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# Robust Design for RFID System Testing and Applications

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***Abstract* – With increasing applications of RFID (Radio Frequency Identification) technology, reliability requirements for the deployment of RFID readers have become more critical. For a robust deployment of a RFID network, a systematic solution was proposed in this paper. To simplify the reader deployment problem, instead of the traditional 2D circle-like shape assumption, the ellipse/ellipsoid-like shape was taken to represent the signal range of an RFID antenna in this paper. Further, the performance of RFID was estimated statistically.**

**In addition, a deployment tool was designed for users to obtain a recommended layout. For a given area, solutions of number and placement of RFID readers are computed fast and robustly. To avoid reader collision which may result in low efficiency of a RFID network, two simplified mechanisms were proposed. Finally, the practical implementation and simulations were performed to test the practicability of the deployment tool and further to confirm the robustness and adequacy of the proposed models.**

Index Terms - ***RFID, Experiment Design, Response Surface, Taguchi Method, Clustering Algorithm, Reader Collision Problem and Anti-Collision Policy***

## I. INTRODUCTION

The RFID reading region is not only limited by its nature, but also some physical and environmental factors. Since the reading region and reading rate depend upon environment, selecting the right parameters to construct a suitable and robust model is a key point to make an effective deployment planning.

Interrogation zones of readers may interfere with one another due to overlapping. Interference detected by one reader and caused by another reader is referred to as a reader collision [4]. The reader collision problem is a fundamental problem of effectively allocating radio frequency spectrum to readers over time such that their interference with one another is minimized. It mainly occurs in a dense reader environment [10]. The reader collision problem is a special case of the well-studied frequency assignment problem [6] [10][12][13]. Reader collisions prevent the readers from proper communicating with RFID tags. The reading results may be unsatisfactory with reading times and an unacceptable level of misreads. Minimizing the reader collisions is essential and a matter of concern. The reader collision problem aims at minimizing the number of reader collision in a RFID system through efficient allocation of frequency and time resources [8].

In this paper, robust experiment design was employed to seek and discover the main factors affecting the RFID interrogation range. By practically measuring the interrogation zone of a RFID antenna, the result was used to estimate the shape and size for further analysis. The anti-collision mechanisms and the coverage problems were also discussed in this paper. In addition, a RFID reader deployment tool was designed for solving and optimizing the position of RFID readers. Finally, the implementation and simulation results were demonstrated. Fig. 1 illustrates the system architecture.

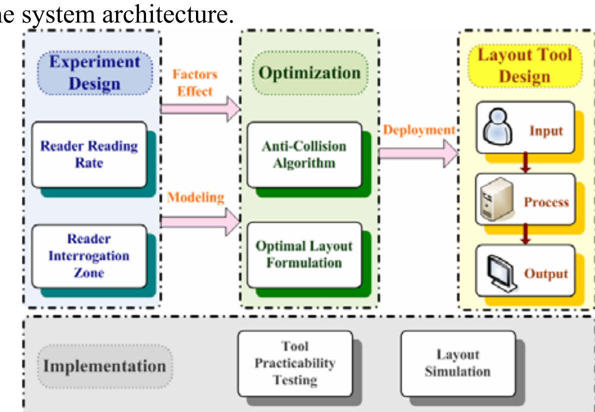


Fig. 1 The robust design for RFID system architecture

This paper is organized into five sections. Section 1 gives a brief description about the RFID system and anti-collision problem. In Section 2, robust design and experiment models are introduced. In Section 3, the reader coverage problem is discussed, and the proposed layout planning tool is introduced. The implementation and simulation of the reader deployment are addressed in Section 4. Finally, conclusions are pointed out in Section 5.

## II. ROBUST DESIGN FOR RFID SYSTEMS

### *A. RFID Interrogation Zone Measurement*

The majority of researches on collision problem had assumed the interrogation zone of a reader as a two-dimensional circle [1][5][9][14]. In practice, the interrogation zone of RFID reader is usually not a circle. This study performed a practical measurement to collect real data and represented interrogation zone with a set of discrete points.

