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EXPERIMENTAL INVESTIGATION OF READING PASSIVE UHF TAGS IN A MULTI-TAG ENVIRONMENT

Yi Zhou
University of Kentucky, unlockmyeye@gmail.com
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Yi Zhou, Student

Dr. Johné Parker, Major Professor

Dr. Haluk Karaca, Director of Graduate Studies

EXPERIMENTAL INVESTIGATION OF READING PASSIVE UHF TAGS IN A MULTI-TAG ENVIRONMENT

THESIS

A thesis submitted in partial
fulfillment of the requirements for
the degree of Master of Science in
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By
Yi Zhou
Lexington, Kentucky

Director: Dr.Johné Parker, Professor of Mechanical Engineering
Lexington, Kentucky 2017

ABSTRACT OF THESIS

EXPERIMENTAL INVESTIGATION OF READING PASSIVE UHF TAGS IN A MULTI-TAG ENVIRONMENT

Recently, the Internet of things (IoT) has emerged as a promising solution for several industrial applications. One of the key components in IoT is passive radio frequency identification (RFID) tags which do not require a power source for operations. Specifically, ultra-high frequency (UHF) tags are studied in this paper. However, due to factors such as tag-to-tag interference and inaccurate localization, RFID tags that are closely spaced together are difficult to detect and program accurately with unique identifiers. This thesis investigates several factors that affect the ability to encode a specific tag with unique information in the presence of other tags, such as reader power level, tag-to-antenna distance, tag-to-tag distance and tag orientation. ANOVA results report reader power level and tag spacing, along with effect interactions power level*tag spacing and tag spacing*tag orientation to be significant at the levels investigated. Results further suggest a preliminary minimum tag-to-tag spacing which enables the maximum number of tags to be uniquely encoded without interference. This finding can significantly speed up the process of field programming in item-level tagging.

KEYWORDS: Iot, solution, RFID, unique identifier, tag-to-tag interference, ANOVA

Author's signature: Yi Zhou

Date: April 25, 2017

EXPERIMENTAL INVESTIGATION OF READING PASSIVE UHF TAGS IN A MULTI-TAG ENVIRONMENT

By
Yi Zhou

Director of Thesis: Dr.Johné Parker

Director of Graduate Studies: Dr.Haluk Karaca

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Chapter 1 Introduction

Radio Frequency identification (RFID) systems provide automatic data collection without a direct line of sight through the radio communication between a reader (interrogator) and a tag (transponder) in which information is stored [1]. There are two different types of RFID systems, active and passive, that vary in their mode of operation and operating performance. In active RFID systems, an active tag possesses its own power source, an internal battery that enables the tag to broadcast its information to a reader and supplies the power to an auxiliary electronic circuit. For passive RFID systems, there are two major different types of passive tags; passive and semi-passive. Passive tags have no internal power source to turn themselves on, but it uses the electromagnetic(EM) field created by a reader to power their internal circuit (IC) and transmit the stored information from these tags back to the reader. Semi-passive tags contain a battery to supply power only to auxiliary components like sensors, user interface etc.

UHF (Ultra High Frequency) passive tag applications are the fastest growing segment of the RFID market today, ranging from inventory management, pharmaceutical, counterfeiting to wireless device configuration [2]. Passive tags are cheaper to manufacture and able to provide automatic identification without a power source [3]. Compared to LF and HF RFID tags, they also have faster data transfer rates [4]. Due to its advantages over a conventional tracking method (like printed ID), more industries are seeking and adopting the RFID option in order to save operational cost and enable multitasking of applications [5]. There was a huge rise in global sale of UHF Gen 2 chips by more than 200 percent in 2010 compared to the prior year [6].

1.1 What is RFID?

A basic RFID (Radio Frequency Identification) system is composed of mainly two components, as shown in Figure 1.1, a receiver and transmitter. They are most commonly referred to as tag and reader, respectively. A reader emits a radio wave at a certain frequency that is received by the tag. The tag is designed to respond with data that is then read by the reader. The distance between the tag and reader can vary from a few centimeters to several meters. Such systems enable us to simultaneously read/write multiple tags and activate remote sensing devices based on their unique identifiers.

Over the last decade, a massive drop in the cost of RFID tags, particularly passive tags, enables a huge market expansion in adoption of RFID. The relatively low cost of tags and small size in form make it suitable in a variety of applications such as access management, inventory tracking, toll collection, etc. This emerging data collection technology has replaced some of traditional data collection technologies such as bar codes and smart cards in many applications [7]. In 2004, Walmart started to deploy

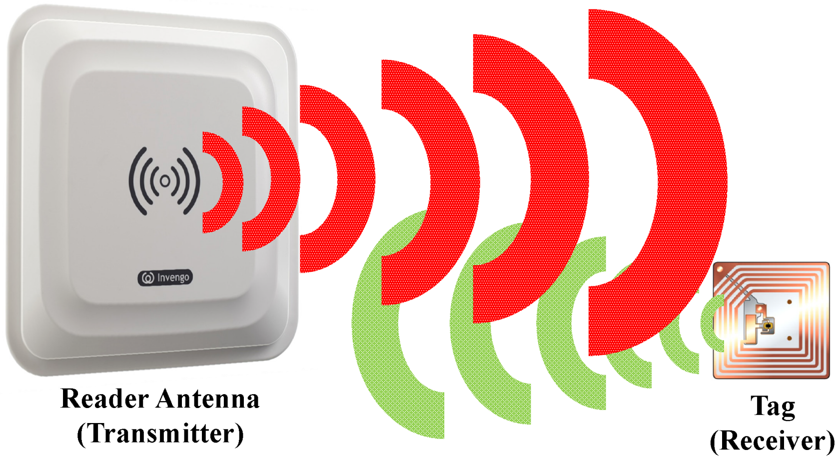

Figure 1.1: BASIC RFID SYSTEM COMPONENTS

RFID to replace barcode for its inventory tracking [8].

Compared to many traditional data collection technologies, some of the typical advantages of RFID are [9]:

- No need for tags to be positioned in a line of sight with a scanner
- RFID tags possess high levels of security with different encrypted information
- Unlike Barcode, RFID tags can be reprogrammed
- Tags have a long read range and are capable of containing large amount of data
- RFID tags have a faster read rate than Barcode; multiple tags can be read at the same time

1.2 Motivation and Problem Description

Passive RFID has been used for decades, but recent developments in the scale and cost of passive UHF RFID tags, with their widespread adoption within the supply chain, have caused explosive growth in its application. Companies such as Lexmark, Zebra Technologies, Honeywell, etc., which have been engaged in marking, tracking and computer technologies, have spent millions of dollars in maintaining and developing of passive RFID solutions over the last few years. Gradually, RFID printers will take over traditional bar code printers in the future market [10].

This research is inspired by Lexmark T654dn RFID laser printer. Like many RFID printers, the Lexmark T654 is able to program a passive RFID tag attached on a single media with unique information, and then print related human readable information on the media. Compared to the other RFID printers, the flexibility in selection of media sizes, ranging in from 5" x 7" inches up to 8.5" x 14" inches (legal-size), makes it stand out. A large media size enables users to attach multiple passive RFID tags on a single media and these passive tags can be programmed all with unique information in one simple process. However, there exists some challenges during the encoding of passive RFID tags. Factors such as tag-to-tag interference and inaccurate localization can significantly affect the reading and tracking of multiple tags. Some environmental factors like certain metals and water also cause attenuation to the RF signal [11, 12]. RFID tags that are closely spaced together are difficult to detect and program accurately with unique identifiers. Thus, schemes to program a specific RFID tag in the presence of other tags can be unreliable. In this scenario, an ideal programming environment would require no detection of non-targeted tags while maintaining a good readability of the target tag. This thesis investigates the optimum formation of multiple tags on a media in order to maintain a high throughput rate of uniquely encoded tags. The result in this work provides a foundation for an optimum tags placement strategy based on several selected near-field RFID tags.

1.3 Thesis Organization

The reminder of this thesis is organized as follows:

Chapter 2: Overview of RFID Technology: Chapter 2 provides the basic concept of RFID and gives a comparison in advantages and disadvantages between two state of the art data collection technologies, RFID and Barcodes.

Chapter 3: RFID System Infrastructure: Chapter 3 introduces basic components in RFID systems, majorly comprised with tags, reader, antenna and middleware.

Chapter 4: RFID System Properties: Chapter 4 introduces the basic RFID coupling mechanism.

Chapter 5: Test Fixture and Key Design Factors: Chapter 5 introduces our experimental test fixture (lexslide) and defines all key design factors in our test set up.

Chapter 6-10: Case studies: Chapters 6 to 10 describes the entire experimental process, from a basic test setup to data collection, from results/discussion to final conclusions.

Chapter 11 : Conclusion and Contribution: Chapter 11 concludes our research work. It highlights research contributions and provides recommendations for future related research work.

Chapter 2 Overview of RFID Technology

2.1 Basics of RFID Technology

Radio frequency identification (RFID) is a subset of a group of technologies also known as automatic identification (or auto-ID), which is a technology used to help machines identify physical objects (for example: items passing through the various stages of an extended supply chain) and provide information about them through automatic data capture [13]. This data must be converted into digital form to be used by computer systems. The aim of most Auto-ID systems is to increase efficiency, reduce data entry errors, and free up staff to perform more value-added functions. There are a host of technologies that fall under the Auto-ID umbrella, as shown in Figure 2.1. These include bar codes, smart cards, voice recognition, some bio-metric technologies (retinal scans, for instance), optical character recognition, and radio frequency identification (RFID).

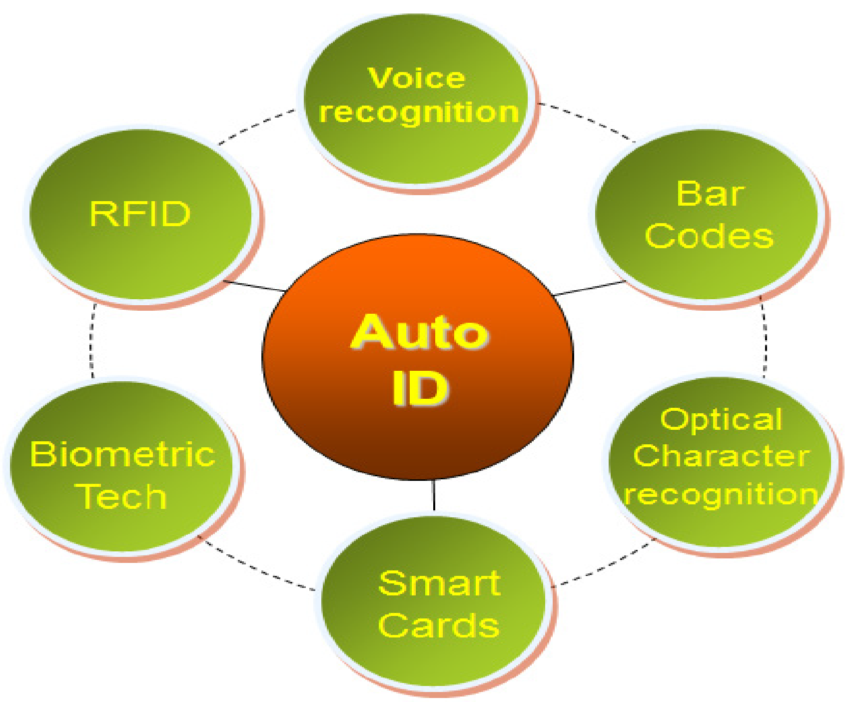

Figure 2.1: BASIC AUTO-ID TECHNOLOGIES

RFID is a generic term for technologies that use radio waves to automatically identify individual items. There are several methods of identifying objects using RFID, but the most common is to store a serial number that identifies a product and perhaps other information, on a microchip that is attached to an antenna (the chip and the antenna together are called an RFID transponder or an RFID tag). The antenna enables the chip to transmit the identification information to a reader. The reader converts the radio waves returned from the RFID tag into a form that can then be passed on to computers [14].

2.2 RFID vs. Barcodes

RFID and barcodes are similar that they are both data collection technologies. In the field of supply chain, the traditional method of tracking and management of products is done through barcodes, which requires line of sight while scanned. RFID that is seen to be an alternative to the barcodes, has more flexibility to track and identify products. RFID tags can be embedded inside the box with insignificant impact on its readability, which increases the security of the tag itself. The automatic reading system can reduce the work and time of scanning process compared to the barcodes [15].

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Figure 2.2: Barcodes

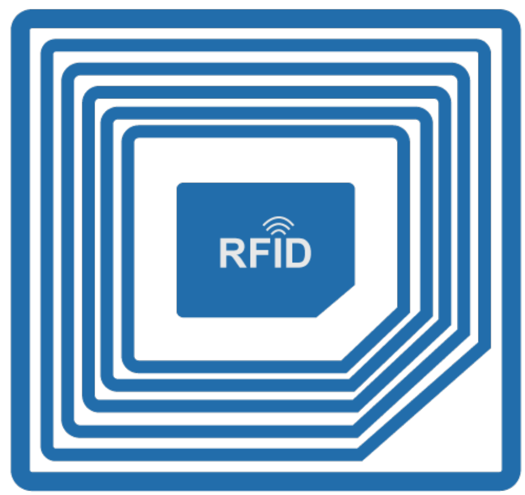


Figure 2.3: RFID

Barcodes: It is comprised of a series of parallel black bars representing identification information, as shown in Figure 2.2. A barcode is read by an optical device such as a scanner. Information in barcode is encoded by varying the widths of the bars and the distances of the spaces between each bar. Recent iterations on the barcode have used different shapes other than the traditional bars and are capable of being read by a greater range of devices [16].

RFID: It is implemented using radio waves to communicate information between a unique item and a system. Rather than using parallel black bars to represent identification information, RFID tags store products/items information with a digital memory bank, as shown in Figure 2.3. A typical RFID system consists of an RFID reader, tags (chips), and at least one antenna. RFID systems can be either active or passive. Active RFID tags contain a battery and periodically transmit information with much greater range than passive tags.

