# Read rate analysis of radio frequency identification systems for business applications

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**Abstract:** This paper presents a study on operational effectiveness of Radio Frequency Identification (RFID) systems in a controlled environment. Logistic regression models are developed to capture the dynamic relationship among implementation factors affecting the performance of an RFID system. Distance and angle between tag and antenna, orientation and position of tag on the container are found to be important factors among other implementation factors. A test bed is used to represent the flow of tagged products on a rolling conveyor passing by an antenna. It is shown that controlled and designed experimentation about RFID yields valuable data that, subject to appropriate statistical models, may result in a better practical understanding of the technology. In addition to the performance assessment and evaluation for RFID systems with respect to various factors, this study also aims to establish a reliable literature base for the development of this technology in the future.

**Keywords:** radio frequency identification; RFID; performance analysis; logistic regression; distance; angle; position.

**Reference** to this paper should be made as follows: Buyurgan, N., Ertem, M.A. and Chimka, J.R. (2007) 'Read rate analysis of radio frequency identification systems for business applications', *Int. J. Radio Frequency Identification Technology and Applications*, Vol. 1, No. 2, pp.147–163.

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## 1 Introduction

Today's high trend of achieving global, modern, technology-focused, highly flexible, quality-driven and cost competitive enterprises forces companies to find affordable and independent business solutions. These solutions should allow them to improve their core competencies and react swiftly to rapidly changing customer wishes.

Radio Frequency Identification (RFID) is one of the fastest growing technologies these days that companies rely on. It provides potential of an individualised identification to a pallet, case or item and offers greater visibility. The main advantage of the technology is transmitting the information without any physical contact or even straight line of transmission, which overcomes the enormous shortcomings of the prevalent sensing technologies by eliminating human interaction and error (Sabetti, 1998; Sutton, 1993).

Recently, RFID has received attention from both industry and government with many 'revolutionary' applications in today's working environment. Several market estimates in various studies indicate that RFID technology will be an important figure of manufacturing, retail and service sectors in a time horizon of 3–4 years (RFID Group, 2005). Wal-Mart, the world's largest retailer, announced in June 2003 that its top

100 suppliers would be required to put RFID tags on all cases and pallets of consumer goods shipped to a limited number of Wal-Mart distribution centres and stores by January 2005. The USA Department of Defence also released its own mandates on the process of integrating RFID into its shipping procedures in July 2004. Many other companies followed these efforts (Hardgrave et al., 2005).

Although RFID is not a new technology, its benefits are more visible than ever. However, without proper appreciation of RFID including its potentials, capabilities and drawbacks, implementation of this technology will bring nothing more than costs. One of the major problems that many companies face is not spending adequate time to evaluate the technology in their business applications. Only a few studies in the literature give test results related to factors contributing the performance of RFID technology. Besides, well performed/designed experiments and proper statistical analysis of these test results are not widespread.

This paper presents a study on operational effectiveness of RFID technology in a controlled laboratory environment. The contribution of this paper is threefold:

1. to develop practical test set-ups and mathematical analysis procedures in order to investigate the effects of the implementation factors on the effectiveness of an RFID system
2. to verify the significance of these factors and
3. to demonstrate the use of logistic regression models for the analysis of success/failure read rates.

The major motivation is to demonstrate the practicality of the experimental tests as well as data analysis procedures. Identifying of the system parameters, acquiring some understanding of these parameters and obtaining the dynamics of the effects on system performance are also addressed by using a sample set-up. A series of statistical analyses are performed in order to test the operational effectiveness of RFID systems. In addition to the performance assessment and evaluation for RFID systems with respect to various factors, this study also aims to contribute to the RIFD literature for the deployment of this technology in the future. Furthermore, statistical analyses also provide insights into the arrangements that should be considered while implementing RFID systems into a facility. Statistics would seem appropriate here since there is variation that is whether or not a tag has been read. An important goal should perhaps be to better understand this variation by answering the question, "What might be affecting whether or not the tag is read?"

The rest of this paper is organised as follows: The literature review is given in Section 2. Section 3 describes the test methodology and environment in detail. The logistic regression model and the analysis of test results based on this model are given in Section 4. Discussion and future work are presented in Section 5.

## 2 Literature review

An overview of RFID technology is provided in Finkenzeller (2004) for those who are not familiar with the technology. An outline on RFID system components is also given in Rao (1999). Unlike the introductory literature, the accessibility of publicly available testing and analysis of RFID systems is not prevalent in the literature other than a few white papers; nevertheless some results have been disseminated. A preliminary out-of-stock analysis for Wal-Mart stores is performed in Hardgrave et al. (2005). In that study, the focus is on the analysis of the given RFID data, assuming that the collected information is reliable. The results indicate that RFID technology made a contribution to reduce the out-of-stocks in the 12 test stores from which daily data is collected for seven months.

A study comparing eight different commercially available RFID systems is presented by Porter et al. (2004). Laboratory baseline performance tests are conducted as well as warehouse passive interference tests. Investigation consists of different practical performance tests such as capture zone test, tag orientation test and speed test as well as tests with tags mounted on different types of containers (empty, filled, plastic shrink wrap, etc.). The results of that study show that none of the eight systems meets all application requirements. The researchers conclude that orientation of RFID tags, number of tags in the capture zone and direct contact of tag with metal also affect the read rates of the systems.