For capturing the interrogation zone of an RFID antenna, a clean simulating environment was constructed for a RFID



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system. Some necessary assumptions are made for data gathering:

- Electromagnetic field is symmetric.
- Performance is uniformly distributed in each grid.
- Human and environmental errors are ignored.

Table 1 shows the facilities of the experiment. The reader was placed in a height of 90 cm from ground. The tag was placed on the cardboard box to minimize the interference from attaching material. The reader read the tag and was monitored to see how many times it successfully read the tag in a time interval. The number of reads had been translated to a reading rate [11].

Table 1 Equipment specifications

| Equipment | Brand | Specification | Quantity |
|---|---|---|---|
| RFID Reader | thingMagic | Mercury3, Passive, 915MHz | 1 |
| Antenna | thingMagic | Separated | 1 |
| RFID Tag | | Passive, 915MHz, EPC Class 1 | 2 |
| Personal Computer | | With user interface | 1 |

After the data gathering process and mapping the data into the space, as presented in Fig. 2, red points represent the higher reading rate while blue represent the worse.

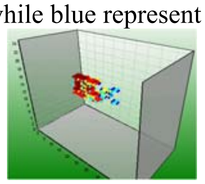


Fig. 2 The representation of 915MHz RFID interrogation zone [7]

For simplifying problem when computing the required readers and adding flexibility, the ellipse-like shape is chosen to represent and simulate the shape of interrogation zone by observing Fig. 2. The main advantage is that the length and the width are adjustable to fit and describe a real reader.

### B. Experiments for RFID Reading Rate

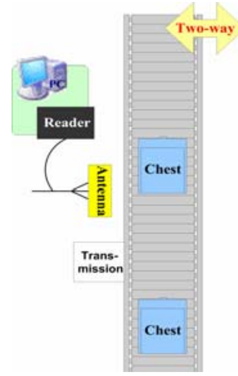
To realize the performance of an RFID system and find out the factors which affect the reading performance of a RFID significantly, an experiment is designed by referring to Taguchi method [2]. In the beginning of this 915 MHz RFID experiment, all possible factors are taken into consideration. Consequently, four controllable factors with two uncontrollable (noise) factors were included. The orthogonal array and SNR are used in experimental design and data analysis.

1). Facilities and Locations

The arrangement of the RFID lab is shown in Fig. 3 and the necessary facilities in the experiment are listed in Table 2.

2). Factor Selection and Analysis

While designing the experiment, some uncontrollable factors were identified in the experiment. Finally, two factors were considered and set as noise factors – material in the chest, and if there were interferences (electric wave, electric equipment ...) nearby. Four factors were chosen to be controllable factors and assumed to be adjusted by the RFID users. Giving each factor 3 levels, the factors and the response levels are listed in Table 3.




Simplified sketch

Fig. 3 Lab arrangement

Table 2 The facilities in 915MHz RFID experiment

| Equipment | Brand | Specification | Quantity |
|---|---|---|---|
| RFID Reader | Alien | Passive, 915MHz | 1 |
| Antenna | Alien | Separated | 1 |
| RFID Tag | Alien | Passive, 915MHz<br>EPC Class 1 | 110 |
| Chest (No.3) | | Inner size : 460*310*300mm<br>Outer size : 550*390*320mm | 12 |
| Delivery Track | | Length :30m,<br>Velocity :0~210m/min | 1 |
| Personal Computer | Leon | With Alien user interface | 1 |

Table 3 Identify factors for 915MHz reading rate experiment

| Factor | Levels | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| A. Velocity of the transportation ($V_d$) | 50 m/min | 100 m/min | 200 m/min |
| B. Antenna Distance ($D_{at}$) | 0.5 m | 2 m | 3.5 m |
| C. Tag direction ($T_{dir}$) | Long Edge | Upper | Short Edge |
| D. # of tags (N) | 1 | 3 | 10 |

Based on orthogonal array, an $L_9$ experiment was constructed. Because of two noise factors, one had 2 levels and the other had 3 levels. There were 2*3*9=54 trials and each trial was repeatedly read for 100 times. Quality characteristics in this RFID test included reading rate, reading time, and reading distance. Reading rate was chosen as the quality characteristics. This study aims to maximize the signal to noise ratio, which leads to the less quality loss of reading rate, as

$$\eta = -10 \log_{10}\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right) \quad (1)$$

3). Experiment Results

The RFID experiment system is presented in Fig. 4.