The major differences between two auto data collection technologies are summarized in the Table 2.1 below:

Table 2.1: Comparison of Bar Codes and RFID Tags

	Barcodes	RFID
Readable through objects	No, must be line of sight	Yes
Data capacity	<20 characters with linear	100s-1000s of characters
Update	No	Yes
Reliability	Wrinkled or smeared labels will not be read	Nearly flawless read rate
Orientation dependence	Yes	No
Read speed	Slow	Very fast (ms)
Marginal Cost	$0.01 per label	$0.05-$1.00 per tag
Simultaneous scanning of multiple tags	No	Yes (10-1000 tags per second)
Passive (automated) data collection	No	Yes (via portals and smart shelves)
Ruggedness	No	Yes

2.3 UHF RFID Protocols and Standards

To provide universal specifications for RFID systems, there are two major organizations, ISO and EPCglobal that work together to approve protocols and standards. These standards and protocols make it possible to adopt UHF RFID systems worldwide. Although these two organizations provide the main RFID standards organizations, there is also a plethora of other standards that apply to niche areas of RFID.

The ISO RFID standards fall into a number of categories according to the aspect of RFID that they are addressing [17]. These include: air interface and associated protocols; data content and the formatting; conformance testing; applications; and various other smaller areas. In addition to the ISO RFID standards, there are also the standards from EPC Global. In 1999, a number of industrial companies with MIT set a consortium known as the Auto-ID Consortium with the aim of researching and standardizing RFID technology. In 2003 this organization was split with the majority of the standardization activities coming under a new entity called EPCglobal. The Auto-ID Center retained its activities associated with the research into RFID technologies.

To standardize the RFID tags [18], the Auto-ID Center has classified the RFID tags, as shown in Table 2.2 below:

Table 2.2: EPCglobal Tag Classes

Class 0	Basic read-only passive tag using backscatter where the tag was programmed at the time the tag chip was made.
Class 1	Basic read-only passive tag using backscatter with one-time non-volatile programmed capability.
Class 2	Passive backscatter tag with up to 65k of read-write memory.
Class 3	Semi-passive tag with up to 65 k read-write memory and a battery incorporated to provide increased range.
Class 4	Active tag embedded with a battery to enable extra functionality within the tag and also to provide power for the transmitter.
Class 5	An active tag that provides additional circuitry to communicate with other class 5 tags.

2.4 Passive vs Active RFID Comparison

The primary difference between passive and active RFID tags is that passive tags have no battery and require an external source to power signal transmission, and active tags contain a battery and can transmit signals autonomously. In a passive RFID system, a reader provides power for a tag and creates interrogation signals. It transmits a continuous sine wave and receives backscattered data from the tag at the same frequency at the same time. For an active RFID system, the working distance can be much longer (up to a few hundred meters). Active tags possessed with their own power sources, can use higher transmit power and make use of receivers with higher sensitivity due to active amplification.

The major differences between passive and active systems [18] are described in Table 2.3 below:

Table 2.3: Comparison of Passive and Active RFID

	Passive	Active
Read Range	Up to 40 feet (fixed readers) Up to 20 feet (handheld readers)	Up to 300 feet or more
Power	No power source	Battery powered
Tag Life	Up to 10 years depending upon the environment the tag is in	3-8 years depending upon the tag broadcast rate
Tag Size	Sticker to credit card size	Varies depending on application
Industries/Applications	For inventorying assets using handheld RFID readers (daily, weekly, monthly quarterly, annually). Can also be used with fixed RFID readers to track the movement of assets as long as security is not a requirement.	For use with fixed RFID readers to perform real-time asset monitoring at choke-points or within zones. Can provide a better layer of security than passive RFID.
Readers	lower cost	higher cost
Required Signal Strength	High	Low
Range Data Storage	Small read/write data (128b)	Large read/write data (128kb)

Chapter 3 RFID System infrastructure

Basic components of RFID system are, as shown in Figure 3.1

- Tag (Transponder)
- Reader (Interrogator)
- Antenna
- Middleware (Computer)

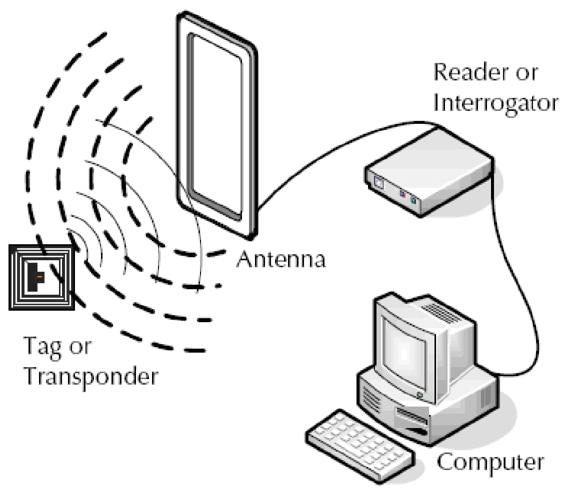


Figure 3.1: Basic RFID system components

3.1 Tags

In general, there are three types of RFID tags, as shown in Figure (3.2) (3.3) (3.4) ***active, passive, semi-passive***.

Figure 3.2: Active tag

Figure 3.3: Passive tag

Figure 3.4: Semi-passive tag

Active tag: It contains a battery and does not depend on the reader signal to generate a response. As a result, the active tag can be read at much greater distances, with read distances up to 100 yards [19]. Active tags may be either read-only or read/write, thus allowing data modification by the reader. Data storage on active tags may range up to 8K bytes. Data rates are also faster in the active tag, thus making electronic toll collection and weigh station bypass highly successful applications of RFID. There are also active tags that provide off-tag communication via RS232/RS485 protocols, or JBUS to provide such information as fuel levels and odometer readings for transportation gate control applications. As one might suspect, the active tag is more expensive, with prices ranging from $20 to over $100 per tag. The variety of tags is almost endless. In any given application, the designer must decide the application requirements and then look at the offerings. The choice may be driven by performance, cost, both, or even something else, as there are many choices driving the final solution.

Passive tag: Passive tag is the most prominent type in use within RFID today. In general, they are the most simple. The tag does not contain a battery and depends on the strength of the reader RF signal to cause the tag to generate a response. In general, the passive tag contains a serial number, typically 96 to 128 bits in length. The serial number will most often be just a serial number with no connection to a particular product or application. The serial number can be read and then used to establish a relationship to a product within an application database [20]. Since the passive tag does not contain a battery and depends on the reader signal to generate a response, the read range is typically short, ranging from a few inches to no more than 10 feet. The read speed is slow, with reads taking 25 to 50 milliseconds to complete. From these two parameters, applications that come to mind are personnel access, parking lot access, and similar uses. In each application the tag moves at a relatively slow speed, allowing time to read the tag information and make the correlation to information within the database. The tag may take many forms, from identification badges to license plate encapsulated tags to flexible tags for attaching to curved surfaces. Tag prices range from a few pennies to $10.

Semi-passive tag: Semi-passive tag operates similarly to the passive tag, using the reader signal to cause a response from the tag [20]. The primary difference is that the semi-passive tag does have a battery, not for generating a response, but to power electronics that are used in conjunction with off-board sensors such as a thermal sensor. The sensor reading is incorporated into the tag return signal along with the tag serial number. Unsurprisingly, the semi-passive tag has most of the limitations noted for the passive tag in terms of slow read speeds and short read distances. The price point for semi-passive tags is higher than that for the passive tag, with prices ranging from $10 to $50.

3.2 Reader/Interrogator

An RFID reader, also known as an interrogator, is a device that provides the connection between the tag data and the enterprise system software that needs the information. The reader communicates with tags that are within its field of operation, performing any number of tasks including simple continuous inventorying, filtering (searching for tags that meet certain criteria), writing to selected tags, etc. The reader uses an attached antenna to capture data from tags. It then passes the data to a computer for processing. Just like RFID tags, there are many different sizes and types of RFID readers. The reader used in this paper is shown in Figure 3.5. Readers can be affixed in a stationary position in a store or factory, or integrated into a mobile device such as a portable, handheld scanner. Readers can also be embedded in electronic equipment or devices, and in vehicles [21].

Figure 3.5: Skyetek m9 Reader

3.3 Antenna

An antenna is a device used to transform an RF signal, traveling on a conductor, into an electromagnetic wave in free space. Antennas demonstrate a property known as reciprocity, which means that an antenna will maintain the same characteristics regardless if it is transmitting or receiving. Most antennas are resonant devices, which operate efficiently over a relatively narrow frequency band. An antenna must be tuned to the same frequency band of the radio system to which it is connected; otherwise the reception and the transmission will be impaired. When a signal is fed into an antenna, the antenna will emit radiation distributed in space in a certain way. A graphical representation of the relative distribution of the radiated power in space is called a radiation pattern [22].

RFID antennas can be categorized in two classes: reader antenna and tag antenna.

Reader antenna: RFID readers and reader antennas work together to read tags. Reader antennas convert electrical current into electromagnetic waves that are then radiated into space where they can be received by a tag antenna and converted back to electrical current. Just like tag antennas, there is a large variety of reader antennas and optimal antenna selection varies according to the solution's specific application and environment. The two most common antenna types are linear and circular polarized antennas. Antennas that radiate linear electric fields have long ranges, and high levels of power that enables their signals to penetrate through different materials to read tags. Linear antennas are sensitive to tag orientation; depending on the tag angle or placement, linear antennas can have a difficult time reading tags. Conversely, antennas that radiate circular fields are less sensitive to orientation, but are not able to deliver as much power as linear antennas [23]. Choice of antenna is also determined by the distance between the RFID reader and the tags that it needs to read. This distance is called read range. Reader antennas operate in either a "near-field" (short range) or "far-field" (long range). In near-field applications, the antenna uses magnetic coupling so the reader and tag can transfer power. In near-field systems, the readability of the tags is not affected by the presence of dielectrics such as water and metal in the field. In far-field applications, the range between the tag and reader can be up to tens of meters. Far-field antennas utilize electromagnetic coupling and dielectrics can weaken communication between the reader and tags.

Tag antenna: Tag antennas collect energy and channel it to the chip to turn it on. Generally, the larger the tag antenna's area, the more energy it will be able to collect and channel toward the tag chip, and the further read range the tag will have. There is no perfect antenna for all applications. It is the application that defines the antenna specifications. Some tags might be optimized for a particular frequency band, while others might be tuned for good performance when attached to materials that may not normally work well for wireless communication (certain liquids and metals, for example). Antennas can be made from a variety of materials; they can be printed, etched, or stamped with conductive ink, or even vapor deposited onto labels. Tags that have only a single antenna are not as reliable as tags with multiple antennas. With a single antenna, a tag's orientation can result in dead zones, or areas on the tag where incoming signals cannot be easily harvested to provide sufficient energy to power on the chip and communicate with the reader [18]. A tag with dual antennas is able to eliminate these dead zones and increase its readability.

Chapter 4 RFID System Properties

4.1 Frequency

Frequency is a key factor of RFID operation system, which refers to the size of the radio waves used to communicate between RFID components [24]. RFID systems throughout the world operate in low frequency (LF), high frequency (HF) and ultra-high frequency (UHF) bands. Radio waves behave differently at each of these frequencies with advantages and disadvantages associated with using each frequency band. If an RFID system operates at a lower frequency, it has a shorter read range and slower data read rate, but increased capabilities for reading near or on metal or liquid surfaces. If a system operates at a higher frequency, it generally has faster data transfer rates and longer read ranges than lower frequency systems, but more sensitivity to radio wave interference caused by liquids and metals in the environment. Basically, the frequency bands, as shown in Figure 4.2, could be classified as following:

- Low frequency (LF)
- High frequency (HF)
- Ultra-high frequency (UHF)

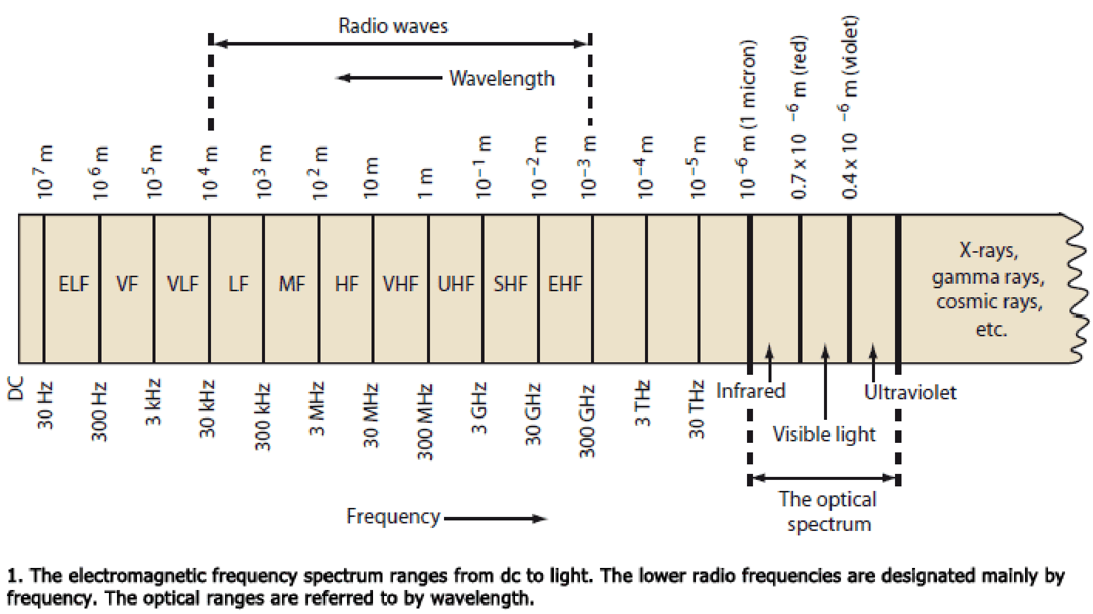


Figure 4.1: Electromagnetic Frequency Spectrum

The LF band: it covers frequencies from 30 KHz to 300 KHz. Typically LF RFID systems operate at 125 KHz, although there are some that operate at 134 KHz. This

frequency band has slower read speed than the higher frequencies, but is not very sensitive to radio wave interference.
The HF band: it ranges from 3 to 30 MHz. Most HF RFID systems operate at 13.56 MHz with read ranges between 10 cm and 1 m. HF systems experience moderate sensitivity to interference. HF RFID is commonly used for ticketing, payment, and data transfer applications.
The UHF band: it covers the range from 300 MHz to 3 GHz. Systems complying with the UHF Gen2 standard for RFID use the 860 to 960 MHz band. While there is some variance in frequency from region to region, UHF Gen2 RFID systems in the U.S. operate between 900 MHz and 915 MHz. The read range of passive UHF systems can be as long as 12 m, and UHF RFID has a faster data transfer rate than LF or HF. UHF RFID is the most sensitive to interference, but many UHF product manufacturers have found ways of designing tags, antennas, and readers to keep performance high even in difficult environments. Passive UHF tags are easier and cheaper to manufacture than LF and HF tags. UHF RFID is used in a wide variety of applications, ranging from retail inventory management, to pharmaceutical anti-counterfeiting, to wireless device configuration. The bulk of new RFID projects are using UHF opposed to LF or HF, making UHF the fastest growing segment of the RFID market.