Two reports on performance analysis of tags from different vendors testing with varying distances, varying orientation, near water and metal placement as well as yield quality are released by the RFID Alliance Lab at the University of Kansas (Deavours, 2004, 2005). Collision from multiple tags is analysed in Vogt (2002). The determination of the optimal number of read cycles to reach a predetermined assurance level is shown. Pentilla et al. (2004) studied the detection velocities of the tags considering high speed applications like road tolls. Multiple tags and single tags differ in results; the former gives acceptable results for 4 m/s, whereas the latter can go up to 12 m/s.

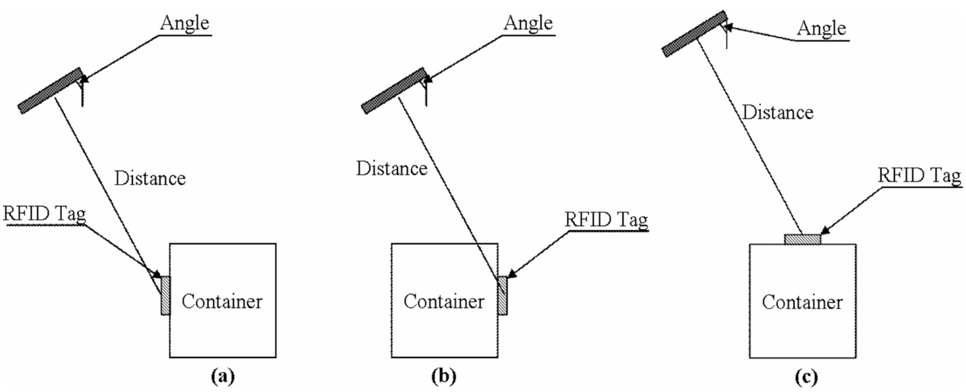
Read zone can be defined as the volume inside which the antenna can communicate with the tags (Rao et al., 1999). Two papers regarding the analysis of read zone are by Keskilammi et al. (2002, 2003). They analyse three factors affecting the read zone: frequency used for detection, antenna gain and polarisation mismatch between reader antenna and the transponder (tag) antenna. The results indicate that 915 MHz proves to be better than 2.45 GHz and 5.8 GHz for frequency, antenna gain is directly proportional to read range and power loss increases when mismatch is greater than 45°. Siden et al. (2001) deal with performance decrease of passive RFID systems by employing a tilt to the RFID tag. According to that study, read zone of the system decreases while bending angle is increased. Rao et al. (1999) formulises the read zone of an RFID system depending on the random directions for tags and antennae.

Performance analysis of RFID systems, presented in this paper, is based on statistical models. A test bed is used to represent the flow of tagged products on a rolling conveyor passing by antennae. The same test bed with different set-ups was also used in previous studies. The details of the test bed can be found in Scott (2004). Using the test bed, a series of experiments with 54 implementation factor combinations are conducted in order to assess the operational effectiveness of RFID systems. The performance metric for the system is selected as successful read rates in read zone between the tags (transponder) and antennae (transmitter). Logistic regression models are utilised with experimentation data based on the results. It is shown that controlled and designed experimentation on RFID systems yields interesting and useful data that, subject to appropriate statistical models, may result in a better practical understanding of the technology.

## 3 Methodology and test environment

A previously developed test bed which consists of a conveyor system is used in the University of Arkansas AT&T Material Handling Laboratory in order to conduct the experimentation. The conveyor system installation is designed to represent the flow of product throughout a processing facility. Various important implementation factors such as antenna types, angle, distance, conveyor speed, power of readers, content of the container and tag orientation that affect operational effectiveness of an RFID system are considered during the experimentation. Due to exponentially growing complexity of interrelations among these factors some of them are considered as constant values during the experimentation. This method also allows focusing on application parameters as well as RFID system variables in addition to the environmental conditions. Conveyor speed of the system is set to 25 m/min believing that the flow of products throughout a processing facility can be represented with this speed. Ten Class-0 passive type tags are randomly selected and placed on empty containers in order to avoid any interference of content materials. Two high-gain antennae from the same vendor are attached to a reader. Radio Frequency (RF) of the antenna is 915 MHz, UHF band. The RF method used in the reader technology is frequency hopping spread spectrum. Power supply of the reader is 24vDC at 1.2 amps and power output is 1 watt. The room temperature is kept at approximately 18°C. Major implementation and system factors that vary during experimentation are distance, angle, tag orientation and antenna. *Distance* is defined as the shortest orthogonal distance of tag's centre of gravity from the antenna's centre of gravity. For the experiments, 30, 60 and 90 cm are used as the three levels of distance. *Angle* is the face angle of the tag with respect to antenna. 30°, 45° and 60° are selected levels. *Tag orientation* determines the faces of the container on which tags are placed. Three levels for tag orientation are same side, opposite side with respect to antenna and top of the container. Figure 1 shows the distance and angle concepts with respect to three different tag orientations.

