

# Factors Affecting RFID System Performance and Non-parametric Analysis

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**Abstract** Many factors can affect radio frequency identification (RFID) system performance. This paper focuses on three selected factors: the RF attenuation, the tagged material, and the tag orientations angle. The effect of the RF attenuation on the response rate of the BlueBean RFID Development Lab System was tested and read ranges at various tag orientations angles were measured. A design of experiments (DOE) method was used to understand and quantify the relative influence of the three factors on the read range of the BlueBean RFID system. There are two main methods of measuring tag performance. The first method uses fixed distance to the tag and finds the minimum transmitted power at which the tag becomes detectable. The second method uses fixed transmitted power while the tag is being moved away until it cannot be read. Both the two experimental methods were used and a comparative study of the two methods was conducted using a non-parametric method based on the *U* test.

**Keywords:** Radio frequency identification (RFID), Design of experiments (DOE), *U* test, RF attenuation, read range, response rate

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## 1. Introduction

Wireless system performance is contingent on several antenna characteristics and propagation channel properties. The antenna features are comprised of: operating frequency band, gain features, matching, polarization, and attraction to nearby objects with different properties. The propagation channel properties include: path loss and spatial and temporal fading statistics. An RFID system is a wireless system. Path loss between the two communicating antennas depends on frequency, antenna height, receive terminal location relative to obstacles and reflectors, and link distance, among other factors such as the propagation environment including other tags in the vicinity and the object the tag is placed on [1,2].

RFID readers typically transmit with maximum allowable effective isotropic radiated power (EIRP) using directional antennas with high gain to maximize read range [1]. The space around the reader antenna can be divided into two main regions: far field and near field. In the far field, electric and magnetic fields propagate outward as an electromagnetic wave and are perpendicular to each other and to the direction of propagation. In the near field, the field components have different angular and radial dependence. The near field region includes two sub-regions: radiating, where the angular field distribution is dependent on the distance, and reactive, where the energy is stored but not radiated. When the tag antenna is located

in the far field of the reader antenna, the mutual effect of antennas is minimal and the antenna performance parameters (gain and impedance) can be specified independently from each other [3].

Factors affecting the performance of the BlueBean RFID Development Lab System will be considered. In this paper, the authors focus on three factors including the RF attenuation, the tagged material, and the tag orientations angle. The following study will be conducted: 1) the effect of RF attenuation on the response rate; 2) two main methods of measuring tag performance; 3) a non-parametric analysis based on the *U* test to study whether or not there is a significant difference between the two methods; 4) the effect of the tag orientations angle on the read range; and 5) a design of experiments (DOE) study to understand and quantify the effects of the three factors on the read range..

## 2. Related Works

Gain is one of the parameters that describe an antenna's radiating ability. Antenna gain is used to measure the ability of an antenna to converge radio waves in a certain direction. The absolute gain of an antenna (in a given direction) is defined as the ratio of the power density of an antenna radiated to a certain far field point to the power density at the same point which would be radiated by a lossless isotropic emitter [4,5]. An antenna's gain

combines its directivity and electrical efficiency and describes how well the antenna transforms input power into radio waves. Antenna efficiency is either expressed as the ratio between its radiation resistance and its total resistance or as the ratio between its input power and its radiated power [6]. The antenna size and gain are proportional. The higher the gain, the larger the antenna. The antenna gain and the beam width are mutually dependent; the higher the gain (the larger the size) the narrower the beams [7]. Higher gain antennas can work at a longer range than the lower gain counterparts. Therefore, omni-directional antennas have smaller gain and the ones that cover a narrower area will have a higher gain [5]. The antenna gain is not a constant. Rather, it is a function of the antenna's own orientation [8].