4.2 RFID Coupling Mechanism

The means by which the RFID tag and reader communicate is known as the RFID coupling mechanism. There are several ways in which the RFID reader can communicate with the RFID tag. The main RFID coupling techniques that are involved are:

- RFID capacitive coupling
- RFID inductive coupling
- RFID backscatter coupling

RFID capacitive coupling: it is used for short ranges where a form of RFID close coupling is needed. Basically, the system uses capacitive effects to provide the coupling between the tag and the reader. RFID capacitive coupling operates best when items like smart cards are inserted into a reader [25]. In this way, the card is in very close proximity to the reader rather than having coils or antennas. Capacitive coupling uses electrodes where the plates of the capacitor provide the required coupling. For short ranges where a form of RFID close coupling is needed. As the name implies, the system uses capacitive effects to provide the coupling between the tag and the reader. Although an plane ground return is required, the capacitance between the reader and card tag provide a capacitor through which a signal can be transmitted. By modulating the load, the data is returned to the RFID reader.

RFID inductive coupling: it is for slightly longer ranges, however, still is a near field effect, where the distance between the coils must be kept within the range of the effect that normally is taken to be about 0.15 wavelength of the frequency in use. Functionally, inductive coupling is the transfer of energy from one circuit to another via the mutual inductance between the two circuits. Like other RFID systems, both the tag and the reader will have induction or “antenna” coils. When the tag is placed close enough to the reader the field from the reader coil will couple to the coil from the tag. A voltage will be induced in the tag that will be rectified and used to power the tag circuitry. To enable data to be passed from the tag to the reader, the tag circuitry changes the load on its coil and this can be detected by the reader as a result of the mutual coupling [25].

RFID backscatter coupling: it uses the RF power from the antenna reader to energize the tag. Basically it reflects back some of the power given by the reader, but the properties of RF signal has been changed to adapt the requirements. Unlike capacitive coupling and inductive coupling, backscatter coupling operates outside the near field region [26]. A reader antenna emits electromagnetic energy (radio waves). No electromagnetic field is formed. Instead, the tag gathers energy from the reader antenna, and the microchip uses the energy to change the load on the antenna and reflect back an altered signal. Notice that several factors such as cross sectional area, and the antenna properties within the tag would significantly affect the way that the signal is reflected back to the antenna reader. In particular the antenna will pick up and re-radiate energy, and the way this energy is re-radiated is dependent upon the antenna properties and distance. The re-radiated signal properties can be changed by changing factors such as adding or subtracting a load resistor that crosses the antenna.

4.3 Field Regions

When a high frequency current flows in an antenna, it generates a high frequency electromagnetic field in the surrounding space. The detailed structure of this field is usually quite complex and strongly depends on the antenna shape. Close to the antenna, except in some simple academic cases, there is very little we can say about the electric and magnetic fields without involving complex numerical calculations. But as we move away from the antenna, the field tends to look like spherical waves. The greater the distance is, the better the resemblance to spherical waves. Spherical waves are convenient because many calculations can be performed with simple equations. Basically, the field could be separated into three different regions, as shown in Figure 4.2, each having a character:

- reactive near-field region
- radiating near-field (Fresnell)
- far-field region (Fraunhofer)

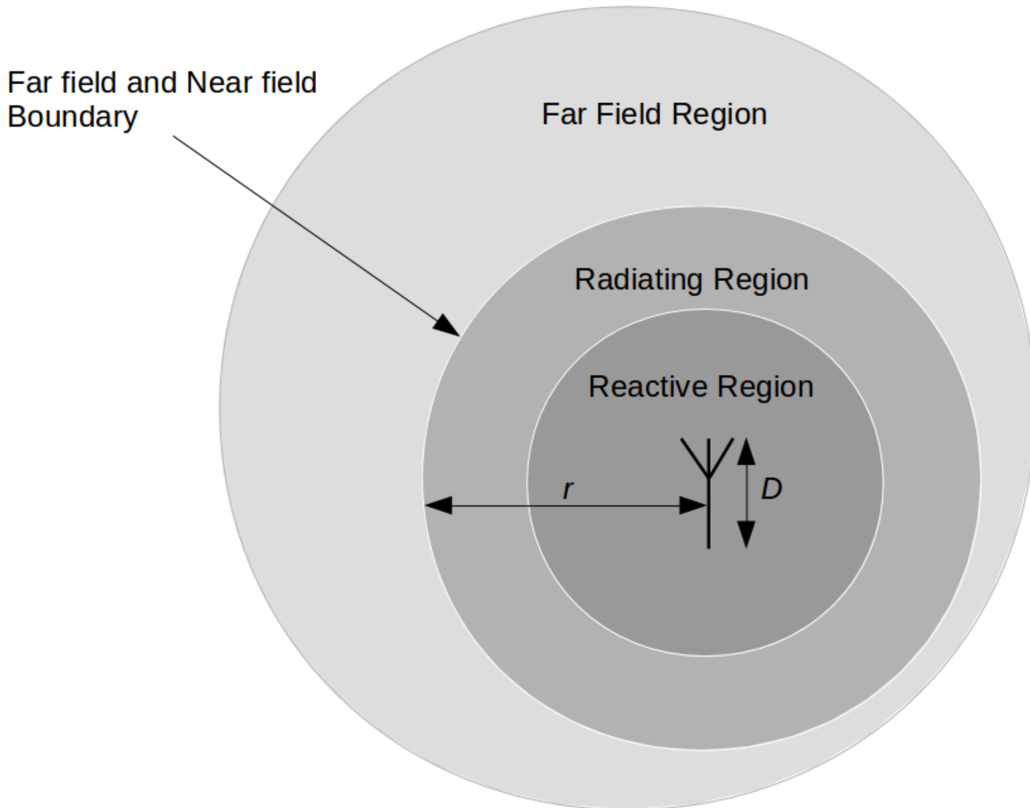


Figure 4.2: Electromagnetic Frequency Spectrum

Wave propagation function is given by: $f = \frac{C_0}{\lambda}$ (C_0: Speed of light)

Reactive near-field region: It is a region immediately surrounding the antenna where the reactive field predominates. The electric and magnetic fields are not necessarily in phase with each other and the angular field distribution is highly dependent upon the distance and direction from the antenna [27].

The boundary of this region is commonly given as: $R < 0.62\sqrt{\frac{D^3}{\lambda}}$

near-field region (Fresnel): It is a region surrounding the reactive near-field region described above. Here, the radiation field predominates, the electric and magnetic fields are in phase, but the angular field distribution is still dependent upon the distance from the antenna. This means that almost all the field in this region radiates. However, unlike the Far Field region, the shape of the radiation pattern may vary appreciably with distance [27].

The region is commonly given by: $0.62\sqrt{\frac{D^3}{\lambda}} < R < \frac{2D^2}{\lambda}$

Far-field region (Fraunhofer): It's a region surrounding the reactive and radiating near-field regions described above. It extends to infinity and represents the vast majority of the space the wave usually travels. Here, the entire field radiates, the angular field distribution is essentially independent of the distance from the antenna and can be approximated with spherical wave-fronts. Since we are very far from the antenna, its size and shape are not important anymore and we can approximate it as a point source. The electric and magnetic fields are in phase, perpendicular to each other and perpendicular also to the direction of propagation.

Chapter 5 Test Fixture and Key Design Factors

5.1 Fixture Design

To conduct our multi-tag experimental tests, a few modifications have been made from the previous test fixture on the single tag study by Proffitt and Lum [28–30]. The new Lexslide fixture has five main components, as shown in Figure 5.1, described as follows:

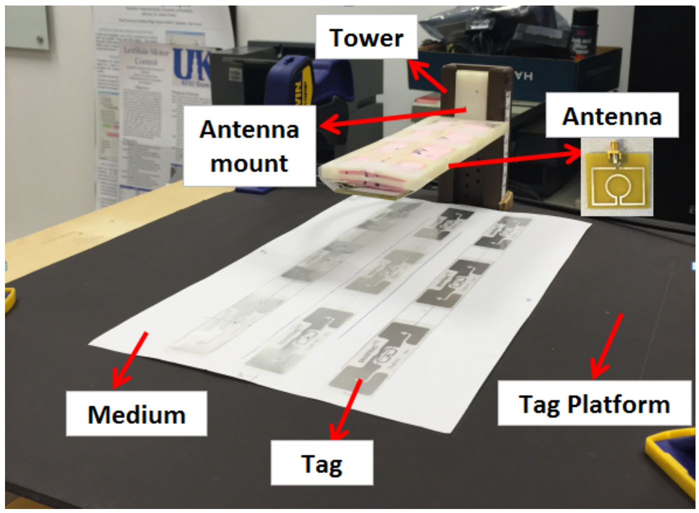


Figure 5.1: Test Fixture

- *Tag Platform:* The tag platform has significantly changed compared with the previous testing structure. Some registration lines are printed on the tag platform to locate the tags' media.
- *Tower:* The tower holds the antenna mount and allows the air gap to be adjusted vertically. This flexibility to adjust the distance between antenna and tags lets experimenters study RFID system performance in both the near field and far field regions.
- *Antenna Mount:* The mount can translate vertically to allow the air gap to be adjusted, also it is attached to the tower and cantilevers over the tag platform.
- *Reader antenna :* The antenna is an interchangeable component, which can be switched to different antennas to meet testing requirements.
- *RFID media:* The media is an interchangeable component, which can be replaced with other types and sizes.
- *Tag:* Tags are used as an interchangeable component.

5.2 Design Components

The primary components of this fixture include:

Interchangeable hardware components

- Reader
- Multiplexer
- Cables
- Antenna
- Tags
- Media holder Materials

Adjustable programming variables

- Air gap
- Power levels
- Frequency
- Orientation
- Tag spacing
- Tag number

5.3 Key Design Factors

Air gap: It is defined as the unobstructed distance between target tag center and reader antenna center. In this hardware design, the largest air gap is 100mm and smallest air gap is 0mm, as shown in Figures (5.2) (5.3).

Reader power levels: A Skyetek m9 is the reader selected in this paper; the highest power applied is 27dbm and the lowest power applied is 10dbm. Also power level is adjustable in steps of 0.1dbm. Power levels in the research were divided into 5 settings: 10 dBm, 14.2 dBm, 18.5 dBm, 22.8 dBm, 27 dBm. Table 5.1 shows the relationship between W and mW.

Tag number: The tag number is defined as how many tags are attached to the media and ready to be programmed, as shown in Figures (5.4) (5.5) (5.6). In this investigation, tag number could significantly affect testing results such as readability and cross-programming.

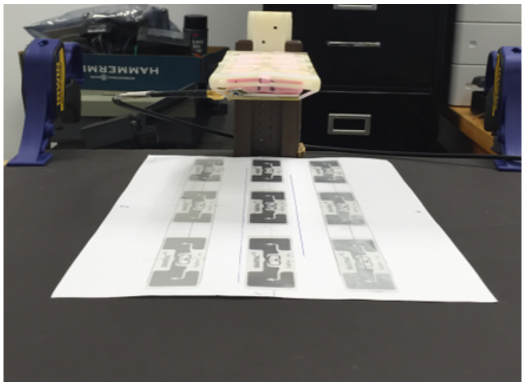


Figure 5.2: Largest Air Gap 100mm

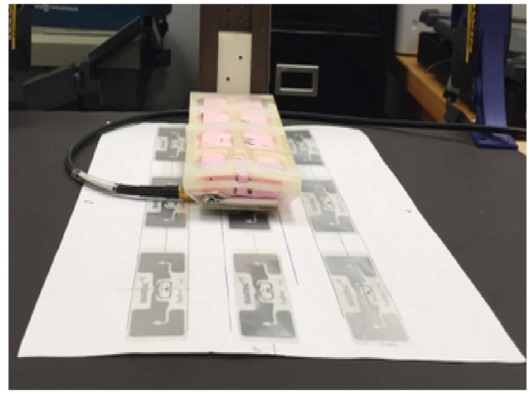


Figure 5.3: Smallest Air Gap 0mm

Table 5.1: Power Unit Conversion

Decibel milliwatts (dBm)	Watts (W)
10	0.01
14.2	0.026
18.5	0.07
22.8	0.191
27	0.501

Figure 5.4: 3 Tags

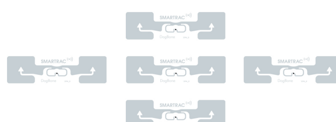


Figure 5.5: 5 Tags

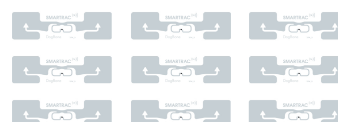


Figure 5.6: 9 Tags

Tag spacing: The tag spacing is defined as a distance from center to center of two adjacent UHF passive tags. Increasing or decreasing the tag spacing at certain conditions significantly impacts the total tag read rate.

Tag orientation: The tag orientation is defined as the in-plane angle between the tag and reader antenna axes; in this thesis, four different tag angles with 0°, 90°, 180°, and 270°are selected, as shown in Figures (5.7) (5.8) (5.9) and (5.10).

