different paths have the different curves for the same number of reference tags at the case of uniform motion. Each figure has 7 curves and each curve corresponds to the relationship of identification value over time in a path under a particular arrangement. For comparing the curves, the maximum identification value is shown in Table 1.

Table 1. Maximum identification value of each curve

Path	1	2	3	4	5	6	7
Straight	2.2499	2.2452	2.2496	2.2500	2.2499	2.2499	2.2499
Diagonal	2.2497	2.2496	2.2500	2.2500	2.2500	2.2485	2.2491
Curved	2.2486	2.2492	2.2494	2.2500	2.2500	2.2492	2.2495

From Table 1, we could find that the identification values of different paths are comparable and the closer the geometric center, the bigger the identification values, so the dynamic identification performance of RFID positioning system could be optimized by adjusting motion path of target close to the geometric center of reference tags.

In the case of the same number of tags, an optimum path is selected and the identification value β varies over time in different paths, as shown in Fig. 7 (a-d) represent the results of three, four, five and six reference tags. The three curves of partial Fig. 7 respectively correspond to three paths. The identification efficiency at different paths is different while the speed is the same. Then, the average values of the selected time period of different paths could be calculated and compared to evaluate the optimal path. In addition, the more the number of tags exists, the larger the identification value is. Therefore, it is an effective measure to improve the RFID system performance to increase the number of tags appropriately.