Polarization is another important consideration for RFID reader antennas. For maximizing tag range, antenna polarization of the tag must be matched to that of the reader antenna. Most RFID tags available on the market are linearly polarized. At the same time, many RFID reader systems use circular polarized antennas to ensure that tags can be read in any orientation [1]. Linear antennas operate best when the tag orientation is known and fixed. The tag antenna and the reader antenna have to be matched in polarization. Circular polarized antennas are used when the tag orientation is unknown [7]. Circular-polarized antennas are less sensitive to transmitter - receiver orientation and work better 'around corners'. However, the operating range of a linear-polarized antenna is more than that of a circular-polarized antenna. The operating range of an antenna also depends upon its gain which is its ability to focus radio waves [5]. Ultra-high-frequency (UHF) RFID systems usually adopt linearly polarized antennas as tag antennas because of their low cost and easy fabrication. However, many RFID systems are used to detect mobile items, for example, in the RFID application of supply chains, the cargo on which is mounted a tag will be transported along a supply chain. In these situations, RFID reader antennas often adopt circular polarization to ensure in most of the cases the system can perform correctly [4].

The important aspects of RFID tag antenna design include optimization of tag antenna gain, polarization, directionality, impedance matching, etc. Tag sensitivity, tag range, and tag differential radar cross section (RCS) are main tag performance characteristics. Tag sensitivity is the minimum signal strength (field or power) at the tag location needed to power up (read) the tag. It is a function of the chip threshold power sensitivity, tag antenna gain, and match between tag antenna and high (power collecting) impedance state of the chip. Tag range is typically defined as the maximum distance at which tag can be read. This characteristic depends not only on tag sensitivity but also on system parameters. It is a function of EIRP transmitted by the reader, propagation environment path loss, and tag sensitivity. Write range (maximum distance at which the tag can be written to) is usually lower than read range (typically, 70% of it). Differential RCS of an RFID tag depends only on tag itself and determines the power of the modulated signal backscattered to the reader. It is a function of the tag antenna gain and the matching between the tag antenna and the two modulating states (high and low) of the chip impedance [1].

### 3. Characteristics and Security Issues of RFID Systems

A critical factor in the adoption of radio frequency identification (RFID) technology is the level of read-accuracy that is achieved. With passive tags, the read-accuracy depends on the volume of the region that receives sufficient power from the reader. Most current research considers the powering region of a reader to be determined only by its read range (i.e., distance). However, read-accuracy also depends on the relative orientations of reader and tag antennas and their polarizations. In particular, when tag positions are not fixed, the locations of reader antennas relative to the tags can have a significant effect on the success of the interrogation processes. RFID tags usually cannot be read with 100% accuracy in the real world due to factors such as limitations in the read range, tag orientation or interference (from water, metal or other tags. Liquids absorb the RF signal; Metals reflect the signal. It is possible to either use multiple readers or multiple antennas for a single reader (or perhaps a combination of both) to improve read accuracy [8].

Since antenna characteristics change when the tag is placed on different materials or when objects are present in its vicinity, tag detuning, and gain penalty are two important factors, which degrade tag antenna performance, with direct impact on the read range. Tag detuning addresses the variation in operation frequency and, in consequence, impedance mismatching at the RFID band. Gain penalty addresses the variation in the antenna available gain [9].

Absorption, multipath fading polarization losses, and impedance mismatch can affect the RFID system performance as follows [10]:

1. Absorption: Any material between a tag and a reader will reduce the power available to the tag; the amount of degradation depends on the amount and nature of that material.

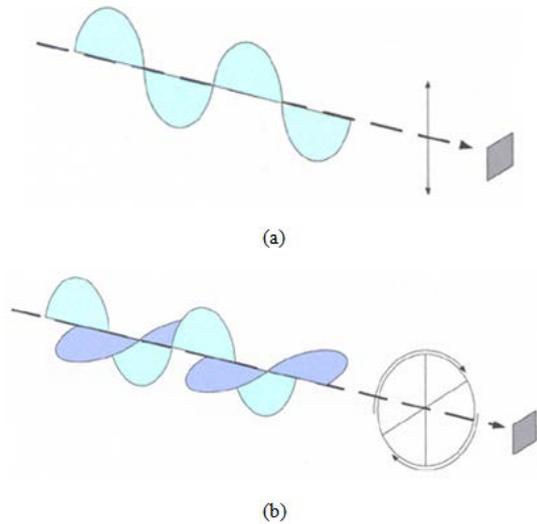
2. Multipath fading: Fading is caused by interference between two or more versions of the transmitted signal, which travel along multiple (different) paths and combine at the receiver to result in a signal with widely varying strength.