5.4 Basic Hardware Components

Experimental Reader: The reader (SkyeModule M9) as shown in Figure 3.5, has been selected, because it is a small multi-protocol ETSI 302 208 compliant UHF (862 - 955 MHz) RFID reader platform that supports a wide variety of UHF RFID tags. The SkyeModule M9 can read and write to transponders based on the EPC

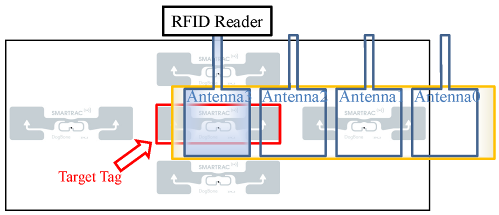


Figure 5.7: SMARTRAC “Dogbone” ORIENTATED AT 0°

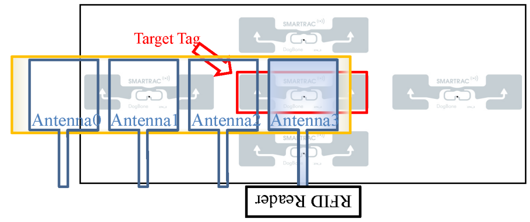


Figure 5.8: SMARTRAC “Dogbone” ORIENTATED AT 180°

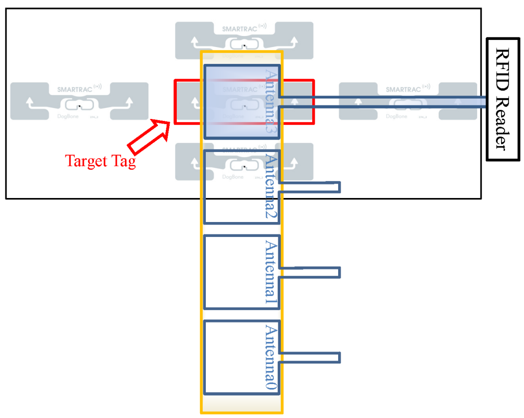


Figure 5.9: SMARTRAC “Dogbone” ORIENTATED AT 90°

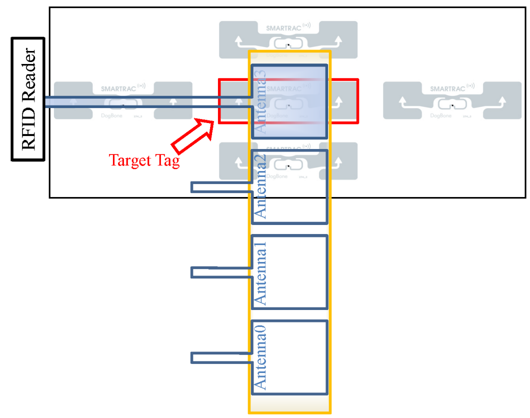


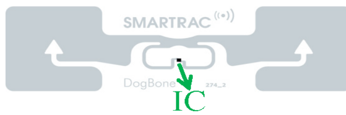
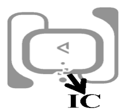
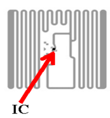
Figure 5.10: SMARTRAC “Dogbone” ORIENTATED AT 270°

Class1 Gen1, ISO 18000-6B and ISO 18000-6C (EPC C1G2/Gen2) air interface and communications standards. The RF output power of the M9 is software-adjustable from 10-500 mW. The M9 has been tested for regulatory compliance for the world’s major markets including North America, Europe (ETSI 302 208) and Korea. The fundamental properties of the M9 include:

- Common communications protocol: All SkyeTek readers use the SkyeTek Protocol v3 (STPv3) to drive low level communications. The SkyeTek APIs built on top of STPv3 to facilitate reading tags.
- Multiple communications interfaces: TTL Serial, SPI, I 2C, and native USB allows to connect to a host PC with or without a serial port. These options are software-selectable to support both loosely and tightly coupled integration. The SkyeModule M9 also has seven programmable GPIO pins for I/O connections to peripherals.
- The SkyeModule M9 is optimized to support a communication rate of 40/80 kbps.
- Serial data rates are adjustable from 9.6 to 115.2 kbps. Field-upgradable firmware provides forward compatibility for adding future tag protocols, security features, and customized enhancements.

Experimental Tags: Three types of tags, as shown in Table 5.2, were selected for this study: *dogbone, alien bio and alien square.*

Table 5.2: Experimental Tag Specifications

Tag Pictures	Tag Name	EPC Memory	Integrated Circuit (IC)
	DOGBONE	96 bits	Impinj Monza-3
	ALEIN BIO	128 bits	Alien Higgs-3
	ALIEN SQUARE	96-480 bits	Alien Higgs-3

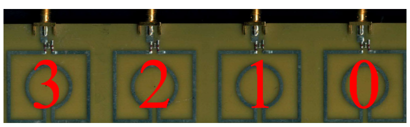
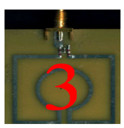
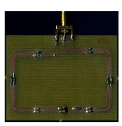
- The dogbone is a passive far-field/near-field tag which can be programmed in both near field and far field regions. Because of its unique shape, there is a small loop in the middle, providing near field functionality and a relatively large antenna surrounding the inner loop providing far-field functionality. Also, the dogbone is one of the most popular tags across a wide cross-section of industries. It has a reputation of being an extremely reliable and versatile RFID tag, which has led to its broad adoption across many applications.

- Alien Bio is a near field passive tag. In terms of its rapid programming of serialized tags and excellent read/write performance, it widely has been applied in pharmaceutical production facilities and handheld reader usage for logistics and supply chain.

- Alien Square is a small form-factor, general-purpose RFID inlay, well-suited for item level tagging of apparel, pharmaceuticals, or high value consumables where geometries are constrained. In light of the small square form factor, it has been chosen in this research investigation.

Experimental Antennas: Three antennas designed for near field applications are selected and shown in table 5.3.

Table 5.3: Experimental Antenna Specifications

Antenna Pictures	Antenna Name	Dimension	Vendor
	Skyetek Loop	Length 191mm Width 31mm	Skyetek
	Single Skyetek Loop	Length 41mm Width 31mm	Skyetek
	Lexmark Loop	Length 55 mm Width 31mm	Lexmark

Chapter 6 Case 1: Skyetek Loop Array with Dogbone Tag

6.1 Test Setup

To effectively investigate RFID system performance within the near-field region, the fixture illustrated in Figure (6.1) was designed to efficiently and accurately adjust the design factors investigated in this study. Thus, the fixture can modify factors such as the air gap (vertical distance between a target tag and a reader antenna), tag placement (in-plane offset horizontal and vertical distances of the tag center with respect to the antenna center), tag orientation (in-plane rotation of the tag axis with respect to the reader antenna), and tag speed (with respect to a fixed antenna array). This fixture allows the system performance with respect to each individual factor and factor interactions to be better characterized and understood.

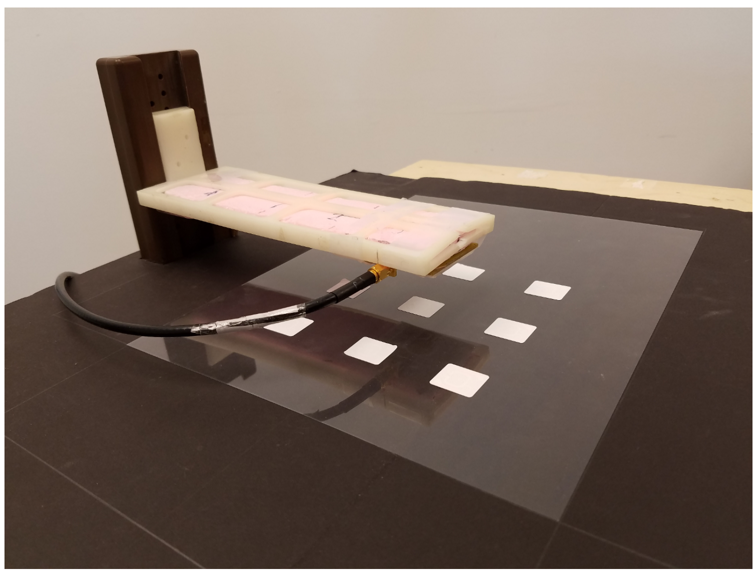


Figure 6.1: TEST FIXTURE SETUP

To provide a baseline study of the effect of the chosen design factors in a multi-tag environment, near-field tags and antennas were selected. The selected antenna "Skyetek Loop" is a near-field microstrip loop array antenna (Figure 6.3). It has four individual loop antennas with the same shape and size. For testing purposes, antenna number 3 is selected here. For this design, the generated magnetic field is reasonably confined in the near-field region.

The smartrac "Dogbone" tag (illustrated in Figure 6.2) is selected for inital tests, since it has been used as the benchmark tag for the single tag performance from previous research [28–30]. "Dogbone" tags and inlays are designed for global supply chain, industrial and RTI (real time information) applications offering excellent performance in demanding logistical and industrial applications. The Dogbone IC (integrated circuit) or tag chip is shown in (Figure 6.2). It contains memory which stores the product's electronic product code (EPC) and other variable information so that it can be read and tracked by RFID readers. An embedded commercial UHF RFID reader, the SkyeModule M9, was used in all experimental tests.

Figure 6.2: SMARTRAC "Dogbone" RFID TAG

The factorial experimental design was conducted according to FCC regulations [10], with a pseudo-random hop between US UHF frequencies (902 to 928MHz), during all read attempts.

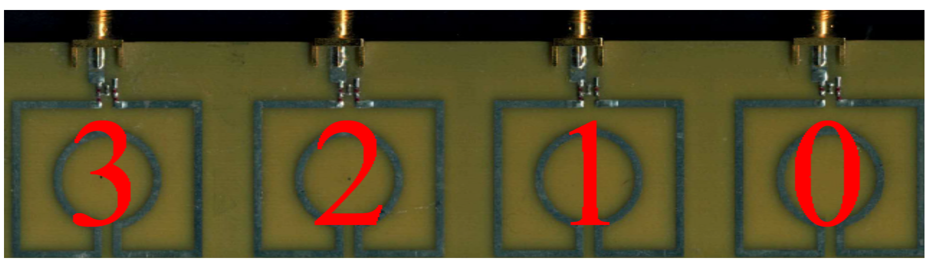


Figure 6.3: SKYETEK "Loop Array" ANTENNA

6.2 Experimental Factors

In a successful multi-tag programming application, every individual tag should be successfully read and programmed with a unique identifier by the end of the process. For this initial base-line design, one tag "the center tag" will be selected as the target. As shown in Figures (6.4) (6.5) (6.6) and (6.7), the center tag has the most near neighbors in the multiple tag design. It will be the most difficult tag for the reader antenna to successfully detect and encode in comparison to the other tags in the design. Thus, if we can fully understand the performance of the center tag as the target tag and optimize its solution, this solution can ultimately be generalized for the other tags in the design. Hence, the center tag is selected as the target-tag and the surrounding tags will be deemed as non-targeted tags in the rest of the work.

Three different tag read rates are tracked in this investigation and defined as follows:

- Total tag read rate is defined as a ratio of successful reads of both target tag and non-target in total read attempts.

- Target tag read rate is defined as a ratio of the successful reads of the target-tag in total read attempts.
- Non-target tag read rate is defined as a ratio of the successful reads of non-target tags in total read attempts.

It is desired that the non-target tag read rate be zero, even if the target read rate is lower to achieve a zero non-target read rate; however, a sufficient target read rate is necessary for effective tag programming.

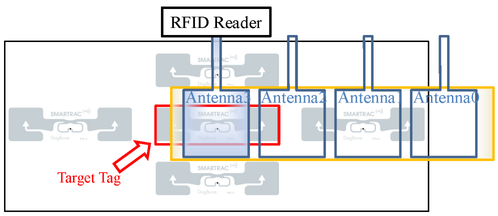


Figure 6.4: SMARTRAC "Dogbone" ORIENTATED AT 0°

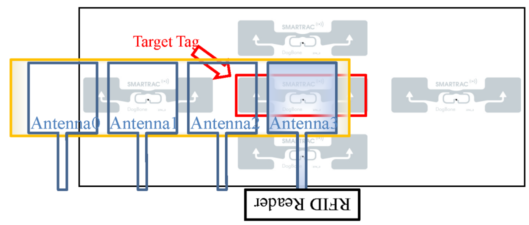


Figure 6.5: SMARTRAC "Dogbone" ORIENTATED AT 180°

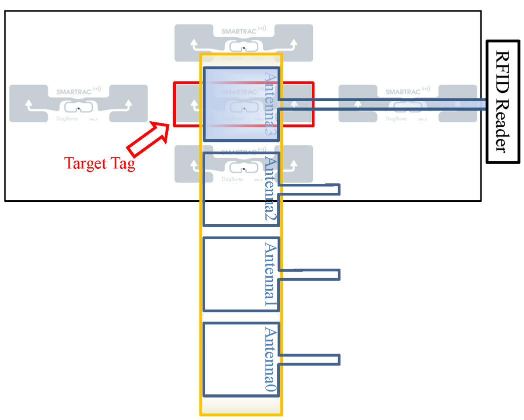


Figure 6.6: SMARTRAC "Dogbone" ORIENTATED AT 90°

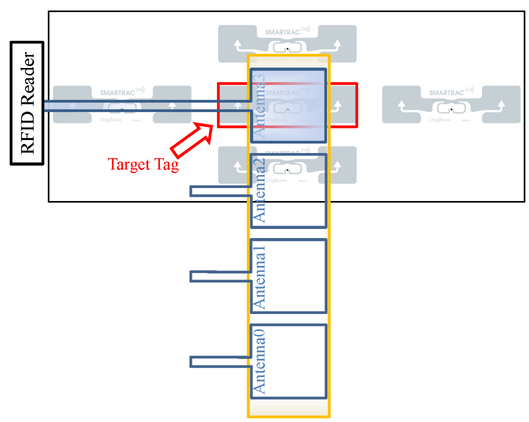


Figure 6.7: SMARTRAC "Dogbone" ORIENTATED AT 270°

Based on the previous single tag studies [28–30], air gap, tag orientation and power level were found to be the most significant factors to the tag read rate, so they are selected in this case study. Tag number and tag spacing are also selected, because they are unique factors in the multi-tag enviroment, and are expected to affect our system performance. According to [31–33], the near-field region is considered to be significantly less than the wavelength λ. Thus, five air gaps are selected inside the near-field region by $5mm, 10mm, 15mm, 20mm$ and $25mm$. Tag orientation was found to be another important design factor in single tag experimental tests. The tag orientation is defined as the in-plane angle between the tag and reader antenna axes, as shown in Figures (6.4) (6.5) (6.6) and (6.7). While single tag readability can also vary significantly with tag angle, in a multi-tag environment, interference from non-targeted tags can also be affected by tag orientation.