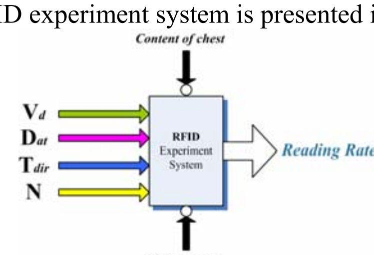



Fig. 4 RFID experiment system

Each control factor is adjustable and has three levels. Notice that the tags can be attached on the chest in three directions.

- Overall result

In this experiment, the most important one is SNR, which is the measurement of variation in the RFID reading rate. After the data were summarized, the reading rate is translated into SNR. Thus, analysis of variance (ANOVA) was performed and listed in Table 4.

Table 4 ANOVA table for SNR

| | 1 | 2 | 3 | DF | SS | MS | F |
|---|---|---|---|---|---|---|---|
| $V_d$ | 31.97 | 30.58 | 27.25 | 2 | 76.07 | 38.03 | 1.33 |
| $D_{at}$ | 34.10 | 29.77 | 28.13 | 2 | 114.76 | 57.38 | 2.01 |
| $T_{dir}$ | 35.78 | 23.65 | 32.57 | 2 | 474.61 | 237.31 | 8.29 |
| N | 29.74 | 32.43 | 29.84 | 2 | 28.53 | 14.26 | 0.50 |
| Error | | | | 4 | 114.45 | 28.61 | |
| Total | | | | 12 | 808.41 | | |

While $F_{2,4,0.05}$ equals to 6.94, there is a significant effect on factor $T_{dir}$ (C). That is, when using the RFID in practice, it is better to concern more on the allocation of antenna and tag direction. From the experiment results, when the antenna was almost parallel with the tags (on the same side and direction), the reading rate was better than other tag directions.

Separating the noise factor from the experiment results, as shown in Fig.5, the three levels – empty, liquid, metal were sketched on the same plot. It is easy to distinguish the three different levels. Clearly, the empty chest has the highest reading rate, and the metal content performs the poorest. The surrounding noise factor includes electric wave, electrical equipment and human. However, there was no obvious difference by separating this noise factor.

- Optimum setting

There was no statistical difference from three levels on the velocity of the delivery track ($V_d$), the distance between antenna and tag ($D_{at}$), and number of tags at a time (N). After the statistical analysis, tag direction ($T_{dir}$) is a significant factor. The tag attached on the long edge can have better reading rate. In other words, if the antenna was parallel (on the same side and direction) to the tags, the reading rate is better than other directions. In addition, through the effect plot, there was a large difference between different materials contained in the chest. The tags perform poor if there is fluid or metal in the chest. In summary, the content in the chest, the tag attachment, the allocation of antennas, and the direction of tags are important causes for practical RFID applications.

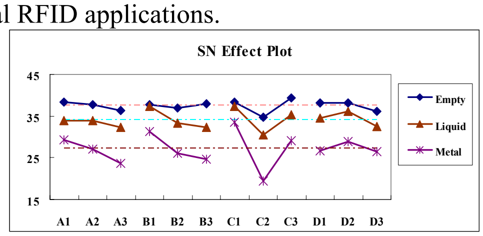



Fig. 5 Separated SN effect plot

*C. 915MHz RFID Interrogation Range Experiment*

The same environment is used to measure the interrogation zone and the assumptions hold in this 915MHz RFID interrogation range experiment. The reader is set to repeatedly read for 100 times, and the maximum interrogation range is defined as the farthest distance where the reading rate is above 20%. The reading rate under 20% is neglected as out of the interrogation zone.