3. Polarization losses: The ability to power a tag is further significantly reduced by polarization losses, which occur when the RF energy from the reader is not polarized in the optimal orientation for the tag.

4. Impedance mismatch: Any impedance mismatch at the tag antenna will reduce the power available. Typically tags are designed to be impedance matched when operating in free space, and the proximity of the object to be tagged (no matter what it is made from) will have a detuning effect.

Figure 1 shows linear polarization and circular polarization. For linear polarization, the electromagnetic wave propagates entirely in one plane (Vertical or Horizontal) in the direction of the signal propagation. The RFID antenna and RFID tag should be matched in polarization to obtain the best read rates. For circular polarization, the electromagnetic wave propagates in two planes creating a circular effect making one complete revolution in a single wavelength timeframe. This is best

to use when tag orientation is unknown, but at least 3dB is lost when compared to a linear polarized antenna ([http://skyrfid.com/RFID\\_Antenna\\_Tutorial.php](http://skyrfid.com/RFID_Antenna_Tutorial.php)).



**Figure 1.** Classification of polarization: (a) linear polarization and (b) circular polarization

Security is an important issue in RFID systems [18]. There are the following security attacks [19] to RFID systems:

1. *Eavesdropping*: The adversary can monitor the wireless unsecured communication easily and collect the information transmitted by a tag.

2. *Spoofing*: An adversary may replace a valid item with a fake tag or replace the tag of an expensive item with that of a fake tag with data obtained from a cheaper item.

3. *Denial of Service*: An adversary may initiate a Denial of Service attack (DOS) to bypass or avoid Security systems. A DOS attack is easily carried out by placing a large number of fake tags for identification by a reader.

4. *Tampering*: Another avenue for attacking an RFID security mechanism might be a physical attack on an RFID tag or a reader to discover the information stored in tag.

5. *Man in the middle attack*: An adversary can modify the response of the tag to the reader.

6. *Replay Attack*: The attackers can eavesdrop the response message from the tag, and retransmit the message to the legitimate reader.

7. *Data loss*: The protocol can be damaged by power interruption, hijacking, and database desynchronization.

Security protocols for RFID systems were discussed on the basis of security, implementation cost, and practical implementation possibility. These security protocols include Kill Tag, Hash-Lock, Enhanced Hash Lock, Selective Blocker Tag, Tag Broker Model, and Molnar Wagner controlled delegation [19].

## 4. The RFID System and the Research Method

A BlueBean RFID Development Lab System (with an Alien RFID fixed reader ALR-9900) [13,14] was used in experiment in the Automated Identification Technology lab at Mississippi Valley State University, USA. It is

shown in Figure 2. The BlueBean RFID Development Lab System mainly includes a BlueBean RFID Development Lab Kit, the Alien RFID Gateway demonstration software [14], and a computer. The BlueBean RFID Development Lab Kit mainly includes a portal and an ALR-9900 RFID reader with a pair of antennae. Only one antenna was used in this research. The RFID portal is on wheels for easy transport. Several main parameters and features of the ALR-9900 RFID reader [13] are provided in Table 1. Before using the ALR-9900 RFID reader, open the ‘Alien RFID Gateway’ software from the shortcut on the desktop.

The width of the RFID portal center is 1890 mm. The distance between the reader antenna and the vertical pole of the RFID portal is 105 mm. The height of the reader antenna center was 920 mm; the height of the tag center was 965 mm during the experiment.

An RFID tag with a UPM Belt Antenna and an Impinj Monza 5 chip was used for the reading operation of the BlueBean RFID Development Lab System. The protocol support of the tag complies with EPC Class 1 Gen 2 and ISO 18000-6C. The maximum read range can be measured when the tag was moved slowly away from the fixed reader until the reader cannot read the tag.