Figure 6.8: 3 Tags

Figure 6.9: 5 Tags

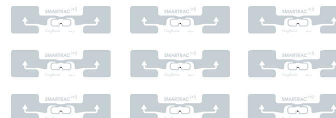


Figure 6.10: 9 Tags

Power level is another significant design factor in single tag experimental tests and will also be investigated in multi-tag experimental tests. Test levels used in this study were $10dbm$, $14.2dbm$, $18.5dbm$, $22.8dbm$, and $27dBm$ ($10mW$, $26mW$, $71mW$, $190mW$ and $500mW$, respectively), as presented in Table 6.1. Tag number and tag spacing are unique design factors in the multi-tag investigation. The number of tags was held at 3, 5 and 9, as shown in Figures (6.8) (6.9) (6.10). The tag spacing is defined as the distance from the IC center of a target tag to the IC center of an adjacent tag along one axis. Because of the form factor of "Dogbone" tag, note that the non-target tags in vertical and horizontal direction are arranged with a different tag spacing of the target tag center along the x and y axes, as shown in Figures (6.11) (6.12) (6.13) (6.14) and (6.15).

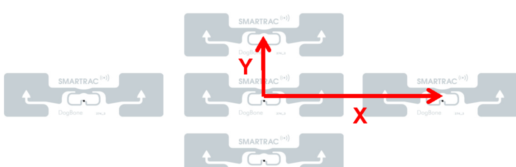


Figure 6.11: SMARTRAC "Dogbone" $30mm$

Figure 6.12: SMARTRAC "Dogbone" $35mm$

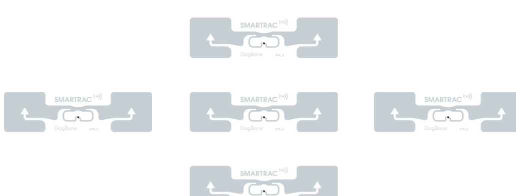


Figure 6.13: SMARTRAC "Dogbone" $40mm$

Figure 6.14: SMARTRAC "Dogbone" $45mm$

Figure 6.15: SMARTRAC “Dogbone” 50mm

Table 6.1: FACTORS AND LEVELS

Tag Type	Air Gap(mm)	Tag Space(mm)	Power Level(dbm)	Tag Orientation	Tag Number
Dogbone	5	30	10	0°	3
	10	35	14.2	90°	6
	15	40	18.5	180°	9
	20	45	22.8	270°	
	25	50	27		

6.3 Data Collection

Testing was conducted in an RF friendly enviroment, which experienced minimal interference from extraneous factors such as metal objects, the presence of water and other competing frequencies from testing environment. All observation tags were pre-programmed with unique information for all experimental setups; therefore experimenters are capable of identifying the exact detected tag in all tests. One hundred repeated measures were customized for an individual run where the reader attempts one hundred successive times to read tags. Replicates are multiple experimental runs with the same factor settings (levels). They are subject to the same sources of variability, independently of each other [34]. Three replicates or experimental runs were conducted for all tests. Data analysis and summary table of multi-tag experimental tests at 5mm air gap, tag spacing at 50mm with 3 tags at 27dbm power level with four different tag orientations, is presented in Table 6.2, from collected raw data. Again, each run has a hundred repeated measures and 3 replicates applied for all tests; thus the RF system will make in total 300 attempts (100 $\times$ 3) with respect to each tag power level to identify “Dogbone” tags. A corresponding “Dogbone” pattern chart of the above example is illustrated in Figure (6.16). Notice that identified “target tags” is presented with a green color; identified “non-targeted tags” is marked with a red color; nothing identified is shown with a blue color. See Appendix A for the complete pattern charts with all factors and their levels listed in Table 6.1.

Table 6.2: “Dogbone” DATA SUMMARY

Power Level	27dbm			
Tag Orientation	0°	90°	180°	270°
Target Tag	14	15	8	0
Non-Targeted Tag	8	23	0	24
No	278	262	292	276

@*Air gap: 5mm; **Tag Number: 3; ***Tag space: 50mm

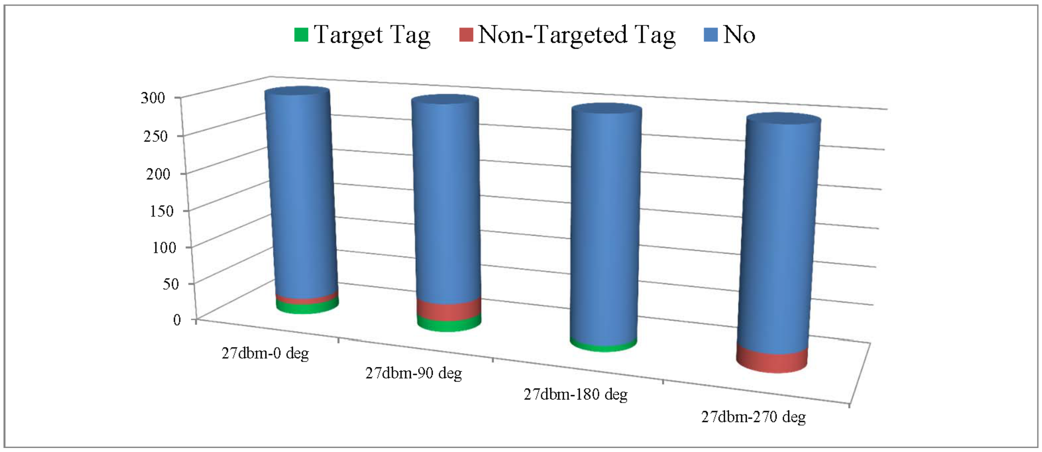


Figure 6.16: “Dogbone” DATA PATTERN CHART

6.4 Data Analysis

The 2^k factorial design as one of the most important screening designs, was applied to explore the design factors that have the most significant effects on the system response. The 2^k refers to designs with k factors where each factor has just two levels, low (-) and high(+). In our case, the k factors are the air gap, tag spacing, power level, tag orientation and tag number. According to the “Dogbone” pattern charts in Appendix A, the level of the high and low of each factor was chosen by the experimenter and is shown in Table 6.3. With three replicates applied for each test, a total number of 2^5 x 3 (96) runs was performed by the end of the process. The effect of factors and their interaction from ANOVA are shown in Table 6.4.

6.5 Results and Discussion

Our objective of applying the 2^k factorial design method is to identify those factors that have significant effects on the system performance with respect to the overall read rate (where the total read success rate is the number of positive reads in 100 successive attempts to read tag data). Thus, we removed all the higher order interactions (interactions between three or more factors) from our data analysis in Table 6.4, since they are negligible in the case design. The level of significance in this analysis is

Table 6.3: 2^k FACTORS AND LEVELS

Factors	Level(ft) Low (-)	High (+)
Air Gap(mm)	5	25
Tag Space (mm)	30	50
Power Level (dbm)	10	27
Tag Orientation	0	90
Tag Number	3	9

Table 6.4: TABLE OF ANOVA FOR “Dogbone”

Source	F-critical	F-Value
Air Gap	2.37	15.98
Tag Space	2.37	1.52
Power Level	2.37	32.9
Tag Orientation	2.61	123.36
Tag Number	3.01	9.66
2-Way Interactions		
Air Gap*Tag Space	1.65	0.88
Air Gap*Power Level	1.65	15.32
Air Gap*Tag Orientation	1.75	8.35
Air Gap*Tag Number	1.94	5.45
Tag Space*Power Level	1.65	5.28
Tag Space*Tag Orientaion	1.65	12.57
Tag Space*Tag Number	1.65	0.51
Power Level*Tag Orientaion	1.75	34.85
Power Level*Tag Number	1.94	6.16
Tag Orientation*Tag Number	2.12	5.12

Note: All F-crit=3.9412; α=0.05 (95% confidence interval)

determined at a=0.05. Results showed that the tag orientation and power level were both found to be significant at the levels investigated. Illustrated in Figure 6.17, the overall tag read rate decreased as the tag orientation switched from 0° to 90°. The tag spacing, one of the unique design factors in the multi-tag investigation, was found to be significant, as were many the effect interactions such as the tag spacing*power level and tag spacing*air gap. Moreover, the total tag read rate increased as the tag spacing increased from 30mm to 50mm, as illustrated in both Figure 6.17 and Appendix A. It can be implied that the signal interference from the non-targeted tags to the radio decreased as the tag spacing increased.

Tag number, another unique factor in the multi-tag investigation, was found not to be significant, as were all effect interactions with this factor, including the air gap*tag number, tag spacing*tag number, power level*tag number and tag orientation*tag number. Hence, the tag number will be screened out and not considered as a key factor in future experimental designs. Instead of 3 tags and 9 tags, a number of 5 tags will be selected for all future experimental designs, since it can provide us the best experimental tag layout where it is symmetric of the non-targeted tags to the target tag in both the vertical and horizontal directions. Shown in Figure (6.11), geometrically the symmetric setup gives the non-targeted tags an equal opportunity to be identified by our radio. Air gap was not found to be significant from the main effect result in the Anova Table 6.4. However the majority of interaction effects such as the air gap*power level, air gap*tag orientation and air gap*tag orientation were found to be significant. Plus, the air gap was the most significant factor in the single tag experimental investigation [28–30]. Thus, we decided to keep the air gap as a key design factor for the next experimental design.

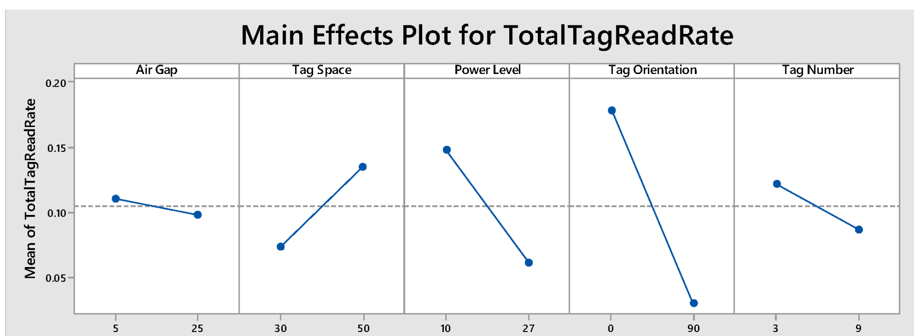


Figure 6.17: "Dogbone" MAIN EFFECT PLOTS

As expected, a few non-targeted tags, marked with a red color from both the example in Figure (6.16) and full "Dogbone" pattern charts in Appendix A, were identified by the radio from different positions on the media. In our case design, the detection of any non-targeted tags is considered as a failure. Again, every individual tag should be successfully read and programmed with an unique identifier by the end of the process. If any non-targeted tags are identified instead of the target tag, it will be programmed with the target tag information. According to Figure (6.18), all identified non-targeted tags are located either underneath the antenna array or at the bottom of the media. Presumably, the failure prompted in those positions can be caused by signal deflections from the unused antennas numbered 0, 1 and 2 (Figure 6.3), where the identified non-targeted tags was positioned right underneath. Another assumption of the detection of the non-targeted tags is that the radio antenna is aligned with the target tag IC center but not the tag center, physically/geometrically where the radio antenna is closer to the non-targeted tag at the very bottom of the media. Those two assumptions will be further investigated in the following experimental designs until we can find a solution where no non-targeted tags are identified by the radio.

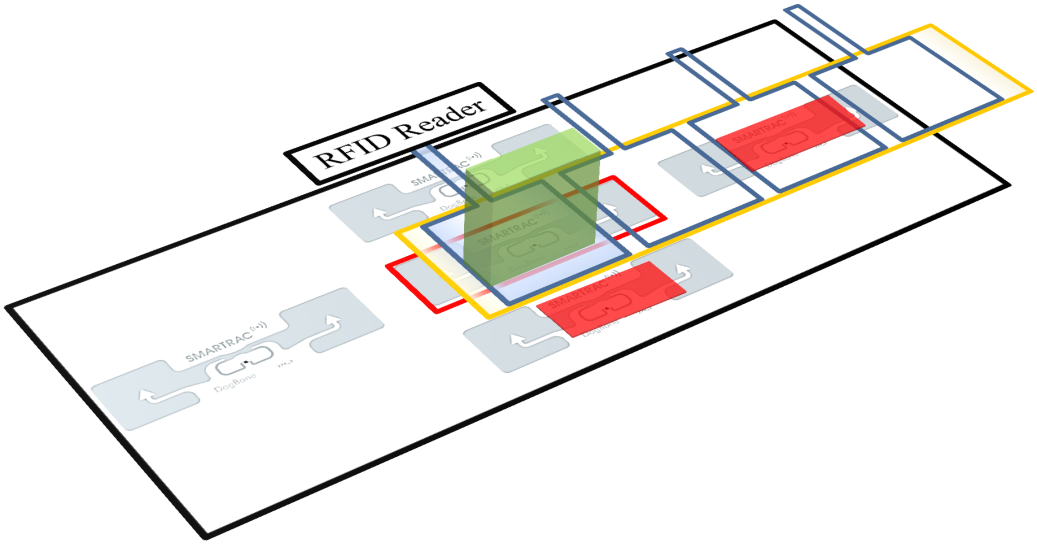


Figure 6.18: POSITIONS OF NON-TARGETED TAGS

All investigated factors; air gap, power level, tag spacing, tag orientation and tag number affect the results of detection with the non-targeted tags. However, the air gap was the most important in this case. While it was not significant from the result of 2^k analysis, it did impact results of the identification of the non-targeted tags. For example, as illustrated in detail in Appendix A, only few non-targeted tags were identified at 3tags_20mm, but many at 3tags_10mm. Again, from the perspective of the identification of non-target tags, the results keep us interested in the air gap.

6.6 Conclusion

Based on the results of the 2^k factorial design, and data patterns in Appendix A for all investigated factors with their respective, we suggest that tag number be removed as a factor in future investigation, as it is not significant in the 2^k design. Tag spacing, power level and tag orientation are all significant and we will keep them as the key factors in the next experimental design. Air gap was not shown to be significant from the 2^k factorial design result. However it did impact the identification of the non-targeted tags from the data pattern charts. Since the air gap is more likely to be a key factor in the multi-tag application, it will still be selected in the next experimental case. Moreover, we found that the highest tag read rate, with respect to tag orientation is at 0° and air gap at 10mm. When tag spacing is at 45mm, the radio has the best tag read rate and least detection on non-targeted tags. Tag read rate dropped significantly as the power level switched from 18.5dbm to 22.8dbm. Because of the limitation to the size and shape of the “Dogbone”, an equal tag spacing to the non-targeted tags in the vertical and horizontal could not be used. In the next design, we will select an alternative size/shape qualified near-field tag to replace the "Dogbone" and give a further investigation on the multi-tag application.