**Figure 1** Distance and angle concepts for different tag orientations: (a) same side; (b) opposite side and (c) top of the container




Together with the two antennae from the same vendor these levels with four factors add up to 54 different combinations. Each of the 54 combinations was observed an average of about 287 times with each of two antennae, using ten different tags that are controlled for in the models. A closed loop conveyor is used for the experiments and two antennae are placed at two ends of the conveyor with different perspectives for the same run. Thus in each run, two sets of data are collected. Experimental design is given in Table 1. Each model is based on 15,480 observations.

**Table 1** Experimental design for the study

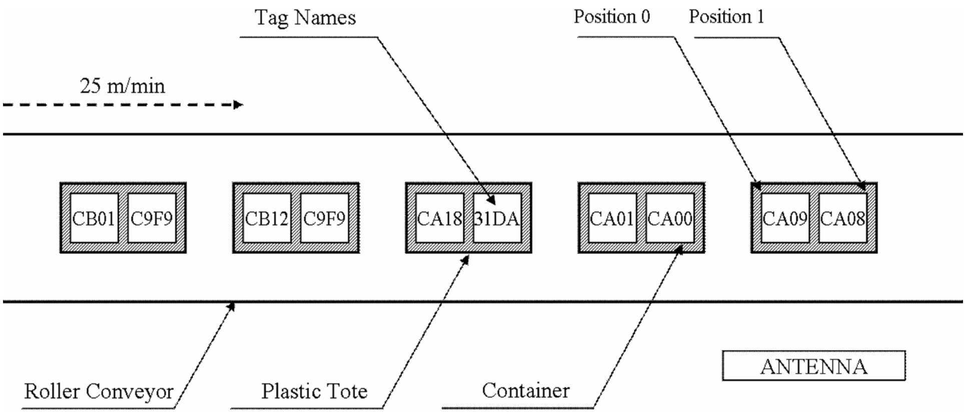
| *Run order* | *Implementation factors and levels* | | | *Antenna number* | *Cycle number* |
|---|---|---|---|---|---|
| | *Distance* | *Angle* | *Orientation* | | |
| 1 | 12 | 60 | top | A1 | 55 |
| 2 | 36 | 45 | top | A2 | 55 |
| 3 | 24 | 45 | opposite side | A1 | 59 |
| 4 | 12 | 45 | opposite side | A2 | 59 |
| 5 | 36 | 30 | top | A1 | 55 |
| 6 | 24 | 30 | top | A2 | 55 |
| 7 | 24 | 45 | same side | A1 | 57 |
| 8 | 24 | 30 | same side | A2 | 57 |
| 9 | 24 | 60 | opposite side | A1 | 54 |
| 10 | 12 | 30 | opposite side | A2 | 54 |
| 11 | 36 | 45 | same side | A1 | 57 |
| 12 | 36 | 30 | same side | A2 | 57 |
| 13 | 36 | 30 | opposite side | A1 | 56 |
| 14 | 24 | 30 | opposite side | A2 | 56 |
| 15 | 24 | 60 | top | A1 | 57 |
| 16 | 12 | 30 | top | A2 | 57 |
| 17 | 36 | 45 | opposite side | A1 | 56 |
| 18 | 36 | 30 | opposite side | A2 | 56 |
| 19 | 24 | 45 | top | A1 | 66 |
| 20 | 36 | 60 | top | A2 | 66 |
| 21 | 12 | 30 | opposite side | A1 | 59 |
| 22 | 24 | 45 | opposite side | A2 | 59 |
| 23 | 12 | 60 | same side | A1 | 61 |
| 24 | 24 | 45 | same side | A2 | 61 |
| 25 | 12 | 60 | opposite side | A1 | 60 |
| 26 | 36 | 45 | opposite side | A2 | 60 |
| 27 | 24 | 30 | opposite side | A1 | 56 |
| 28 | 36 | 60 | opposite side | A2 | 56 |
| 29 | 36 | 30 | same side | A1 | 59 |
| 30 | 12 | 30 | same side | A2 | 59 |
| 31 | 24 | 30 | top | A1 | 59 |
| 32 | 36 | 30 | top | A2 | 59 |
| 33 | 12 | 30 | top | A1 | 58 |
| 34 | 12 | 45 | top | A2 | 58 |
| 35 | 12 | 45 | opposite side | A1 | 60 |
| 36 | 12 | 60 | opposite side | A2 | 60 |
| 37 | 12 | 30 | same side | A1 | 50 |

**Table 1** Experimental design for the study (continued)

| *Run order* | *Implementation factors and levels* | | | *Antenna number* | *Cycle number* |
|---|---|---|---|---|---|
| | *Distance* | *Angle* | *Orientation* | | |
| 38 | 24 | 60 | same side | A2 | 50 |
| 39 | 36 | 60 | same side | A1 | 56 |
| 40 | 12 | 45 | same side | A2 | 56 |
| 41 | 36 | 45 | top | A1 | 55 |
| 42 | 12 | 60 | top | A2 | 55 |
| 43 | 12 | 45 | same side | A1 | 58 |
| 44 | 36 | 60 | same side | A2 | 58 |
| 45 | 12 | 45 | top | A1 | 66 |
| 46 | 24 | 60 | top | A2 | 66 |
| 47 | 36 | 60 | opposite side | A1 | 55 |
| 48 | 24 | 60 | opposite side | A2 | 55 |
| 49 | 24 | 60 | same side | A1 | 50 |
| 50 | 36 | 45 | same side | A2 | 50 |
| 51 | 36 | 60 | top | A1 | 55 |
| 52 | 24 | 45 | top | A2 | 55 |
| 53 | 24 | 30 | same side | A1 | 59 |
| 54 | 12 | 60 | same side | A2 | 59 |

Two empty containers with attached RFID tags are placed into a plastic tote. *Position of the tag* is defined as whether it is the first one passing by the antenna or not. Figure 2 demonstrates the test bed with position. Note that the tags are identified according to the last four digits of their Electronic Product Code (EPC) numbers (EPCglobal, 2006).