**Figure 2.** The BlueBean RFID Development Lab System

**Table 1.** Several main parameters and features of the ALR-9900 RFID reader

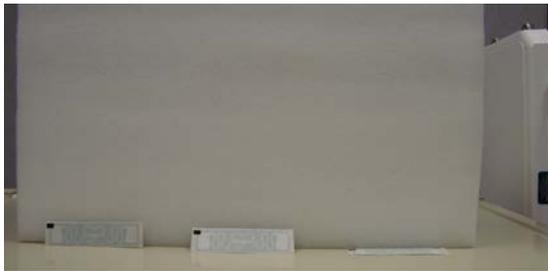
Item	ALR-9900 RFID reader
Architecture	Point-to-multipoint reader network, mono-
Supported RFID tag	EPC Gen 2; ISO 18000-6c
Antenna	4 ports, mono-static topology, circular
Frequency range	902.75 MHz – 927.25 MHz
RF power	Max 4 watts EIRP with Alien Antenna

There are two main methods of measuring tag performance. The first method uses variable power and fixed distance to the tag. The transmitted power is varied to find the minimum value at which the tag becomes detectable. The second method uses fixed transmitted power and variable distance to the tag. The reader transmits with constant power while the tag is being moved away until it cannot be read [1]. The *U*-test, a non-parametric analysis method, is used in this research to study the difference of the two methods.

The BlueBean RFID Development Lab System provides software-controlled digital attenuation (built into the Alien reader) that reduces the emitted power but not the return signal. Thus, the read range of the reader can be varied by varying the attenuation. The RF attenuation value ranges from 0 (no attenuation, maximum power) up to 150 (maximum attenuation, minimum power), in

increments of 10, each “decade” representing an additional 1 dB of RF attenuation [15]. The effect of RF attenuation on the response rate is studied in this research. The response rate is the ratio of number of successful reads to the number of read attempts [16].

Tag orientation can be changed through rotation. Figure 3 shows the tag orientations and angles for four cases. Only three angles are shown for the four cases; there can be more angles such as 135° and 180°. The read range at various angles (0°, 45°, 90°, 135° and 180°) were tested in this research.



(a)

Case I: Tag orientation angles are 0°, 45°, and 90°, respectively from left to right (for less height).



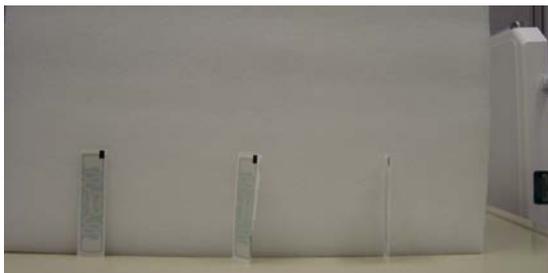
(b)

Case II: Tag orientation angles are 0°, 45°, and 90°, respectively from left to right (for larger height).



(c)

Case III: Tag orientation angles are 0°, 45°, and 90°, respectively from left to right (for less height).



(d)

Case IV: Tag orientation angles are 0°, 45°, and 90°, respectively from left to right (for larger height).

Figure 3. Tag orientations and angles

A design of experiments (DOE) method [11,12] was used to analyze how various factors impact the maximum read range of the BlueBean RFID Development Lab system. The DOE method helps eliminate unnecessary or undesirable experimentation and provide accurate information. Three independent factors and one dependent variable were used. The dependent variable is the maximum read range. The three independent factors include: the RF attenuation, the tagged material, and the tag orientations angle. The three factors are each tested at two different levels. The levels generally are the minimum and maximum (or lowest and highest) target values for a factor. The factors and the level description are listed below:

The RF attenuation: maximum value when the tag can be read (-1) and 0 value (without attenuation) (+1)

The tagged material: stapler with steel (-1) and book (paper) (+1)

The tag orientations angle: with the least read range (-1) and with the largest read range (+1)