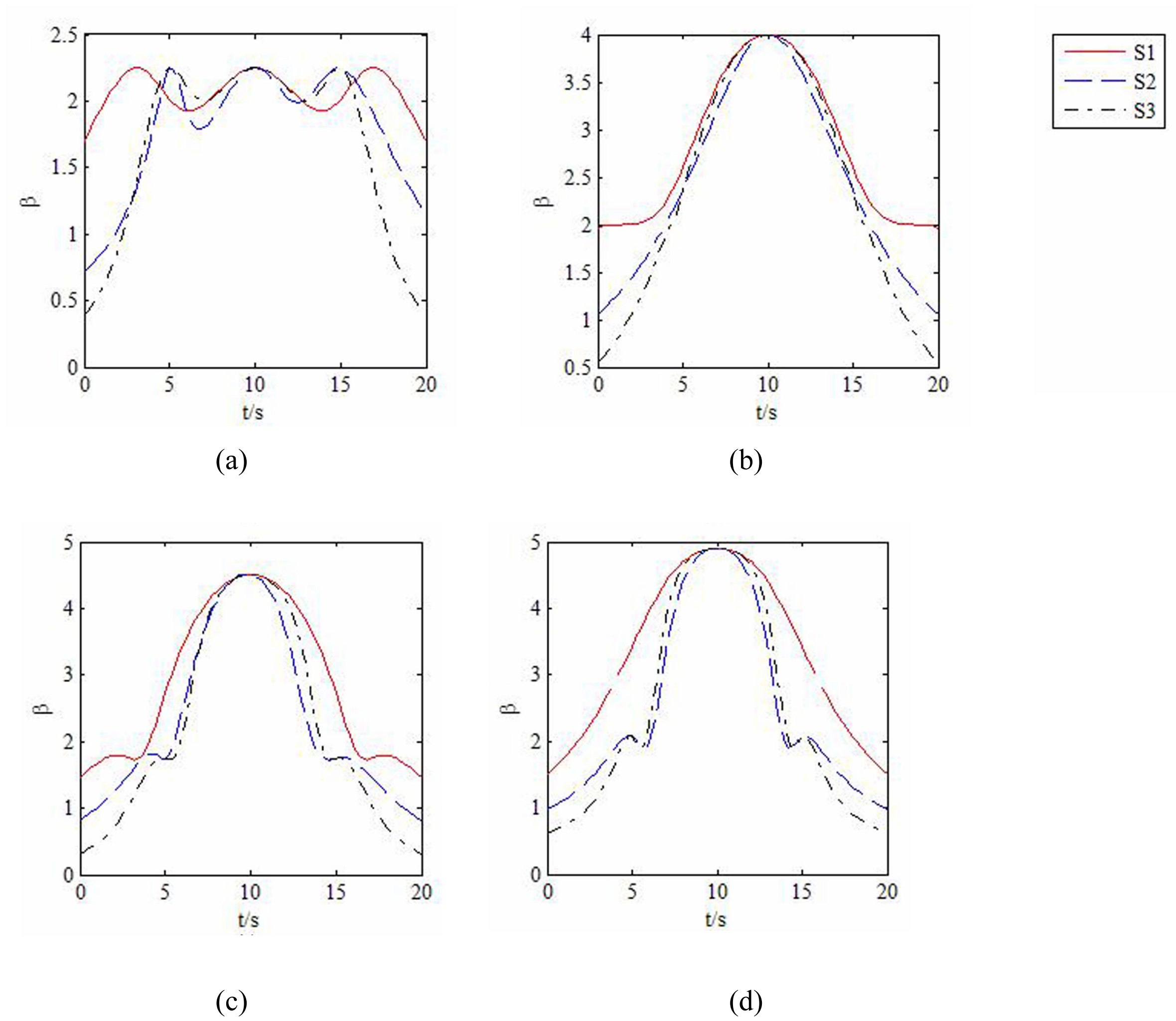


Fig. 7. Identification value over time at different paths

4.2 Target's Uniform Motion at Different Rates

For contrasting the identification value at different motion rates of the target, we take the diagonal paths for example. Setting three kinds of constant motion (the velocity are set 0.5m/s, 1.0m/s and 1.5m/s respectively). Introducing the data into Equation (7), we could obtain the relationship of identification value with time, as follows:

$$\beta = |I_r(P)| = \sum_K \sin^2(\arctan(\frac{f_1(0,t)-x_i}{f_2(0,t)-y_i}) - \arctan(\frac{f_1(0,t)-x_j}{f_2(0,t)-y_j})) \quad \textbf{(8)}$$

According to Equation (8), the variation of identification value over time corresponds to different number of tags, as shown in Fig. 8.