**Figure 2** Conveyor system test bed with RFID system




Tags are being read continuously by the antenna from their entrance to the reading envelope from one side until their departure from the other side. Since multiple reads in the reading envelope will not be analysed, synchronisation of the reader and the tag position in each run are kept out of the scope of the test environment. Whether a tag is being read for multiple times or for a single time while it is in the reading envelope does not make any difference in our analysis for the success/failure rates considering the shortest orthogonal distance between tag and antenna. It is noticeable that one cannot claim that angle and distance levels are not changing in a moving conveyor, but for the sake of experimental ease, these factor levels are measured in this shortest orthogonal distance as a reference point.

## 4 Logistic regression model and analysis of test results

The formal statement of simple logistic regression is as follows: $Y$ is a Bernoulli random variable with parameter $E[Y] = \pi = \Pr(y = 1)$ when the response variable is binary (Neter et al., 1996). Then, the logistic regression model is given by:

$$E[Y] = \frac{\exp(\beta_0 + \beta_i X_i)}{1 + \exp(\beta_0 + \beta_i X_i)} \tag{1}$$

where $X_i$, $i = 1,\ldots,k$, are qualitative or quantitative independent variables. Here we will estimate two such models (see Equations (3) and (4)), one for each of two antennae or replicating experiment.

Logistic regression models of *success* are fit for the data, obtained from the experimentation, where *success* is a 0/1 variable describing whether or not an RFID tag has been successfully read. The experiment is conducted in two sets. In each set, implementation factors (i.e. distance, angle, orientation, etc.) are kept identical as well as the number of replications. However, two different antennae are used in each set, analysis results of each hopefully to verify the other. Implementation factors and their levels can be summarised as

1 *Distance*: 30, 60 and 90 cm.

2 *Angle (A categorical variable)*: 30° (angle = 1), 45° (angle = 2) and 60° (angle = 3).

3 *Position (A 0/1 variable)*: 1 (Tag is placed on the first container) and 0 (Tag is placed on the second container).

4 *Orientation (A categorical variable)*: 1 (Tag is placed on the same side of the container relative to the antennae), 2 (Tag is placed on the opposite side of the container relative to the antennae) and 3 (Tag is placed at the top of the container).

5 *Tag (A categorical variable)*: controlling for which of ten experimental tags has passed by an antenna.

Before the model fit, indicator variables for *angle*, *orientation* and *tag* are created. Tables 2 and 3 show what is pertinent about main effects models fitted for antennae 1 and 2, respectively. In logistic regression, odds in favour of success is defined as

$$\text{Odds} = \frac{\pi}{1-\pi} = \frac{\Pr(y=1)}{\Pr(y=0)} \tag{2}$$

Odds ratios in Tables 2 and 3 show the change in log-odds, $\ln(\pi/1-\pi)$ for every one unit increase in each independent variable, $X_i$, holding all other variables fixed. Since the model includes independent variables which are binary or categorical, interpretation of these ratios is not a trivial task in a logistic regression model, but some understanding is provided. Among dichotomous independent variables, the odds ratio "approximates how much more likely it is for the outcome to be present among those with $x = 1$ than among those with $x = 0$ (Hosmer and Lemeshow, 2000)". As for the continuous independent variable *distance*, it would be more difficult to interpret and we will be satisfied to test simply its significance in models of read rate. The following analysis is performed with STATA Statistical Software (STATA Corp., 2005). In Tables 2 and 3 can be found odds ratios, their associated standard errors, observations $Z$ = odds ratio/standard error from the standard normal distribution and probabilities Pr > $z$ of observing $Z$ values more extreme than those found here. Hypotheses about the independent variables may be tested then such as in linear regression. Along with figures presented later in this section and in the discussion section, we will acknowledge what may be considered *significant* effects. Since there are so many variables considered either as interesting or simply control variables in each model, we will consider significant only those with reported Pr > $z$ = 0.000.