## 5. Experimental Results and Analysis

### 5.1. The Effect of RF Attenuation on the Response Rate

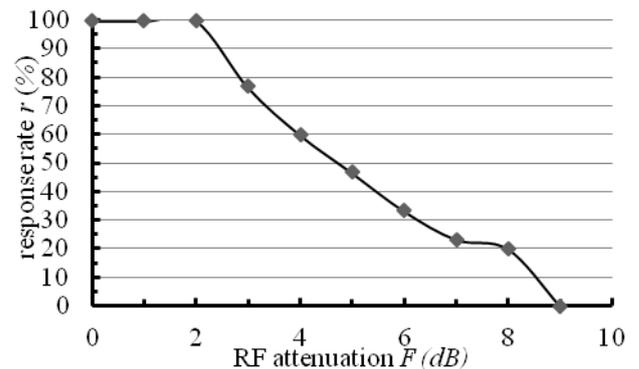


Figure 4. The response rate at various RF attenuation values (distance = 1200 mm)

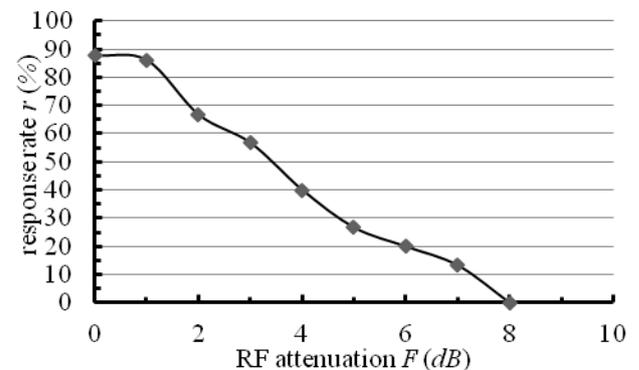


Figure 5. The response rate at various RF attenuation values (distance = 1260 mm)

The response rate is the ratio of number of successful reads to the number of read attempts. Figure 4 and Figure 5 show the response rate at various RF attenuation values for two distance data. The distance was measured between the reader antenna and the tag. The tag orientations angle is 0° in Case I. The results indicate that the RF attenuation

can decrease the response rate greatly. In Figure 3, the response rate  $r$  is 100% when the RF attenuation  $F$  is between 0 and 2 dB; then  $r$  decreases with the increase of  $F$ . When  $F = 9$  dB,  $r = 0$  (the tag cannot be read). Figure 4 shows the situation with the increased distance (1260 mm). The response rate  $r$  is not 100% in Figure 4;  $r$  decreases with the increase of  $F$ ; and  $r = 0$  when  $F$  gets to 8 dB. It means that the distance can cut the response rate  $r$  and the maximum RF attenuation  $F$  (the tag cannot be read at the maximum  $F$ ).

## 5.2. Two Methods of Measuring Tag Performance

The first method uses fixed distance to the tag and finds the minimum transmitted power (the maximum RF attenuation) at which the tag becomes detectable. The second method uses fixed transmitted power (fixed RF attenuation) while the tag is being moved away until it cannot be read. In the experiment, tag orientations angle is  $0^\circ$  in Case I. Figure 6 and Figure 7 show the results of the first method and the second method, respectively.

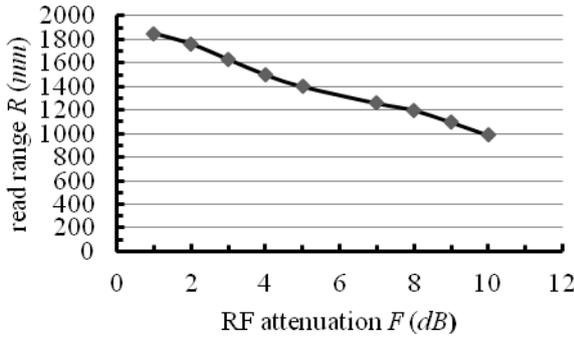


Figure 6. Obtained maximum RF attenuation  $F$  (given the read range  $R$ ) using the first method