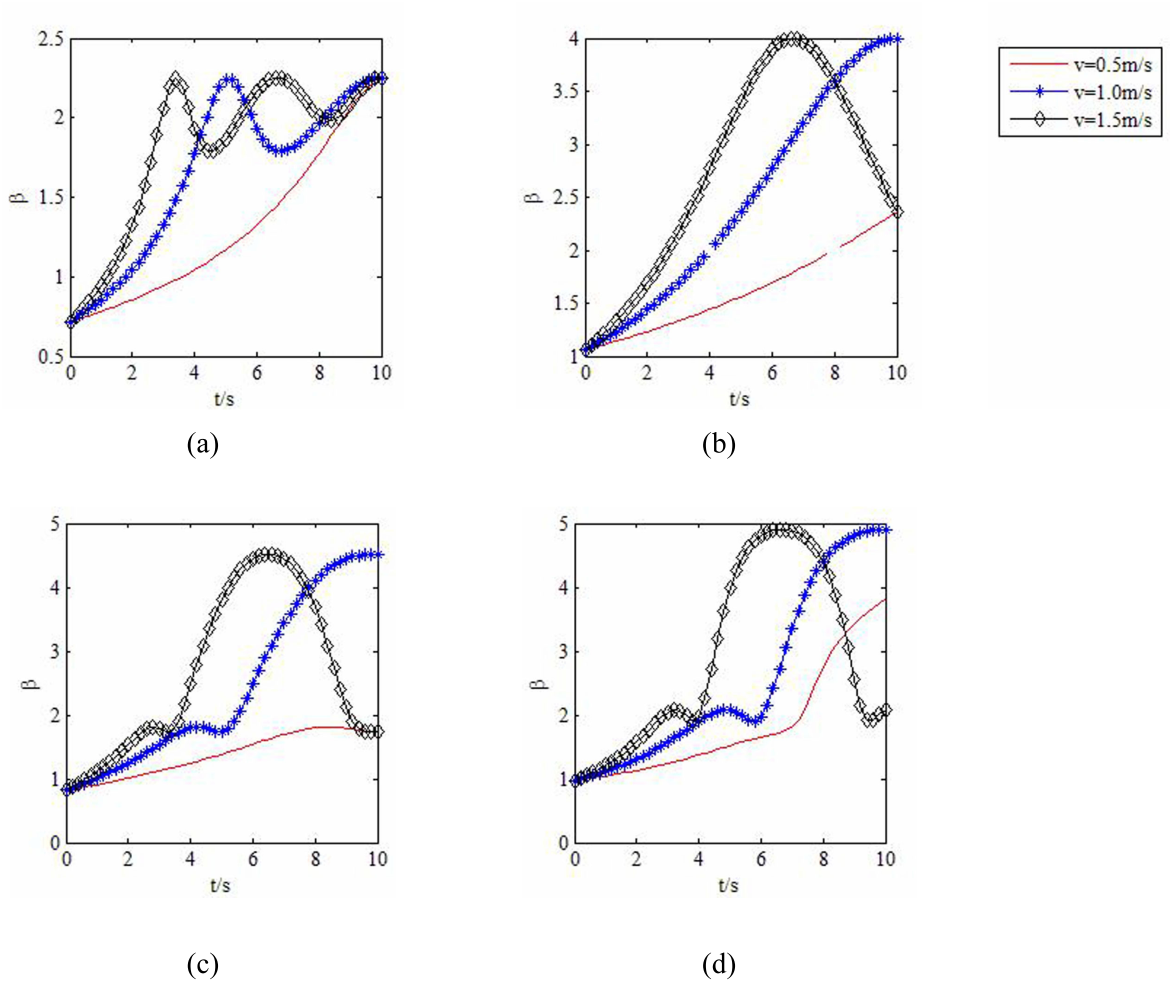


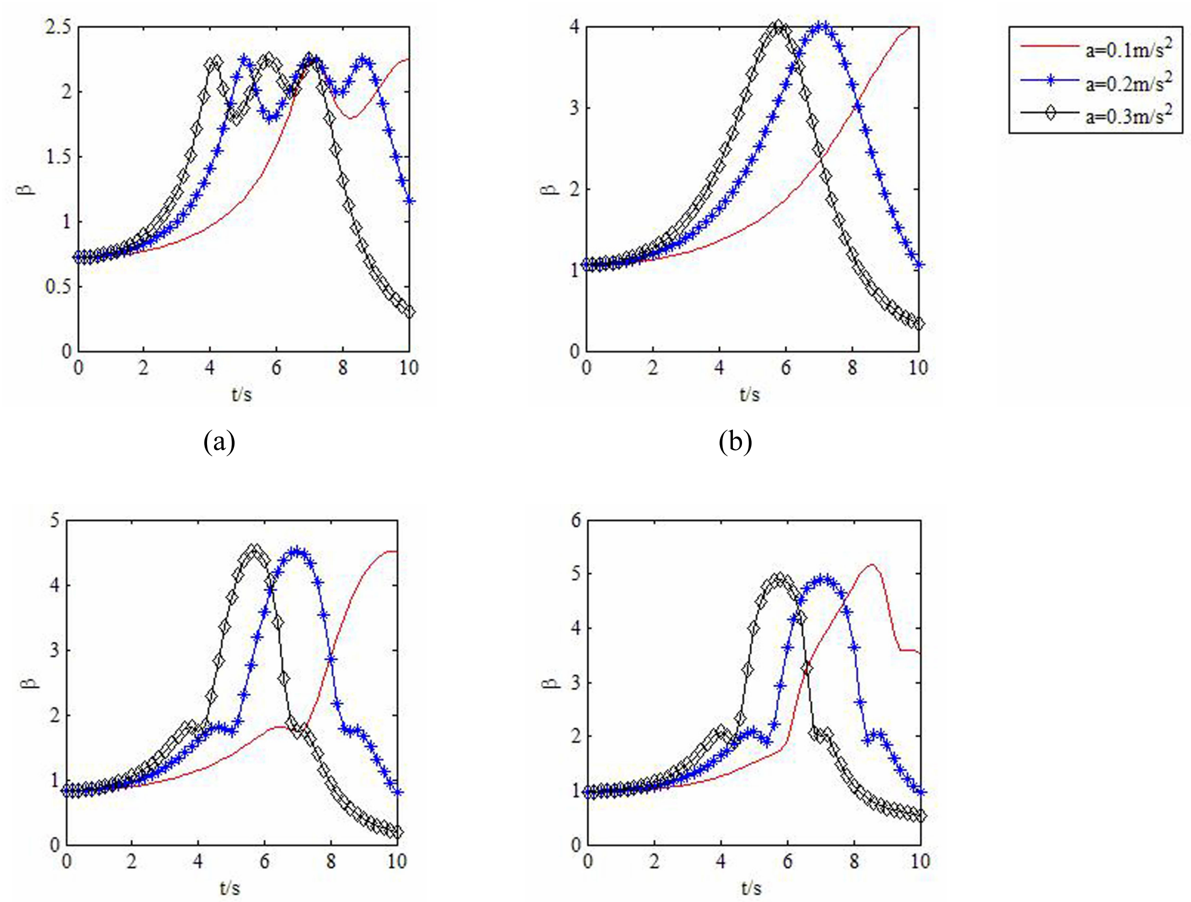
Fig. 8. Identification value over time at different motion rates