**Table 2** Logistic regression result for antenna 1 (experiment 1)

| *Success* | *Odds ratio* | *Standard error* | *Z* | *Pr >Z* |
|---|---|---|---|---|
| Distance ($D$) | 0.873 | 0.005 | –25.41 | 0.000 |
| Position ($P$) | 0.339 | 0.072 | –5.10 | 0.000 |
| angle_45 ($a_{45}$) | 4.307 | 0.525 | 11.97 | 0.000 |
| angle_60 ($a_{60}$) | 0.577 | 0.052 | –6.08 | 0.000 |
| orientation_2 ($o_2$) | 153.992 | 43.754 | 17.73 | 0.000 |
| orientation_3 ($o_3$) | 34.903 | 5.090 | 24.36 | 0.000 |
| tag_2 | 0.605 | 0.105 | –2.91 | 0.004 |
| tag_3 | 1.125 | 0.273 | 0.49 | 0.628 |
| tag_4 | 0.491 | 0.084 | –4.17 | 0.000 |
| tag_5 | 1.278 | 0.318 | 0.99 | 0.323 |
| tag_6 | 0.614 | 0.106 | –2.82 | 0.005 |
| tag_7 | 0.142 | 0.029 | –9.61 | 0.000 |
| tag_8 | 0.734 | 0.167 | –1.36 | 0.175 |
| tag_9 | 0.351 | 0.059 | –6.25 | 0.000 |

We also report for each antenna an approximate logit of the logistic regression model. The following two equations ($g_1$ for antenna 1 and $g_2$ for antenna 2) are approximate in that they include only what is most significant (Pr > $z$ = 0.000).

$$g_1 \approx 6.256 - 0.136D - 1.08P + 1.46a_{45} - 0.549a_{60} + 5.037o_2 + 3.552o_3 \quad (3)$$

$$g_2 \approx 6.347 - 0.091D - 0.555a_{60} + 4.484o_2 + 0.546o_3 \quad (4)$$

**Table 3** Logistic regression result for antenna 2 (experiment 2)

| *Success* | *Odds ratio* | *Standard error* | *Z* | *Pr > Z* |
|---|---|---|---|---|
| Distance (*D*) | 0.913 | 0.005 | –16.41 | 0.000 |
| Position (*P*) | 0.757 | 0.215 | –0.98 | 0.327 |
| angle_45 ($a_{45}$) | 0.819 | 0.097 | –1.68 | 0.092 |
| angle_60 ($a_{60}$) | 0.574 | 0.064 | –4.97 | 0.000 |
| orientation_2 ($o_2$) | 88.563 | 40.022 | 9.92 | 0.000 |
| orientation_3 ($o_3$) | 1.726 | 0.157 | 5.99 | 0.000 |
| tag_2 | 0.433 | 0.099 | –3.66 | 0.000 |
| tag_3 | 0.543 | 0.145 | –2.28 | 0.022 |
| tag_4 | 0.619 | 0.149 | –1.99 | 0.047 |
| tag_5 | 0.573 | 0.154 | –2.06 | 0.039 |
| tag_6 | 0.137 | 0.028 | –9.57 | 0.000 |
| tag_7 | 0.504 | 0.133 | –2.60 | 0.009 |
| tag_8 | 0.529 | 0.141 | –2.39 | 0.017 |
| tag_9 | 0.353 | 0.079 | –4.67 | 0.000 |

In order to measure the predictive power of each model (associated with antennae and Tables 2 and 3), a Receiver-Operating-Characteristic (ROC) curve is graphed for each regression model and the areas under these curves are calculated. The ROC curve is a graph of '*sensitivity*' versus '*1 – specificity*' as the cut-off *c* is varied over all possible cutpoints. The cut-off, *c*, is relied upon to classify a test result as positive. For example, we predict the tag will be read if $\Pr(Y = 1) \geq 0.5$, if $c = 0.5$. Sensitivity, in the ROC curve, can be defined as the fraction of observed successful reads that are correctly classified whereas specificity can be defined as the fraction of observed non-reads that are correctly classified. The curve starts at (0, 0) and continues to (1, 1). The more bowed the curve the greater the predictive power; the area beneath the curve is a measure of the predictive power. 'A model with no predictive power has area 0.5; a perfect model has area 1' (STATA Corp., 2005). Figures 3 and 4 represent ROC curves associated with models fitted for antennae 1 and 2, respectively. The corresponding areas under curves are 0.927 and 0.864. Again the area under the ROC curve provides a measure of discrimination. As a general rule, $0.8 \leq \text{ROC} < 0.9$ is considered excellent discrimination; $\text{ROC} \geq 0.9$ is considered outstanding discrimination (Hosmer and Lemeshow, 2000). The unusually great observed area 0.927 for antenna 1 may be due in part to nearly complete separation, "when a collection of the covariates completely separates the outcome groups" (Hosmer and Lemeshow, 2000, p.138). For a good communication on ROC techniques, see Green and Swets (1989).

Beside the logistic regression model, the data from the experiment results are also analysed individually. The results from both sets of experiments indicate that the tags at greater distances from antennae are less likely to be successfully read when the other implementation factors remain the same. Table 4 gives mean success rates at the three experimental distances for each of the two antennae.