1). Factor Selection and Analysis

The following three factors are identified to be the significant factors:

- Tag direction ($T_{dir}$): Fig.6 depicts the definition of 3 directions.

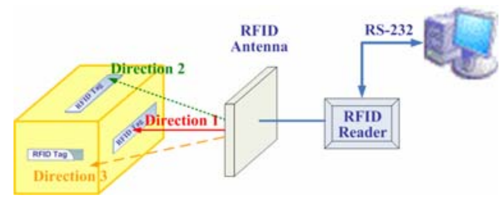



Fig. 6 Definition for the tag direction in 915MHz RFID system

- Number of tags at a time (N).
- Content material ($M_t$)

Given each factor 3 levels, the corresponding levels were listed in Table 5. Notice that the tag direction and material are dummy variables which are used for category variables.

Table 5 Identify Factors in 915MHz experiment

| Factor | Name | Low Level | High Level |
|---|---|---|---|
| *N* | Number | 1 | 10 |
| Tag Direction ($T_{dir}$) | | | |
| *Dir1* | Direction 1 | -- | -- |
| *Dir2* | Direction 2 | 0 | 1 |
| *Dir3* | Direction 3 | 0 | 1 |
| Material (*Mt*) | | | |
| *Em* | Empty | -- | -- |
| *Li* | Liquid | 0 | 1 |

Using a combined array which mixes control and uncontrollable factors together, the second order experiment design is generated by D-Optimal design and the variables of models are selected by stepwise regression. There are 25 runs of experiments and each run of experiments is conducted randomly. Three replicates are chosen for each run and the average value is taken for further estimation.

2). Factor Selection and Analysis

- Models

Since different brands of RFID antennas may vary in size of the interrogation zone, using the constructed models by absolute distance is not suitable when behaving other antennas. A generalized model which translates the interrogation range into ratio format is proposed to substitute the absolute distance model. How much the performance would be affected by factors combination is translated to the remaining ratio, which is predicted by the transformed model. Assuming the readers in the same frequency acting similarly, once the approximate interrogation range is known, the reader performance can be estimated by applying the proposed remaining ratio model. The remaining ratio models for length, width and height of 915MHz RFID interrogation zone are listed below:

$$\begin{aligned}\text{Length}(\%) = {} & 94.21 - 4.4N - 11.1Dir2 - 71.16Dir3 \\ & - 29.97Li - 66.19Me + 2.37N * Dir3 \\ & + 3.06N * Me + 53.66Dir3 * Li + 44.1Dir3 * Me\end{aligned} \quad (2)$$

$$\text{Width}(\%) = 103.19 - 5.55N - 50.26Dir3 - 53.66Li - 69.4Me - 1.8N*Dir2 + 2.31N*Dir3 + 3.09N*Li + 4.76N*Me + 43.22Dir3*Li + 18.06Dir3*Me \quad (3)$$

$$\text{Height}(\%) = 106.68 - 5.35N - 26.88Dir2 - 32.43Dir3 - 60.5Li - 62.82Me + 4.41N*Li + 4.34N*Me + 38.7Dir3*Li \quad (4)$$

3). Experiment Results and Conclusions

In the 915 MHz RFID reading range experiment, two controllable factors (N, $T_{dir}$) and one uncontrollable factor ($M_t$) were considered. The length, width and height of an antenna's interrogation zone were constructed. For a general model to fit readers of different brands, reading range is transmitted into a remaining ratio. Dir. 1 and scattered tags were the better combination for optimal operation.