In Fig. 8, (a) corresponds to the variation curve with time of three reference tags system which move at three kinds of motion speed, (b) is the case of four reference tags, (c) is the case of five reference tags and (d) are the case of six reference tags. Therefore, different moving rates have a significant impact on the performance of target's confirmation and the slower the motion rate is, the sooner the maximum identification value reaches. Therefore, the motion rate could be reduced appropriately without affecting performance.

4.3 Target's Variable Motion along Different Paths

For comparing the identification value in different variable motions of the target, we take the diagonal paths for example. Setting three kinds of variable motion (the initial velocity is set 0 and the acceleration are set $0.1m/s^2$, $0.2m/s^2$, $0.3m/s^2$ respectively). Introducing the data into Equation (7), we could obtain the relationship of identification value with time and acceleration. The variation of identification value over time corresponds to different number of tags, as shown in Fig. 9.

In Fig. 9, (a) corresponds to the variation curve with time of three reference tags system which move at constant and variable speed, (b) is the case of four reference tags, (c) is the case of five reference tags and (d) are the case of six reference tags. From Fig. 9, different accelerations have a significant impact on the performance of target's confirmation and the smaller the acceleration is, the sooner the maximum identification value reaches. Therefore, the acceleration could be reduced appropriately to improving the reorganization performance of RFID positioning system.



(a) (b)

(c) (d)

Fig. 9. Identification value over time at different variable motions

5 Conclusions

The Fisher information matrix is used as the criterion for the RFID positioning system in dynamic IOT environment. It is shown that the geometry features of RFID multiple reference tags exercise a great influence on the positioning performance of RFID system. It is an effective measure to improve the RFID system performance to increase the number of tags appropriately. The findings also indicate that the selected motion path and rate of the target have a direct impact on the positioning performance. Adjusting motion path of target close to the geometric center of reference tags and reducing motion rate and acceleration appropriately could optimize the dynamic identification performance of RFID positioning system. Our work provides an effective way for the development of RFID technology in a dynamic networking environment. In this paper, we analyze the influence factors on the reading and positioning performance of the presented system in theory. A corresponding experimental platform will be built and the test data will be obtained to compare with the simulation results in future work.

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