**Figure 3** ROC curve for antenna 1

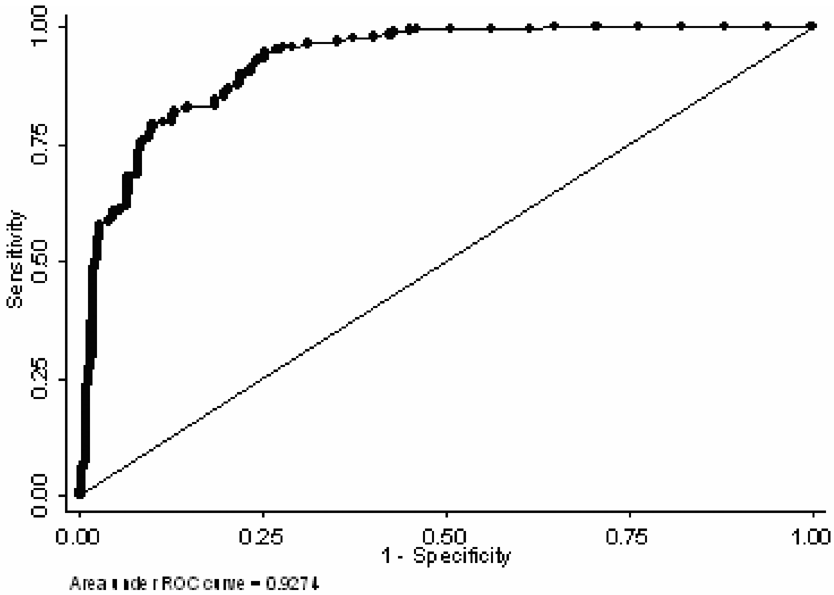



**Figure 4** ROC curve for antenna 2

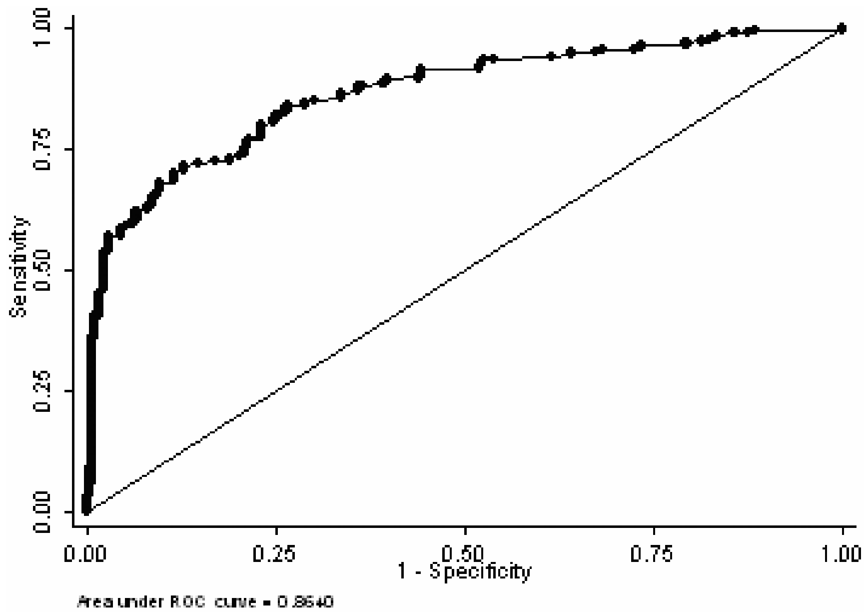
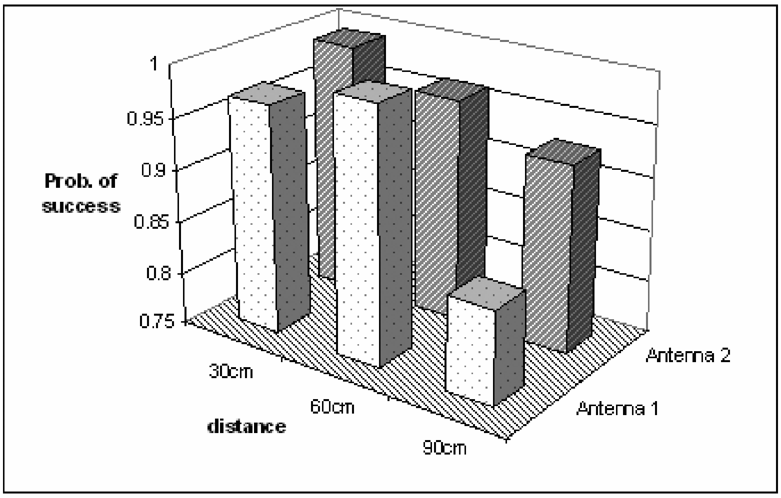



**Table 4** Probability of success for different antennae and distances

| *Mean success* | *30 cm* | *60 cm* | *90 cm* |
|---|---|---|---|
| Antenna 1 | 0.969 | 0.994 | 0.840 |
| Antenna 2 | 0.993 | 0.965 | 0.930 |

As seen in Table 4, there is a consistent increase in the probability of a successful read as the distance decreases for antenna 2, whereas for antenna 1 the data indicate that the probability of a successful read is greater for the distance of 60 cm than any other distances. The observed inconsistency of mean success 0.994 for antenna 1 with 60 cm distance may be due to distances being ratios in scale, for example, 30, 60 and 90 (unlike other independent variables of interest). Were success the response to distance, there would be a negative slope between them. That observations at 30 cm were (on average) less successful than observations at 60 cm was due to chance for antenna 1. Figure 5 shows this difference/anomaly.

**Figure 5** Probability of success different antenna and distance combinations




From the first experiment set with antenna 1, the tags in the second of two positions are found less likely to be successfully read, whereas in set two with antenna 2, positions are alike. Table 5 and Figure 6 show mean success rates in both experimental positions for each antenna.