## III. Optimal Layout and Deployment Planning Tool

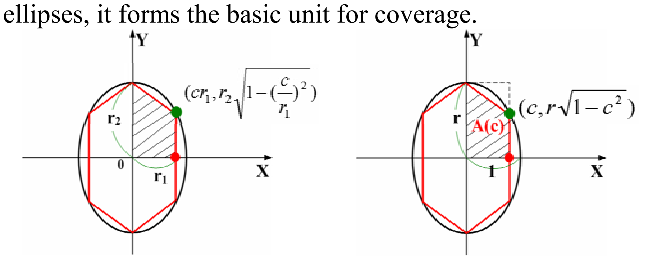
This paper also provides a deployment tool for users to obtain a recommended layout. For a given area, solutions of number and placement of RFID readers can be computed fast and robustly. It suggests a proper deployment for users to reach a high coverage rate. In addition, two simplified mechanism are provided for users to avoid reader collision.

### *A. Minimum Number of Ellipses to Cover a Rectangle*

Given a rectangular area with dimensions $x_R \times y_R$ (denoted by R), it is required to be completely covered. Since the coverage range of the RFID interrogation zone is represented by an ellipse, the complete coverage problem also employs fixed size of ellipses, and the radii equal to the readers' reading range, $r_2$ and $r_1$. Ideally, the minimum number of readers required in the area is obtained as

$$E_i = \frac{\text{Area of the rectangle}}{\text{Area of a ellipse}} = \frac{x_R\, y_R}{r_1\, r_2\, \pi} \quad (5)$$

$E_i$ is implicit since there is no overlap between ellipses and it may not ensure complete coverage. Considering the hexagonal formed by joining edges of six neighbouring ellipses, it forms the basic unit for coverage.




(a) Original axes of an ellipse with $r_1$ and $r_2$ (b) Scaling minor axis to be 1 and major axis to be r

Fig. 7 Simplified sketch for the axes of an ellipse at the coordinate

Since a symmetric hexagon can be divided into four equal trapezoid parts, one of the four trapezoids located in the first quadrant can be expressed as a function of c (assuming r is a given value) as observed in Fig. 7(b) and Eq.(6).

$$A(c) = rc - \tfrac{1}{2}c(r - r\sqrt{1-c^2}) = \tfrac{1}{2}rc\left(1+\sqrt{1-c^2}\right) \quad (6)$$

By linearly differentiating the trapezoid area A(c) by c and making A'(c) = 0 in Eq.(7), it is easy to compute the critical value as a constant c=0.866 in the first and fourth quadrant.

$$A'(c) = \frac{r}{2} + \frac{r}{2}\sqrt{1-c^2} + \frac{rc}{2}\left(\frac{-2c}{2\sqrt{1-c^2}}\right) = \frac{r}{2}\left[1+\sqrt{1-c^2} - \frac{c^2}{\sqrt{1-c^2}}\right] \quad (7)$$

Let $A'(c) = 0$ and $r \neq 0$

$c = \pm\sqrt{3}/2 \approx 0.866$

Returning to the original ellipse condition with axes $r_1$ and $r_2$, the optimal number of readers (ellipses) in each column (n) & row (m) are:

$$n = \begin{cases} Int\left(\frac{y_R}{\sqrt{3}r_1}\right) + 1, & if \quad rem\left(\frac{y_R}{\sqrt{3}r_1}\right) \le \frac{1}{2} \\ Int\left(\frac{y_R}{\sqrt{3}r_1}\right) + 2, & if \quad rem\left(\frac{y_R}{\sqrt{3}r_1}\right) > \frac{1}{2} \end{cases} \quad (8)$$

$$m = \begin{cases} Int\left(\frac{x_R}{1.5r_2}\right) + 1, & if \quad rem\left(\frac{x_R}{1.5r_2}\right) \le \frac{2}{3} \\ Int\left(\frac{x_R}{1.5r_2}\right) + 2, & if \quad rem\left(\frac{x_R}{1.5r_2}\right) > \frac{2}{3} \end{cases} \quad (9)$$

where *Int* is the integer operation and *Int*(*x*) equals to the integer part of *x*, *rem*(*x*) = *x*-*Int*(*x*).