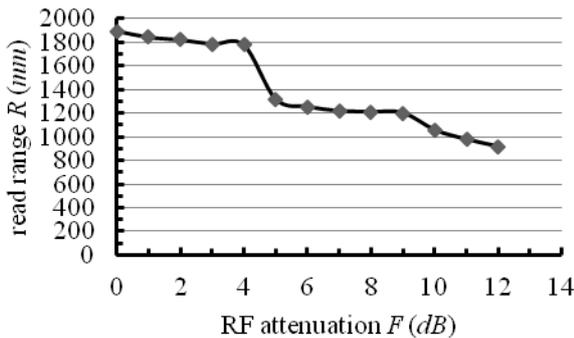


Figure 7. Obtained read range  $R$  (given the RF attenuation  $F$ ) using the second method

Figure 6 and Figure 7 indicate that there is difference between the two experimental methods. The authors conducted a comparative study. The read range  $R$  (the maximum transmission range) is given by the Friis free space equation [6]:

$$R = \frac{\beta}{4\pi} \sqrt{\frac{P_t G_t G_r \tau}{P_{th}}} \quad (1)$$

where  $\beta$  is the wave length;  $P_t$  is the transmitted power from the reader;  $G_t$  is the gain of transmitter antenna;  $G_r$  is the gain of the receiver tag;  $\tau$  is the power transmission

coefficient; and  $P_{th}$  is the minimum threshold power of the reader.  $P_t$  is equal to the maximum power of the reader at the antenna minus the RF attenuation value. Let

$$S = \frac{P_t}{R^2} \quad (2)$$

The parameter  $S$  is used to compare the two experimental methods.  $S$  values are calculated according to the data in Figure 6 and Figure 7. The authors used  $m$  as the unit of  $R$  and  $dB$  as the unit of  $P_t$  to simplify the calculation. The following null hypothesis is formulated:

There is no statistically significant difference in  $S$  between the two experimental methods.

The outcome is: the hypothesis is accepted or rejected at  $\alpha=0.05$ .  $\alpha$  is the level of significance.

The authors used a non-parametric method to test the hypothesis. It is called the  $U$  test, the Wilcoxon test, or the Mann-Whitney test, named after the statisticians who contributed to its development. The major advantage of non-parametric methods is that no specific assumptions (such as normal distribution) about the population or the sample are required. Therefore, non-parametric methods can be used under more general conditions [17]. The  $U$  test is illustrated as follows:

Suppose that  $W_1$  is the sum of the ranks of the values of the first method;  $W_2$  is the sum of the ranks of the values of the second method.  $n_1$  and  $n_2$  are the first sample size and the second sample size, respectively. The statistic  $U$  is decided based on the following  $U_1$  and  $U_2$  statistics:

$$U_1 = W_1 - \frac{n_1(n_1+1)}{2} \quad (3)$$

$$U_2 = W_2 - \frac{n_2(n_2+1)}{2} \quad (4)$$

Let  $U$  be the smaller of the values of  $U_1$  and  $U_2$ . The  $U$  test has the following criterion:

Reject the null hypothesis if  $U \leq U_\alpha$ , where  $U_\alpha$  is given in Table VII [17].  $U_\alpha = 28$  for  $n_1 = 9$ ,  $n_2 = 13$ , and  $\alpha=0.05$ . The  $U$  test results are shown in Table 2. Because 56 exceeds 28, the null hypothesis cannot be rejected. In other words, there is no significant difference between the two experimental methods.

Table 2. The  $U$  test for the between the first method and the second method

$U_1$	$U_2$	$U$	$U_\alpha$	Outcome: Significant difference?
61	56	56	28	No

## 5.3. The Effect of the Tag Orientations Angle on the Read Range

The read ranges at various tag orientation angles for Case I, Case II, Case III, and Case IV were tested. The testing results are shown in Tables 3-6.

Table 3. Read ranges at various tag orientation angles for Case I

Angles	$0^\circ$	$45^\circ$	$90^\circ$	$135^\circ$	$180^\circ$
Read ranges (mm)	1896	2828	1755	1832	1810

In Case I, the angle with least read range is  $90^\circ$ ; the angle with largest read range is  $45^\circ$

**Table 4. Read ranges at various tag orientation angles for Case II**

Angles	0°	45°	90°	135°	180°
Read ranges (mm)	3052	4826	2375	2575	3313

In Case II, the angle with least read range is 90°; the angle with largest read range is 45°.