**Table 5** Probability of success for different antennae and positions

| *Mean success* | *1st position* | *2nd position* |
|---|---|---|
| Antenna 1 | 0.957 | 0.913 |
| Antenna 2 | 0.976 | 0.950 |

In order to compare the categorical variables of interest (angle and orientation), logistic regression models for each experimental set are refit when angle or orientation are different from each one of their levels (e.g. angle ≠ 1 or orientation ≠ 2). For antenna 1, according to Pr > $z$ and differences in odds ratios, the direction of 45° angle between antenna and tag is more suitable for successful reads. The 60° angle has tags least likely to be read in set 1. For antenna 2, 60° angle has tags less likely to be read than those forming 30° and 45° angles with antenna. Table 6 and Figure 7 show mean success rates at the three experimental angles for each of the two antennae.

**Figure 6** Probability of success for different antenna and positions

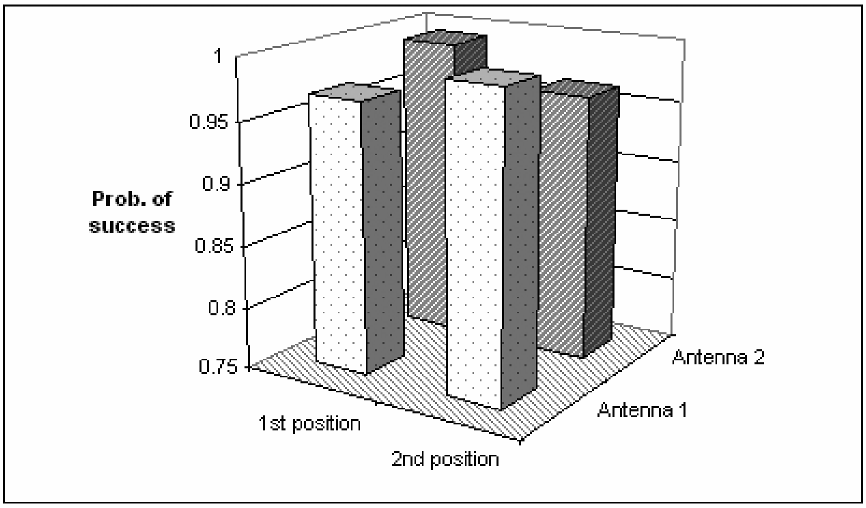
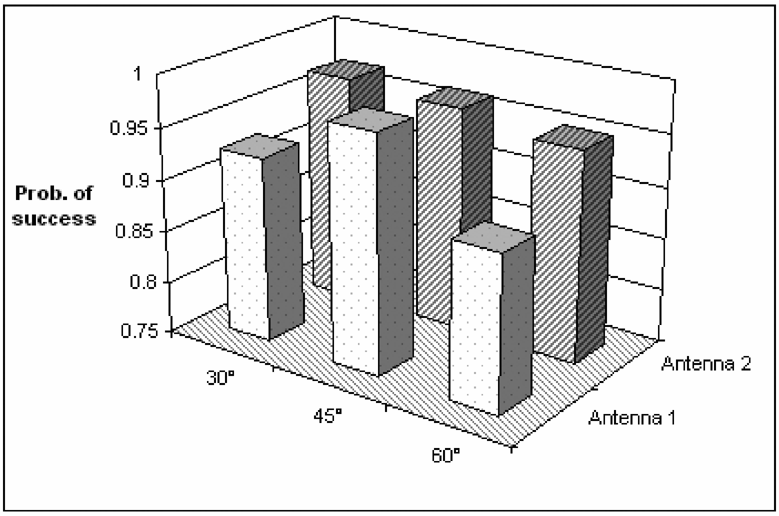



**Table 6** Probability of success for different antenna and angles

| *Mean success* | *30°* | *45°* | *60°* |
|---|---|---|---|
| Antenna 1 | 0.928 | 0.977 | 0.899 |
| Antenna 2 | 0.971 | 0.966 | 0.951 |