In a global Cartesian coordinate with the origin located at the left bottom of the rectangle R, n $r_2$-strips are parallel to the x-axis, which contain m or (m+1) ellipses in each strip to completely cover the rectangle R. The centre of the $k^{th}$ row ($1 \le k \le n$) and $l^{th}$ column ($1 \le l \le m$) is computed in Eq.(10).

The center of $\begin{cases} k^{th} \text{ row } (1 \le k \le n) \\ l^{th} \text{ column } (1 \le l \le m) \end{cases}$ is at $\left[x^{kl}, y^{kl}\right]$

$$\left[x^{kl}, y^{kl}\right] = \begin{cases} \left[\left(\frac{\sqrt{3}}{2} + \sqrt{3}(l-1)\right)r_1, \left(\frac{1}{2} + \frac{3}{2}(k-1)\right)r_2\right], & \text{if } k \text{ is an } odd. \\ \left[\sqrt{3}(l-1)r_1, \left(\frac{3}{2}k-1\right)r_2\right], & \text{if } k \text{ is an } even. \end{cases} \quad (10)$$

### *B. Methodology of Anti-collision*

Assuming in an environment where the reader has been well placed, two clustering method were proposed in this paper to solve reader collision problem.

1.) Rule-based Cluster Method

This algorithm is based on pairs of readers' distance ($d_{ij}$) and interference range.

$$d_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2 + \left(z_i - z_j\right)^2} \quad (11)$$

where ($x_i$, $y_i$, $z_i$) and ($x_j$, $y_j$, $z_j$) are the coordinates for $R_i$ and $R_j$.

While two readers are close to each other, to separate nearby readers is indispensable and requisite. Eq.(12) is a member function to evaluate pairs of readers.

$$w_{ij} = \begin{cases} 1, & d_{ij} > k \times I_{max} \\ 0, & otherwise \end{cases} \quad (12)$$

where $I_{max}$ is the maximum interrogation range and *k* is a multiplier (*k*>1).

The term $k \times I_{max}$ can be replaced by a certain distance which is longer than the interference range, however, Eq.(12) gives a discriminate for pairs of readers, and then the matrix W can be computed by Eq.(13).

$$W = \begin{bmatrix} w_{11} & w_{12} & \cdots & w_{1n} \\ w_{21} & w_{22} & \cdots & w_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ w_{n1} & w_{n2} & \cdots & w_{nn} \end{bmatrix} \quad (13)$$

By summing the element of each row (or column), the first group to start clustering depends on the largest summation of a corresponding reader. It extracts the 0 element then compares the remaining readers in the second hierarchy. The process continues until no readers can be placed in the cluster (it ends with all element values to be 1). Generally, the first cluster is the maximum allowable combination of readers and it carries the most information of the event. This algorithm ends when each reader belongs to a specific cluster.

2.) Eigen-based Cluster Method

Deolalikar [3] proposed an eigen-based for users to simply cluster readers in a RFID network. This paper modified the method and redefined a relation matrix. Suppose there are n readers in a RFID network. Denote each reader as $R_i$, where i=1,...,n. The relation matrix R of the set of readers $\{R_i\}_{i=1,\dots,n}$ can be computed by Eq.(14).

$$R = \frac{1}{k \times I_{\max}} \begin{pmatrix} d_{11} & \cdots & d_{1n} \\ \vdots & \ddots & \vdots \\ d_{n1} & \cdots & d_{nn} \end{pmatrix} \quad (14)$$