**Table 5. Read ranges at various tag orientation angles for Case III**

Angles	0°	45°	90°	135°	180°
Read ranges (mm)	1896	2135	2060	2185	2130

In Case III, the angle with least read range is 0°; the angle with largest read range is 135°.

**Table 6. Read ranges at various tag orientation angles for Case IV**

Angles	0°	45°	90°	135°	180°
Read ranges (mm)	3052	3225	3215	4105	3175

In Case IV, the angle with least read range is 0°; the angle with largest read range is 135°.

### 5.4. DOE Analysis

A two-level factorial DOE methodology was used to study the effects of various factors on the maximum read range of the BlueBean RFID Development Lab System. The selected factors are: the RF attenuation, the tagged material, and the tag orientations angle. They are denoted by *F*, *M*, and *A*, respectively. The maximum read range is denoted by *R*. Each of the three factors has two levels. The DOE approach using a fractional factorial design based on the orthogonality principle requires  $2^3 = 8$  tests. Table 7 shows the three factors, the orthogonal table, and experiment arrangement for testing the maximum read range of the BlueBean reader ALR-9900 based on the orthogonality principle.  $R_1, R_2, \dots, R_8$  represent the maximum read ranges in eight tests, respectively.

**Table 7. Three factors, orthogonal table, and experiment arrangement**

RF attenuation: <i>F</i>	Tagged material: <i>M</i>	Orientation angle: <i>A</i>	RF attenuation: <i>F</i>	Tagged material: <i>M</i>	Orientation angle: <i>A</i>	Read range: <i>R</i> (mm)
-1	-1	-1	max	stapler (steel)	with the least <i>R</i>	$R_1$
1	-1	-1	min	stapler (steel)	with the least <i>R</i>	$R_2$
-1	1	-1	max	book	with the least <i>R</i>	$R_3$
1	1	-1	min	book	with the least <i>R</i>	$R_4$
-1	-1	1	max	stapler (steel)	with the largest <i>R</i>	$R_5$
1	-1	1	min	stapler (steel)	with the largest <i>R</i>	$R_6$
-1	1	1	max	book	with the largest <i>R</i>	$R_7$
1	1	1	min	book	with the largest <i>R</i>	$R_8$

The main effects [11,12] of the three factors (*F*, *M*, and *A*) on the maximum read range *R* can be calculated according to the formulas (5) - (7) [11].  $F_{eff}$ ,  $M_{eff}$ , and  $A_{eff}$  are main effects representing the effect of the RF attenuation, the tagged material, and the tag orientations angle on the read range, respectively.

$$F_{eff} = (-R_1 + R_2 - R_3 + R_4 - R_5 + R_6 - R_7 + R_8) / 4 \quad (5)$$

$$M_{eff} = (-R_1 - R_2 + R_3 + R_4 - R_5 - R_6 + R_7 + R_8) / 4 \quad (6)$$

$$A_{eff} = (-R_1 - R_2 - R_3 - R_4 + R_5 + R_6 + R_7 + R_8) / 4 \quad (7)$$

material is the second most important dominant factor; and the tag orientations angle has the least impact. In Table 13, The tagged material is the most influential factor on the read range while the RF attenuation is the second most important factor; and the tag orientations angle has the least influence. All these results based on main effect analysis indicate that the RF attenuation is the most powerful factor on the read range and that the tag orientations angle has the least influence for Case I, Case II, and Case IV. The tagged material is the most influential factor on the read range and the tag orientations angle has the least influence for Case III.