Chapter 7 Case 2: Skyetek Loop Array with Alien “Bio” tag

7.1 Test Setup

Alien bio was used here in Case 2, due to its square form factor. All tag spacing in vertical or horizontal direction are the same and all non-targeted tags are symmetric to the target tag, as illustrated in Figures (7.2) (7.3) (7.4) and (7.5). The fundamental system setup in Case 2 basically was the same as Case 1 (Chapter 6). All design experiments here were conducted by aligning the radio antenna center with the IC of the target tag. Antenna setup in Case 2 was kept exactly the same as Case 1 (Chapter 6), where the antenna number 3 was selected from the entire loop array (Figure 6.3).

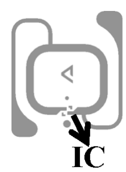


Figure 7.1: ALIEN “Bio” RFID TAG

7.2 Experimental Factors

The same definition was followed here, as in the earlier chapters; i.e., one tag — the center tag — would be selected as the target. Four key factors: air gap, tag orientation, power level and tag spacing, were investigated by using the 2^k factorial design. However, the pattern charts for the entire experimental results were attached in Appendix B as a reference. Two levels of the air gap: 5mm and 10mm, were used. As the tag orientation was found to be significant in Case 1 (Chapter 6). So, four levels of tag orientation, as shown in Figures (7.2) (7.3) (7.4) and (7.5), were selected with the power level in 10dbm, 14.2dbm, 18.5dbm, 22.8dbm and 27dbm (10, 26, 71, 190 and 500 mW, respectively), as shown in Table 7.1. Since the tag number was not found to be significant in Case 1 (Chpater 6). Thus, the number of five tags was selected in Case 2. Four levels of tag spacing, as illustrated in Figures (7.6) (7.7) (7.8) and (7.9), were used as well.

7.3 Results and Discussion

Again, all higher order interactions (interactions between three or more factors) were found to be negligible in the case design. The level of significance in this analysis was determined at a=0.05. Results showed that both the air gap and power level were found to be significant at the levels investigated. The total tag read rate decreased as the air gap increased from 5mm to 10mm, so as to the power level decreased at switch

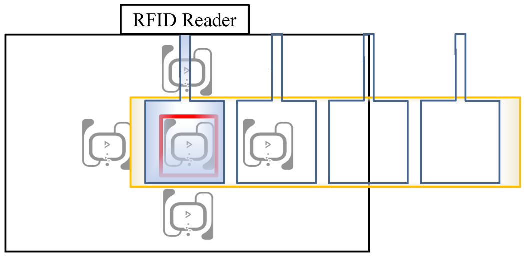


Figure 7.2: ALIEN "Bio" ORIENTATED AT 0°

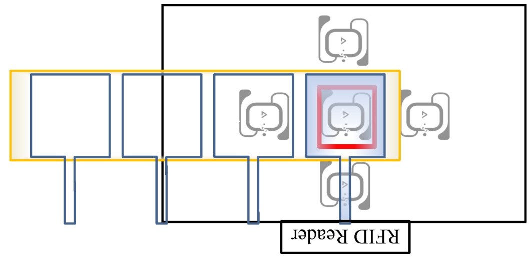


Figure 7.3: ALIEN "Bio" ORIENTATED AT 180°

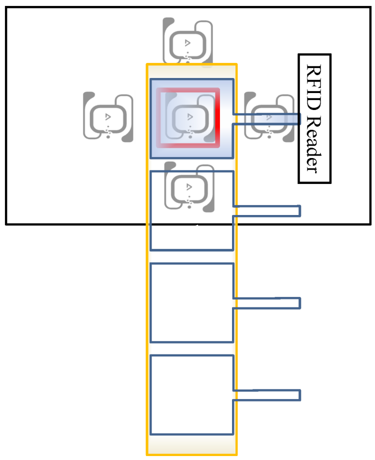


Figure 7.4: ALIEN "Bio" ORIENTATED AT 90°

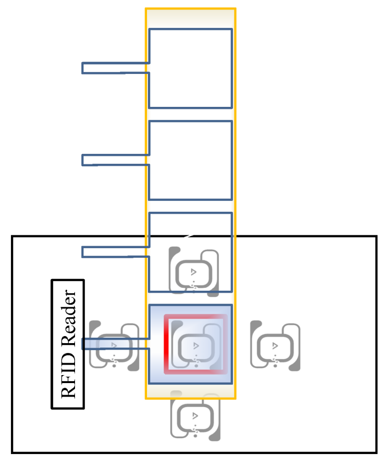


Figure 7.5: ALIEN "Bio" ORIENTATED AT 270°

Table 7.1: FACTORS AND LEVELS

Tag Type	Air Gap(mm)	Tag Space(mm)	Tag Orientation	Power Level(dbm)
"Bio"	5	20	0°	10
	10	30	90°	14.2
		40	180°	18.5
		50	270°	22.8
				27

from 10dbm to 27dbm (Figure 7.10). The tag orientation was found to be significant as well, but the overall tag read rate decreased as it switched from 0° to 90°. Tag spacing, the unique design factor in our study, was also not found to be significant. However, the total tag read rate increased as the tag spacing increased from 20mm to 50mm. Therefore, the results in Case 2 implied that the signal interference from the non-targeted tags to the target tag did exist. As a few unexpected non-targeted tags, marked with a red color, were detected by the radio from different positions on

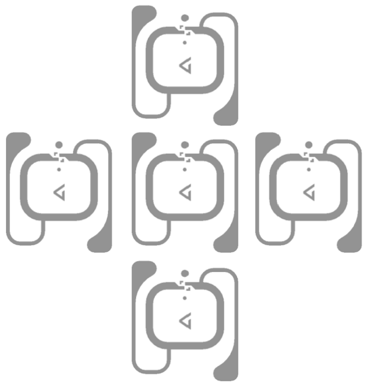


Figure 7.6: ALIEN “Bio” 20mm

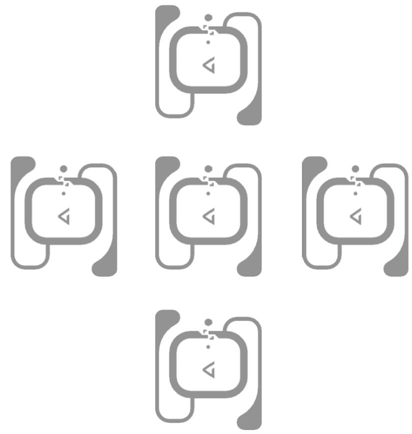


Figure 7.7: ALIEN “Bio” 30mm

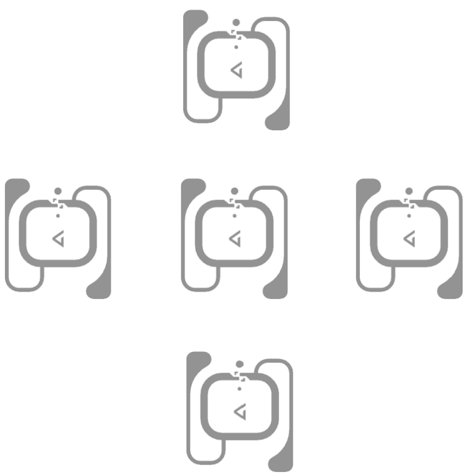


Figure 7.8: ALIEN “Bio” 40mm

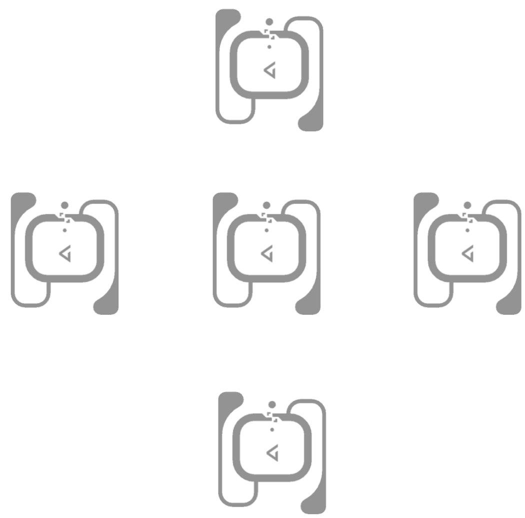


Figure 7.9: ALIEN “Bio” 50mm

the media, as shown in Figure 7.11.

Presumably, the failure prompted in those positions can be caused by the signal deflections from the unused antennas numbered 0, 1 and 2 (Figure 7.11), where the detection of non-targeted tags was below those unused antennas. Another assumption in the detection of those non-targeted tags was that the radio antenna was aligned with the IC of the target tag, but not the center, where the radio antenna was closer to the non-targeted tag at the very bottom of the media.

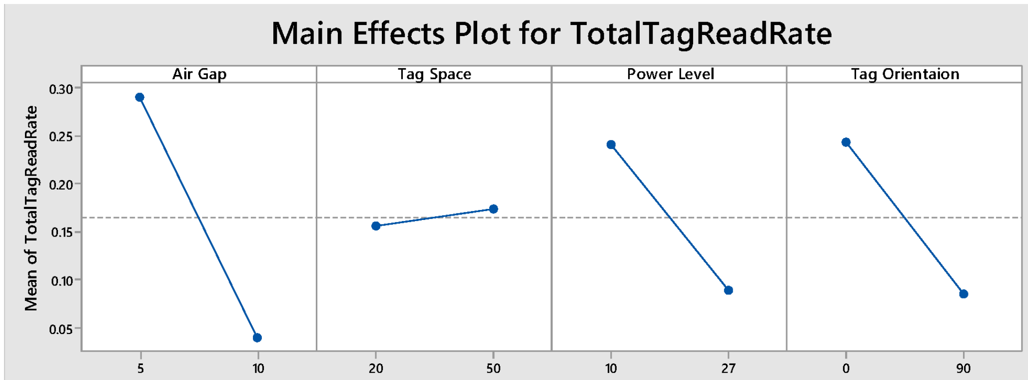


Figure 7.10: ALIEN “Bio” MAIN EFFECTS PLOTS

Table 7.2: TABLE OF ANOVA FOR Alien“Bio”

Source	F-critical	F-Value
Air Gap	3.90	38.74
Tag Space	2.66	11.52
Power Level	2.42	63.21
Tag Orientation	2.66	114.21
2-Way Interactions		
Air Gap*Tag Space	2.66	1.31
Air Gap*Power Level	2.42	5.13
Air Gap*Tag Orientation	2.66	25.41
Tag Space*Power Level	1.81	3.32
Tag Space*Tag Orientaion	1.93	1.35
Power Level*Tag Orientaion	1.81	10.59

Note:α=0.05 (95% confidence interval)

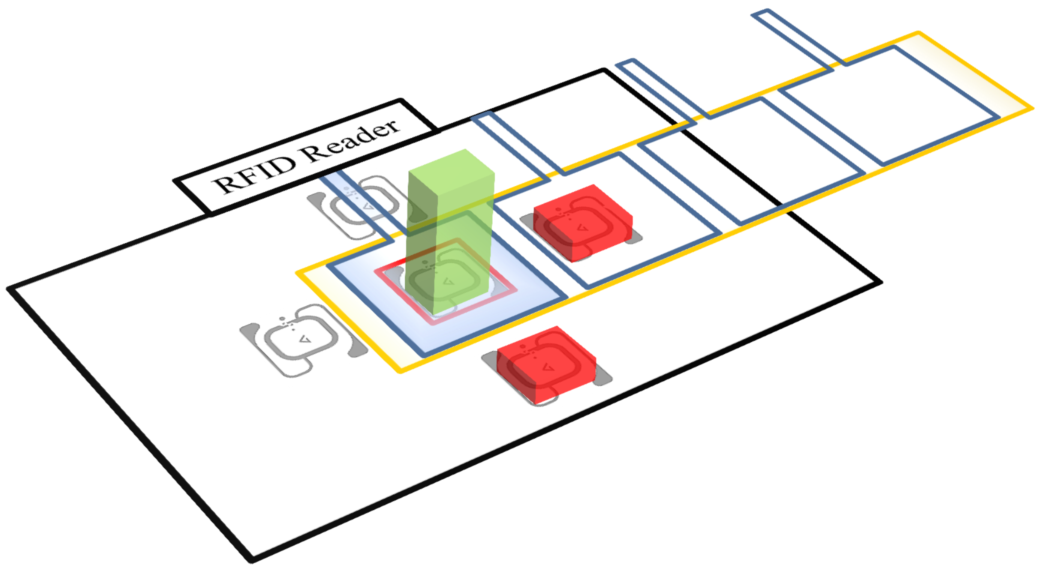


Figure 7.11: POSITIONS OF NON-TARGETED TAGS

Chapter 8 Case 3: Skyetek Loop Array aligned with Alien "Bio" tag center (IC VS Tag Center)

8.1 Test Setup

Recall that both experimental designs in Case 1 (Chapter 6) and Case 2 (Chapter 7) were set up to align the radio antenna center with the tag IC. As noted for these cases, the non-targeted tags located either underneath the antenna array or at the bottom of the media were sometimes identified by the radio instead of the targeted tag, which is a failure. The detection of non-targeted tags could be caused by setting up an undesirable position between the radio antenna and the target tag, where physically the radio antenna was closer to the non-targeted tag at the very bottom of the media. To verify this assumption, an adjusted setup to align the center of the radio antenna with the center of the target tag, as shown in Figure 8.1 was created. The purple circle indicates the center of the target tag and the red circle indicates the target tag IC. Thus, for Case 3, all experimental tests were conducted, with the center of the radio antenna aligned with the center of the target tag.

The Alien Bio tag was selected for this set of experiments, due to its square form-factor; which allows the spacing between the target and non-targeted tags to be identical and symmetric both vertical and horizontal directions.