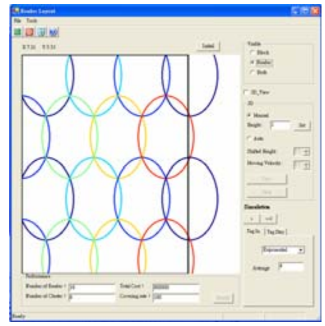
Since the matrix R is symmetric and invertible, $R' = SRS^{-1} = Diag(\lambda_1, \dots, \lambda_n)$ is a diagonal matrix. Sorting the eigenvalues in descending order, S is thus a linear transformation that transforms the input reader set $\{R_i\}_{i=1,\dots,n}$ into a set of transition readers $\{R_i'\}_{i=1,\dots,n}$. The transition readers $\{R_i'\}_{i=1,\dots,n}$ are pairwise uncorrelated because the eigenvectors in the matrix S are independent. By giving the interference scalar ( $k \times I_{\max}$ ) into relation matrix, if the element (in column i and row j) of the matrix R was less than 1, the reader i and reader j cannot be clustered together because they may interfere with one another. Choosing the greatest coefficient in the eigenvector (neglecting the sign of the coefficient), this is an initial element to form a cluster. Pick out the interfered readers until no collision happens. The remaining set forms a desired cluster. The process continues until all readers belong to a specific cluster.

## IV. Implementation and Simulation Results

The correctness and usability of the proposed deployment tool is discussed in this section. The number of readers and their initial locations were also evaluated, and the remaining ratio models of reading range were included in the tool for estimating the interrogation zone for 915MHz RFID readers. In addition to the basic and homogenous layout, the tool is designed for accommodating some visible factors which may cause variations. The expected output of the deployment tool is a robust topology layout that meets the input constraints with the best performance. There are two illustrations for homogenous layout and heterogeneous layout, respectively.

1.) Homogenous Layout

For an 8m by 6m region, in spite of the interference and region variety which may reduce the performance of RFID network, the reader deployment can easily be computed. In addition, the tool provides the clustering function for users to obtain a collision-free network, as shown in Fig. 8.

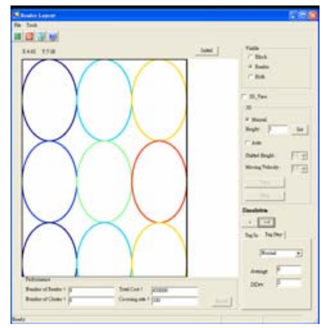


Proposed layout

Fig. 8 The screenshot of a graphical output

2.) Heterogeneous Layout

To consider the interference and region variety, the obstacles may restrict the placement of readers. However, this



Uniform layout

Fig. 9 The graphical output

study had constructed models to estimate the effect on RFID interrogation range. Users may input constraints; the system will generate a layout according to the previous model and display the output for users. The corresponding layout is shown in Fig. 9. The user may set the conditions of blocks in the region. It assumed that the condition was homogenous in a certain block.

### *A. Simulation*

A simulation function is added to the deployment tool. Users can choose suitable tag arrival and departure distributions to simulate the deployment and then obtain an average reading rate. There are four distributions available for users: Exponential, Uniform, Triangular and Normal. Note that the tag is assumed to randomly appear in the simulation environment in accordance with the chosen distribution.

Some necessary assumptions are made:

- Collision is only caused by the reader interference.
- No inter channel interference between the antennas.
- The data processing delay and the channel switching delay are considered negligible.
- No interference and all readers are homogenous.

### *B. Comparison of Different Cluster Methods and Layout Manners*

For a 6m×8m space, a comparison between different cluster methods was made under the following assumptions:

- The interrogation zones were homogenous to be 3m×2m;
- The interfering range was 1.8×3m;
- The tags appear randomly in the concerned space;
- The arriving tag follows an exponential distribution with mean value of 4 and the time tag stay follows a normal

distribution with mean value of 6 and standard deviation value of 2.

Comparatively, Fig. 9 shows a uniform layout which uses fewer readers (9 instead of 16) but it cannot ensure perfect coverage. A comparison between different layout manners and cluster methods were made. After 100-times simulations for each, the comparison is listed in Table 6.