**Table 8. Three factors, orthogonal table, and experiment results for Case I**

F	M	A	F (dB)	M	A	R (mm)
-1	-1	-1	10	stapler	90°	425
1	-1	-1	0	stapler	90°	900
-1	1	-1	10	book	90°	745
1	1	-1	0	book	90°	1840
-1	-1	1	10	stapler	45°	440
1	-1	1	0	stapler	45°	775
-1	1	1	10	book	45°	705
1	1	1	0	book	45°	2828

Table 8- Table 15 shows read ranges at various parameters; main effects and normalized main effects of the RF attenuation, the tagged material, and the tag orientations angle on the read range for Case I, Case II, Case III, and Case IV. Table 8, Table 10, Table 12, and Table 14 are the tables (including the three factors, orthogonal table, and measured read range values) for Case I, Case II, Case III, and Case IV, respectively. In Table 9, Table 11, and Table 15, the RF attenuation is the most influential factor on the read range while the tagged

**Table 9. Main effects and normalized main effects for Case I**

Rank	Effect	Value of effect	Normalized effect
1	F	1007.0	1.000
2	M	894.5	0.888
3	A	209.5	0.208

**Table 10. Three factors, orthogonal table, and experiment results for Case II**

F	M	A	F (dB)	M	A	R (mm)
-1	-1	-1	10	stapler	90°	495
1	-1	-1	0	stapler	90°	1090
-1	1	-1	10	book	90°	1015
1	1	-1	0	book	90°	2105
-1	-1	1	10	stapler	45°	770
1	-1	1	0	stapler	45°	1945
-1	1	1	10	book	45°	995
1	1	1	0	book	45°	4826

**Table 11. Main effects and normalized main effects for Case II**

Rank	Effect	Value of effect	Normalized effect
1	F	1672.8	1.000
2	M	1160.3	0.694
3	A	957.8	0.573

**Table 12. Three factors, orthogonal table, and experiment results for Case III**

F	M	A	F (dB)	M	A	R (mm)
-1	-1	-1	10	stapler	0°	156
1	-1	-1	0	stapler	0°	212
-1	1	-1	10	book	0°	720
1	1	-1	0	book	0°	1896
-1	-1	1	10	stapler	135°	162
1	-1	1	0	stapler	135°	978
-1	1	1	10	book	135°	955
1	1	1	0	book	135°	2185

**Table 13. Main effects and normalized main effects for Case III**

Rank	Effect	Value of effect	Normalized effect
1	M	1062.0	1.000
2	F	819.5	0.772
3	A	324.0	0.305

**Table 14. Three factors, orthogonal table, and experiment results for Case IV**

F	M	A	F (dB)	M	A	R (mm)
-1	-1	-1	10	stapler	0°	562
1	-1	-1	0	stapler	0°	945
-1	1	-1	10	book	0°	954
1	1	-1	0	book	0°	3052
-1	-1	1	10	stapler	135°	866
1	-1	1	0	stapler	135°	1140
-1	1	1	10	book	135°	1015
1	1	1	0	book	135°	4105

**Table 15. Main effects and normalized main effects for Case IV**

Rank	Effect	Value of effect	Normalized effect
1	F	1461.3	1.000
2	M	1403.3	0.960
3	A	403.3	0.276

## 6. Conclusions

The BlueBean RFID Development Lab System with the reader ALR-9900 can be used to test the RFID system performance (such as the read range and the response rate) at various parameters through changing the RF attenuation, the tagged material, and the tag orientations angle. According to the results authors found that the RF attenuation greatly decreases the read ranges of the BlueBean RFID system. The read range is affected with the change of the tag orientations angle. The DOE study of the main effects of three factors (the RF attenuation, the tagged material, and the tag orientations angle) revealed that the tag orientations angle has the least influence on the read range. The RF attenuation is the most influential factor on the read range in most situations; however, the tagged material is the most influential factor while the tag is in some orientations. The testing results using two main methods of measuring tag performance shows there is difference in experimental data between the two methods; however, the results obtained from the non-parametric method based on the  $U$  test indicate that there is no significant difference between the two methods if the level of significance  $\alpha$  is 0.05.

Although this paper focused on the study of the BlueBean RFID Development Lab System, and testing two tagged materials (paper and steel), the methodology of DOE also can be used to study other RFID systems and determine the relative importance for other factors or parameters as well as other materials.

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