**Figure 7** Probability of success for different antenna and angles

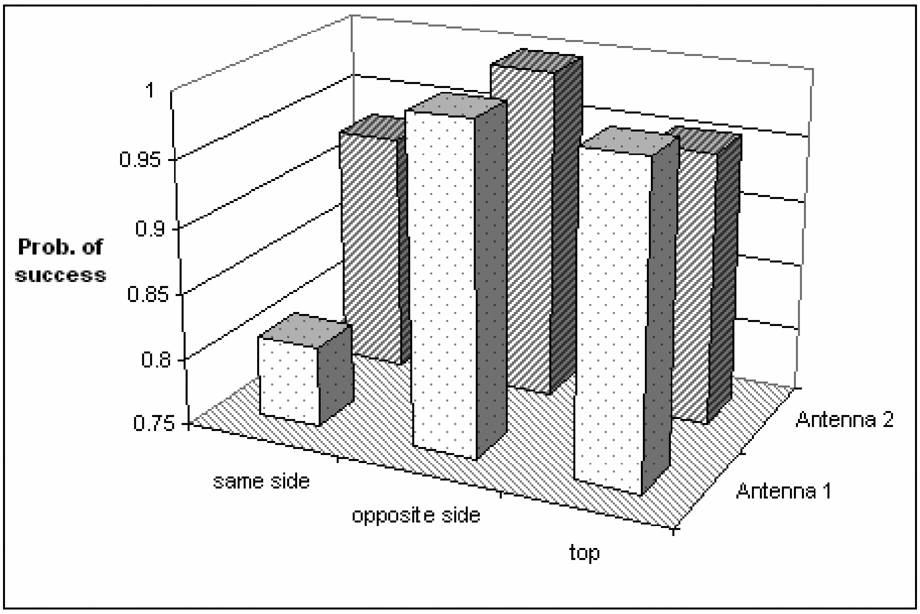



For both antennae, according to Pr > $z$ and differences in odds ratios, the 'opposite' (*orientation* = 2) orientation of antenna relative to tag is most likely to have successful reads. The 'same' (*orientation* = 1) orientation has tags least likely to be read. Table 7 and Figure 8 shows mean success rates in orientations 1, 2 and 3 for each antenna.

**Table 7** Probability of success for different antenna and orientation

| *Mean success* | *Orientation 1* | *Orientation 2* | *Orientation 3* |
|---|---|---|---|
| Antenna 1 | 0.811 | 0.998 | 0.989 |
| Antenna 2 | 0.932 | 0.999 | 0.955 |

**Figure 8** Probability of success for different antenna and orientations




## 5 Discussion and future work

RFID is a system whose electromagnetic characteristics are studied in the telecommunications field to some extent, but the practical problems which result from rapid deployment of the technology are not analysed with robust models. Read rates in an RFID system are well represented with a logistic regression model. Although the parameters in the model cannot be interpreted as easily as with other regression models, the predictive power is noteworthy and logistic regression is obviously more theoretically appropriate than more traditional linear regression with its assumptions of normality.

The results are analysed based on the selected performance measure (successful read rates in read zone). These results are consistent with a number of published papers regarding the tests on application parameters of RFID systems. As distance between the tag and the antenna increases while holding other factors constant, the probability of a successful read decreases (except as noted in regard to Figure 5). Since the radio waves are losing their power through the distance the read rate of an RFID system should decrease although other factors such as radar cross section may be in play. Besides, the experiments are conducted for moving tags. This also affects the change in read rate.

The maximum distance we used here might be increased, but antenna gain should also be increased to acquire the signals at that distance. However, the question of collision in readings might also arise.

The conclusion on facing angles can be drawn as: the smaller the facing angle between antenna and tag, the greater the successful reads in an observation. In other words, the read rate of the system increases as the tag and the antenna face to each other. A 45° angle between antenna and tag can be considered as a threshold, reinforcing Keskilammi et al. (2002, 2003). Two antennae differed in success rates for almost all factor combinations, as well as the predictive power of the models.

Position of the tags, which has not been considered a priori, becomes apparent as a factor. To be the first entering into the read zone results in better readings. Lesser readings of the second tag might stem from signals that cancel each other while passing by the antenna. Enough space between products should be left in order to avoid this interference. The distance between the tags is also an important issue to study the collision of radio waves in the read zone.

For orientation, being on the opposite side to the antenna gave better results. This is an unexpected result because the waves should travel through the container to reach the tag. This result cannot be explained with the factors in consideration. However, it is well known that the radio waves are reflected by conductive materials such as metals, metallised plastic and foil packages. Since the conveyor system used for this experimentation is a large metal object, the waves could be reflected and the readings from the opposite side of the container could give better readings. Using empty card boxes as containers also affects the system. Since there is no absorptive or conductive material in the containers does not hinder the waves travel as they through the containers.

We acknowledge that there are some limitations of this study. As any experimental study performed in a controlled environment, the results are restricted to the given laboratory setting. Environmental factors like cell phones, PC monitors, control screens of machines, tuners and temperature of the room should be taken into account while implementing RFID system into a facility.

For future research, the design of experiments can be modified to include more factors and levels for each factor. Different vendors can be compared for benchmarking the performances of different RFID systems. Alterations to the conveyor system should also be made so that tags can move at a speed of approximately 150 m/min, which is required by some industrial companies. The speed of the conveyor can be controlled to determine the point at which the antennae cannot detect tags.

Experiments are conducted with EPCglobal Gen1 equipment, experiments need to be repeated with EPCglobal Gen2 equipment and the results could be compared as a future work. This future work might also address multiple readings in each pass.

The ability to adjust the gain or power of the reading capability of the antennae provides another opportunity for future research. Besides reading tags, writing to the tags is also an important issue that can be taken into consideration. Different classes of tags can be included to reflect the diverse industry applications.

With respect to the logistic regression models there is the future task of doing more to investigate how interaction and confounding may affect the estimated coefficients. In the meantime, there may be found some sense of these in the illustrations of success probability with respect to the stratification variable (antenna) and distance, position, angle and orientation. Also, since so many of our main effects are significant, interaction might not be of much practical interest here.

In any event, it is shown that controlled and designed experimentation about RFID yields interesting and useful data that, subject to appropriate statistical models, may result in a better practical understanding of the technology.

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