## V. CONCLUSIONS

For a robust deployment of a RFID network, a systematic solution was proposed in this paper. The interrogation zone was measured in practice. By moving the tag cube by cube, layer by layer and assuming the performance of the tag is homogenous in each grid, the RFID antenna's interrogation zone was plotted. To simplify the reader deployment problem, instead of the traditional 2D circle-like shape assumption, the ellipse/ellipsoid-like shape was taken to represent the signal range of an RFID antenna in this paper. Further, the performance of RFID was estimated statistically. By applying Taguchi Method and Response Surface Method, interrogation range model for 915MHz were constructed. Hence, the size and shape of interrogation zone for various scenarios can be quickly estimated by the constructed models.

In addition, a deployment tool was designed for users to obtain a recommended layout. For a given area, solutions of number and placement of RFID readers are computed fast and robustly. Under input constraints, the system suggests a proper deployment for users to reach a high reading rate and ensure a complete coverage. To avoid reader collision which may result in low efficiency of a RFID network, two simplified mechanisms were proposed. Finally, the practical implementation and simulations were performed to test the practicability of the deployment tool and further confirm the robustness and adequacy of the proposed models.

Table 6 Comparison between cluster methods of uniform layout

| Method | Layout Manner | Number of Clusters | Average Reading Rate | Standard Deviation |
|---|---|---|---|---|
| Rule-based | Proposed | 9 | 0.9772 | 0.0251 |
| | Uniform | 6 | 0.8664 | 0.0244 |
| Eigen-based | Proposed | 10 | 0.9707 | 0.0286 |
| | Uniform | 7 | 0.8542 | 0.0256 |
| TDMA | Proposed | 16 | 0.7649 | 0.0399 |
| | Uniform | 9 | 0.6056 | 0.0296 |
| None | Proposed | 0 | 0 | 0 |
| | Uniform | 0 | 0 | 0 |

## REFERENCES


[1] S. Anusha, "RFIDcover: A Coverage Planning Tool for RFID Networks with Mobile Readers," Master Thesis, Graduate Institute of Information Technology, Indian Institute of Technology Bombay, 2005.

[2] J. J. Borkowski and J. M. Lucas, "Designs of Mixed Resolution for Process Robustness Studies," Technometrics, Vol. 39, pp. 63-70, 1997.

[3] V. Deolalikar, M. Mesarina, J. Recker, and S. Pradhan, "Perturbative Time and Frequency Allocations for RFID Reader Networks," HP Tech Report, HPL-2005-162, September 2005.

[4] D. Engels, "The Reader Collision Problem," Technical Report, epcglobal.org, 2002.

[5] Y. Guo and Z. Qu, "Coverage Control for a Mobile Robot Patrolling a Dynamic and Uncertain Environment," Proceedings of World Congress on Intelligent Control and Automation, June 2004.

[6] W. K. Hale, "Frequency Assignment: Theory and Applications," Proceedings of the IEEE, pp. 1497–1514, December 1980.

[7] F. L. Huang, "Development of Radio Frequency Identification Information Platform," Master Thesis, Graduate Institute of Industrial Engineering, National Taiwan University, 2006.

[8] J. K. Ho, "Solving the Reader Collision Problem with a Hierarchical Q Learning Algorithm," Master Thesis, Department of Electrical Engineering and Computer Science, Massachusetts Institute of Technology, 2003.

[9] R. Kershner, "The Number of Circles Covering a Set," In American Journal of Mathematics, Vol. 61, pp. 665, July 1939.

[10] K. S. Leong, M. L. Ng, and P. H. Cole, "The Reader Collision Problem in RFID Systems," Presentation paper white paper series, Edition 1, Auto-ID Labs, 2005.

[11] H. Mallinson, "Enhancing Identity with Location," Master Thesis, Graduate Institute of Manufacturing, Cambridge University, 2003.

[12] B. H. Metzger, "Spectrum Management Techniques," 38th National ORSA Meeting, Detroit, MI, September 1970..

[13] M. D. Yacoub, Foundations of Mobile Radio Engineering, CRC Press Inc., 1993.

[14] http://mathworld.wolfram.com/CirclePacking.html