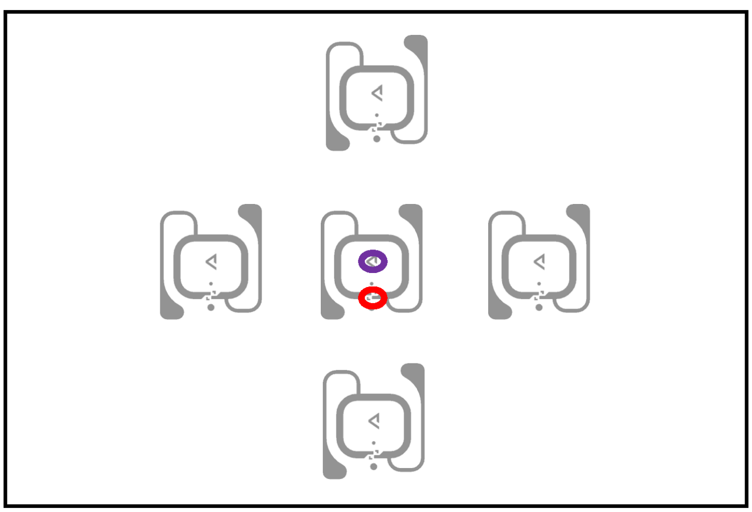


Figure 8.1: IC VS TAG CENTER

8.2 Experimental Factors

The same definition was followed here, as in the earlier chapters; i.e., one tag — the center tag — would be selected as the target. To find out the root cause of the detection of the non-targeted tags, a sufficient total tag read rate must be required in Case 3 ("Bio" tag center). This allowed our experimenter to better observe the experimental results. Also, it became much easier to compare the results from Case 2 ("Bio" IC center), where the result came with a few detections of the non-targeted tag.

So, the air gap in Case 3 was fixed at 5mm, as a low tag read rate occurred at the higher air gap of 10mm in Case 2. Five power levels: 10dbm, 14.2dbm, 18.5dbm, 22.8dbm and 27dbm (10, 26, 71, 190 and 500 mW, respectively), and four tag spacing values: 20mm, 30mm, 40mm and 50mm were selected, as presented in Table 8.1. To reduce the experimental costs, the tag orientations at 0° and 270° were used, since these had the highest tag read rates in earlier tests. A new factor, tag position was added here, with two levels, "IC center" and "Tag center". Again, "IC center" is defined as the center of the radio antenna aligned with the IC of the target tag. And, "Tag center" is defined as the center of the radio antenna aligned with the center of the target tag. Also, notice that by using the Alien Bio, all tag spacing in both vertical and horizontal directions were the same, and all non-targeted tags were symmetric to the target tag.

Table 8.1: FACTORS AND LEVELS

Tag Type	Tag Position	Tag Orientation	Tag Space(mm)	Power Level(dbm)
"Bio"	IC Center	0°	20	10
	Tag Center	270°	30	14.2
			40	18.5
			50	22.8
				27

8.3 Data Collection and Data Analysis

Data was collected with minimal interference from extraneous factors such as metal objects, the presence of water, florescent lighting and other competing frequencies from testing environment. Since all observation tags were pre-programmed with unique information for all experimental setups, experimenters were capable of identifying the exact detected tags for each experimental run.

One hundred repeated measures were customized for an individual treatment, where the RFID radio would attempt 100 successive reads and record which tag (or that no tag) was read. Three replicates or experimental runs were conducted for all tests. All design factors and each of their levels is listed in Table 8.1. To examine the factor effect of the "tag position", the 2^k factorial design method was applied to a subset of the factors presented in Table 8.1; the specific factors used in the 2^k design are presented in Table 8.2.

Table 8.2: 2^k FACTORS AND LEVELS

Factors	Level(ft) Low (-)	High (+)
Tag Position	IC Center	Tag Center
Tag Space (mm)	20	50
Power Level (dbm)	10	27
Tag Orientation	0°	270°

Table 8.3: TABLE OF ANOVA

Source	F-critical	F-Value
Tag Position	3.12	0.88
Tag Space	3.95	31.2
Power Level	4.82	504.13
Tag Orientation	3.12	14.99
2-Way Interactions		
Tag Position*Tag Space	4.16	18.61
Tag Position*Power Level	3.95	7.34
Tag Position*Tag Orientation	4.16	0.37
Tag Space*Power Level	3.12	79.28
Tag Space*Tag Orientation	3.12	1.91
Power Level*Tag Orientation	3.95	0.2

Note:α=0.05 (95% confidence interval)

8.4 Results and Discussion

All the higher order interactions (interactions between three or more factors) were removed from our data analysis in Table 8.3, as they are negligible in the case design. The level of significance in this analysis is determined at a=0.05. Anova results in Table 8.3 showed that tag position was not found to be significant to the system performance on total tag read. The overall tag read rate in Case 3 increased 7.73% at 0°, as well as 2.51% at 270°, compared to the results in Case 2 (Chapter 7). Regardless of the tag spacing, the system performance was consistent and efficient at lower power levels, but poor at 27dbm. The highest total tag read rate occurred at a tag spacing of 20mm and a power level of 10dbm (Figure 8.3). The following design factors and factor interactions were all found to be significant at the levels tested: tag spacing, power level, tag orientation, tag spacing*power level, tag spacing*tag position and power level*tag position.

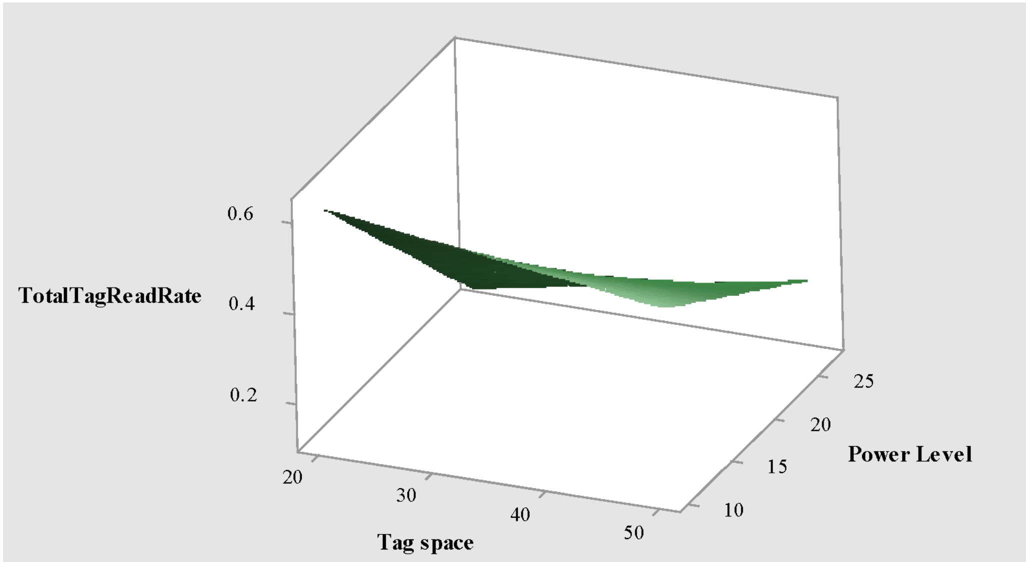


Figure 8.2: 3D SURFACE PLOT/TOTAL TAG READ RATE AT "IC CENTER"

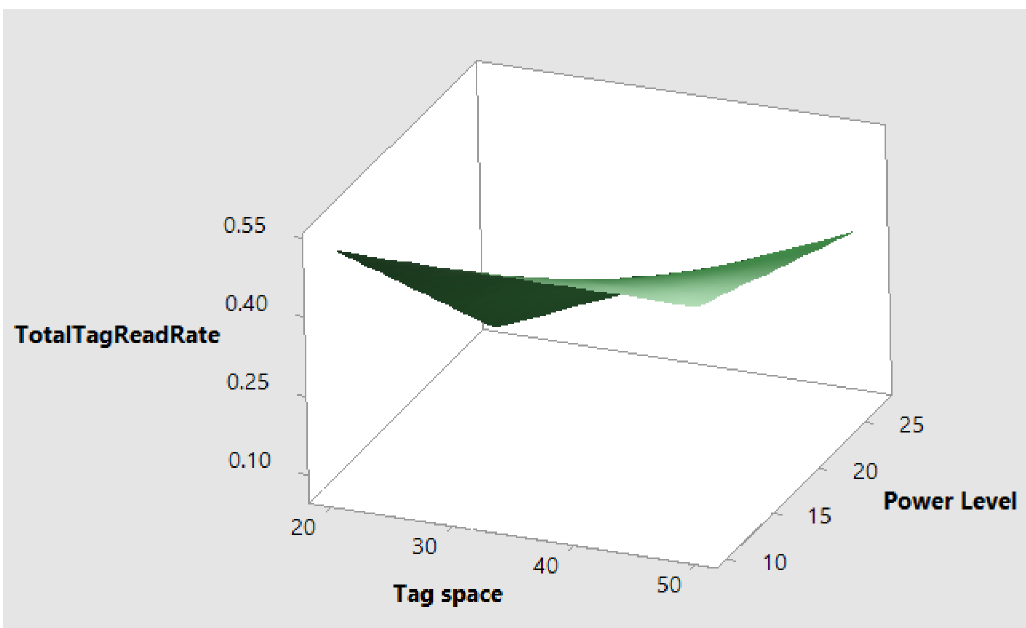


Figure 8.3: 3D SURFACE PLOT/TOTAL TAG READ RATE AT "TAG CENTER"

By using the 2^k factorial design method, scientifically we show that the "tag position", as a new design factor in Case 3, was found *not* to be significant to the system performance in terms of the total tag read rate. However, the primary purpose here was to investigate whether the root cause in the detection of non-targeted tags was due to an undesirable position setup between the radio antenna and the target tag. Therefore, a new method to analyze testing data was given here. The new method to

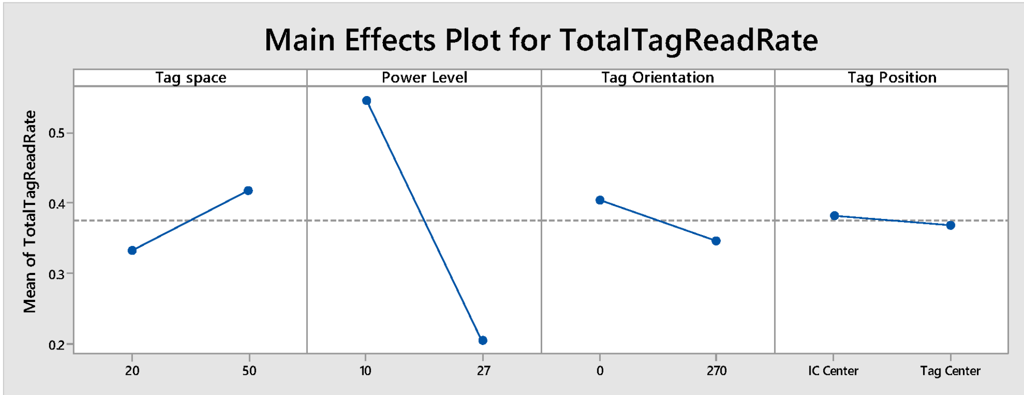


Figure 8.4: MAIN EFFECTS PLOTS

investigate testing data came up with a diagram in a 3D model, as shown in Figures 8.5 and 8.6, which directly reflected the positions of the detecting tags, and their tag read rates.

At 0°, the position of the non-targeted tag at right on the media came up with a read rate at 1.38% for the "tag center", and 0.43% for the "IC center". The "tag center" detected even more non-targeted tags at the same position, compared to the "IC center". Meanwhile, few non-targeted tags were detected at a position on the top of the media with 0.03%. At 270°, the target tag read rate for the "tag center" increased, compared to the results of the "IC center", but again the non-targeted tags were detected with 1.28% at the same position, where the non-targeted tags were identified in the Case 2 (Chapter 7) with a read rate of 0.70%. So, we can not conclude that the tag position is the root cause of the detection on non-targeted tags.

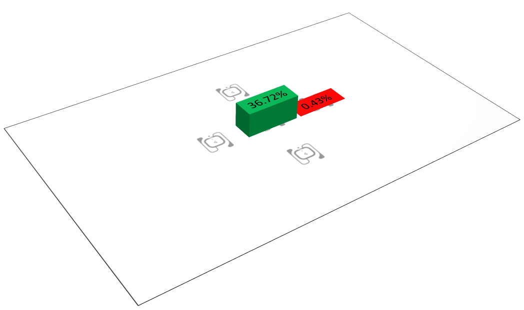


Figure 8.5: Tags Identification at "IC Center" with 0°

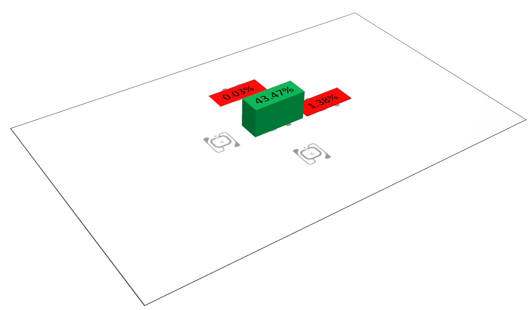


Figure 8.6: Tags Identification at "Tag Center" with 0°

8.5 Conclusion

For Case 3, the system performance was more stable and efficient with respect to the target tag read rate. However, this was coupled with even more positions and detection rates of the non-targeted tag. The power level was found to be the most

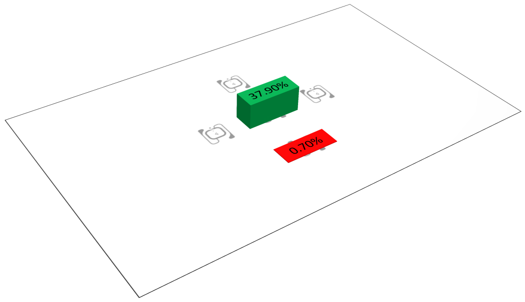


Figure 8.7: Tags Identification at "IC Center" with 270°

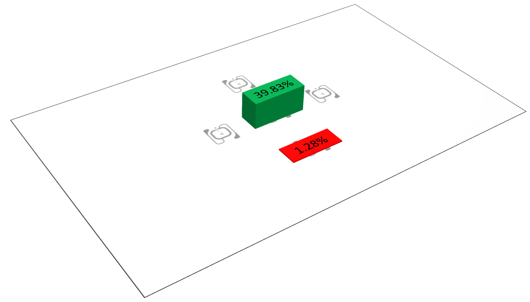


Figure 8.8: Tags Identification at "Tag Center" with 270°

important factor in Case 3. The overall tag read rate decreased as the power level increased, as shown in Figure 8.4. At 0°, the system had a better performance overall. Only at a 50mm tag spacing, we did not find the detection of non-targeted tags; however, the overall tag read rate also increased as the tag spacing increased from 20mm to 50mm. The best system performance with respect to the tag spacing appeared at 40mm.

Chapter 9 Case 4: System Response with a Single Skyetek Loop Compares to the Skyetek Loop Array(Single Loop Antenna Vs Antenna Loop Array)

9.1 Test Setup

As mentioned in Case 2 (Chapter 7), another assumption regarding the detection of non-targeted tags for the multi-tag application is that the signal propagated from the radio was deflected from the unused antennas number 0, 1 and 2 (Figure 9.1). To avoid this likely scenario, a major antenna change was implemented. The unused antennas 0, 1 and 2 were removed from our Skyetek Loop Array, and then antenna 3, illustrated in Figure 9.2, was used in Case 3.

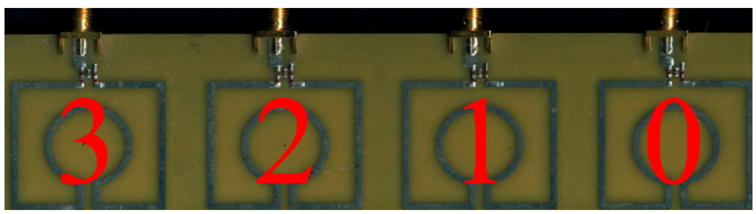


Figure 9.1: Antenna Loop Array

⇓

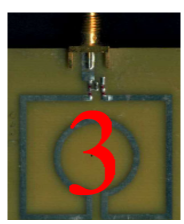


Figure 9.2: Single Loop Antenna

Except for the change in the radio antenna, the basic setup was the same as the previous cases, where the fixture can efficiently investigate factors such as the air gap (vertical distance between the target tag and the reader antenna), tag placement (in-plane offset horizontal and vertical distances of the tag center with respect to the antenna center), tag orientation (in-plane rotation of the tag axis with respect to the reader antenna), and tag speed (with respect to a fixed antenna array).

To fairly compare the test results between Case 2 (Chapter 7) and Case 4, all experimental tests in this chapter were conducted using the same rules defined in Case 2 (Chapter 7), where the center of the radio antenna is aligned with the IC of the target tag.

9.2 Experimental Factors

In cases 1, 2 and 3, non-targeted tags were identified at the end of the process for certain conditions, which was a failure. In Case 3 (Chapter 8), a new factor "tag position" was introduced, but the results from the 2^k factorial design showed that the "tag position" was not a significant factor to the system performance. Also, again the non-targeted tags were detected in certain conditions. In Case 4, a similar experimental design idea was applied. A new design factor "antenna type" was added with two levels "Antenna Loop Array" and "Single Loop Antenna", as shown in Table 9.1. This added factor enabled us to check if the non-targeted tags get detected due to the deflection of the unused antenna 0, 1 and 2 from the Skyetek Loop Array (Figure 9.1).

To achieve a sufficient tag read rate, the air gap was fixed at 5mm. Other design factors and their levels remained the same as they were used in Case 3 (Chapter 8). Notice that by using the Alien Bio in Case 4 tests, all tag spacing in both vertical and horizontal directions are the same and all non-targeted tags are symmetric to the target tag.

Table 9.1: FACTORS AND LEVELS

Tag Type	Antenna Type	Tag Orientation	Tag Space(mm)	Power Level(dbm)
"Bio"	Antenna Loop Array	0°	20	10
	Single Loop Antenna	270°	30	14.2
			40	18.5
			50	22.8
				27

9.3 Results and Discussion

Again, all higher order interactions (interactions between three or more factors) were found to be negligible in the case design. The level of significance in this analysis was determined at a=0.05. Anova results showed that the "antenna type" was found to be significant, with a F-value of 63.63. We also found that the overall tag read rate, as shown in Figure 9.3, dropped to 27.97%, compared to 37.87% in Case 2 (Chapter 7). The tag spacing and power level were both found to be significant. The total tag read rate increased as the tag spacing increased (Figure 9.3), which was expected and consistent with the previous cases. Regardless of the tag spacing, the system performance was reliable at lower power level, and worse at 27dbm. Tag orientation was the only design factor found not to be significant, and the system had a good performance at each tag angle.

Table 9.2: TABLE OF ANOVA

Source	F-Value	F-Crit
Antenna Type	63.63	3.9412
Tag Space	12.54	3.9412
Power Level	706.42	3.9412
Tag Orientation	0.015	3.9412
2-Way Interactions		
Antenna Type*Tag Space	4.08	3.9412
Antenna Type*Power Level	12.54	3.9412
Antenna Type*Tag Orientation	15	3.9412
Tag Space*Power Level	60.5	3.9412
Tag Space*Tag Orientation	42.52	3.9412
Power Level*Tag Orientation	0.92	3.9412

Note:α=0.05 (95% confidence interval)

By using the "Single Loop Antenna" in Case 4, the total tag read rate decreased. However, no non-targeted tags were identified at the end of the process for the single antenna. In any read attempts by the radio in Case 4, the radio always picked up the target tag.

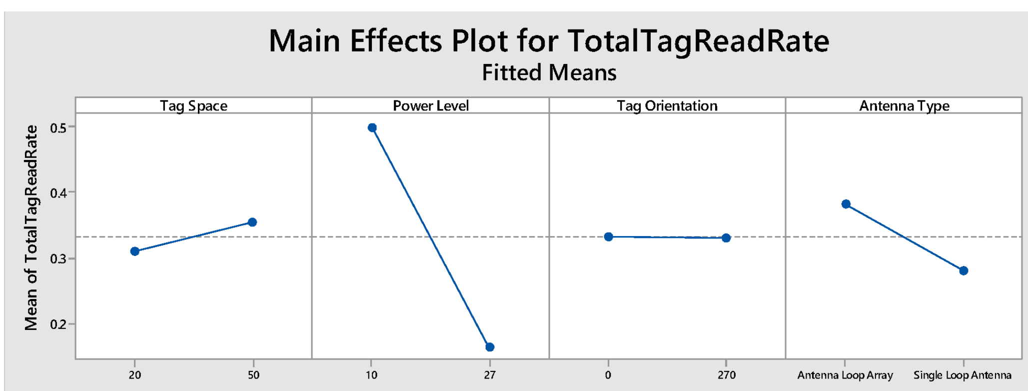


Figure 9.3: ALIEN "Bio" MAIN EFFECTS PLOTS

The results from Case 4 verified that a deflection or some type of interference from those unused antennas must exist. The diagrams to summarize all tests results in Case 4 are shown in Figures (9.4) (9.5) (9.6) and (9.7). These further show that no non-targeted tags were identified at 0° and 270°. But, the target tag read rate was only 28.22% at 0°. It decreased significantly in Case 4, compared to a read rate of 36.72% at 0° in Case 2. At this point, regardless of the factors and their levels the radio always reads the target tag.

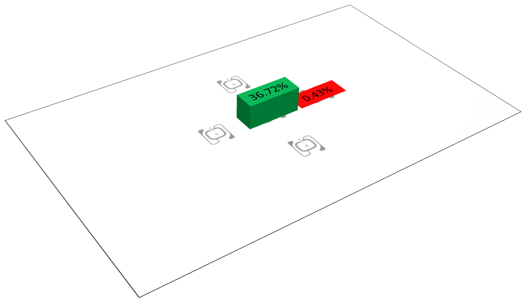


Figure 9.4: Tags Identification with "Skyetek Loop Array" at 0°

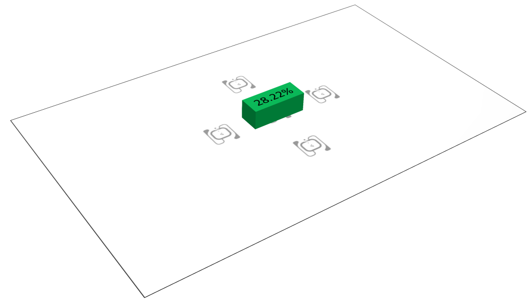


Figure 9.5: Tags Identification with "Single Loop Antenna" at 0°

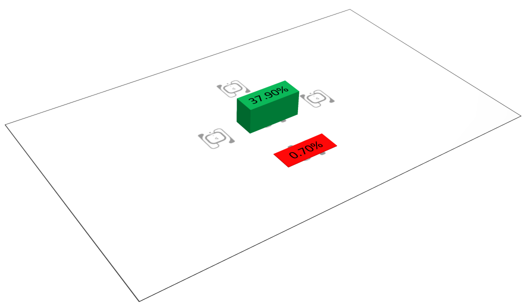


Figure 9.6: Tags Identification with "Skyetek Loop Array" at 270°

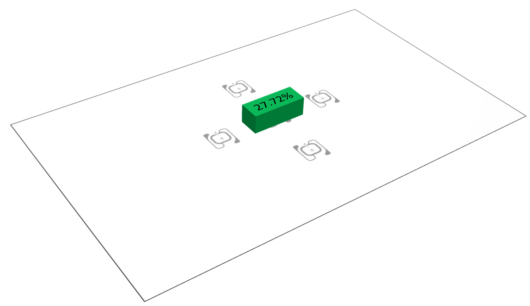


Figure 9.7: Tags Identification with "Single Loop Antenna" at 270°

Chapter 10 System Response with a Single Skyetek Loop Compares to a Lexmark loop (Single Skyetek Loop Vs Lexmark Loop)

10.1 Test Setup

In Case 5, the "Single Loop Antenna" was replaced by a new antenna which we designate as the "Lexmark Loop". Other than the antenna replacement, the experimental setup in Case 5 followed the same test setup as Case 4 (Chapter 9).

10.2 Experimental Factors

To fairly compare the results between Case 4 (Chapter 9) and Case 5, all other factors and levels except the antenna type were the same, as illustrated in Table 10.1. The new antenna "Lexmark Loop" used in Case 5 has a double rectangular loop of wire design. This design aims to concentrate more energy to the very center when the signal power is triggered.

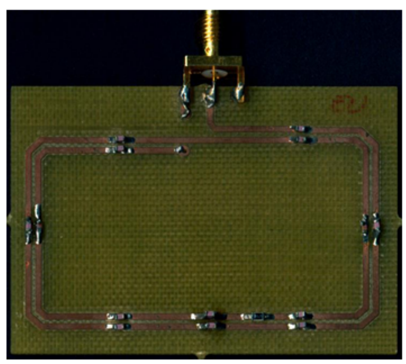


Figure 10.1: LexmarkLoop

Table 10.1: FACTORS AND LEVELS

Tag Type	Antenna Type	Tag Orientation	Tag Space(mm)	Power Level(dbm)
"Bio"	Lexmark Loop	0°	20	10
	Single Loop Antenna	270°	30	14.2
			40	18.5
			50	22.8
				27

10.3 Results and Discussion

The level of significance in Case 5 was determined at a=0.05. The Anova results in both Table 10.2 and Pareto Chart (Figure 10.2) indicate that the tag spacing was found to be the most significant factor in Case 5, with a F-value of 643.75, which strongly exceeds the critical value of 3.94. The tag orientation was the only factor not found to be significant to the system performance.

Table 10.2: TABLE OF ANOVA

Source	F-Value	F-Crit
Antenna Type	68.39	3.9412
Tag Space	643.75	3.9412
Power Level	118.68	3.9412
Tag Orientation	0.75	3.9412
2-Way Interactions		
Antenna Type*Tag Space	459.52	3.9412
Antenna Type*Power Level	29.29	3.9412
Antenna Type*Tag Orientation	3.43	3.9412
Tag Space*Power Level	0.07	3.9412
Tag Space*Tag Orientation	5.38	3.9412
Power Level*Tag Orientation	1.32	3.9412

Note:α=0.05 (95% confidence interval)

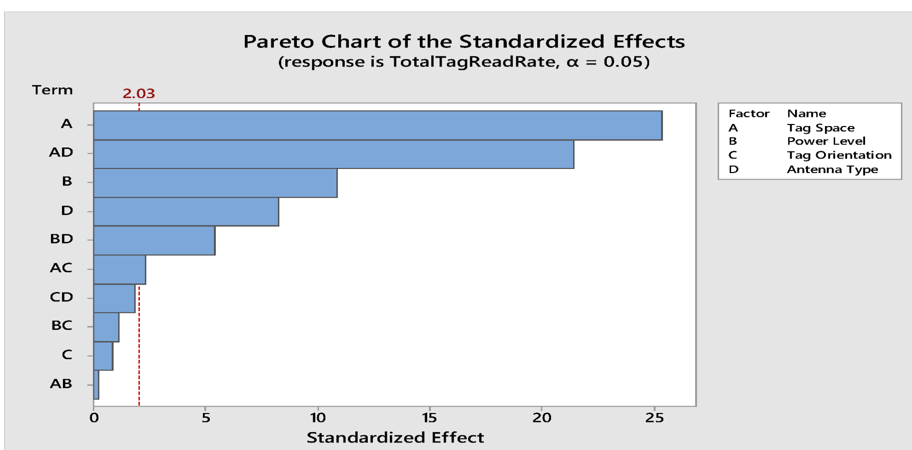


Figure 10.2: Design Factor Effect on Pareto Chart

For the "Lexmark Loop", the target tag read rate in Case 5 increased to 38.78%, compared to 28.22% in Case 4 (Chapter 9) at 0°, as shown in Figures 10.3 and 10.4. But, unfortunately, non-targeted tags in certain position were detected. This significant increase for the target tag read rate verified that the double wire design of the "Lexmark loop" definitely had a positive impact to the system performance in terms of the read rate. Recall that in Case 4 (Chapter 9), a solution was found to make the radio only identify the target tag within a certain attempts. However, the target tag read rate was significantly decreased. This study found that an antenna designed with a double wire enabled itself to concentrate more energy to the very center when the signal power is triggered, compared to the "Single Loop Antenna" design. Thus, it appears that an appropriate modification of the antenna could compensate for the reduction in the target tag read rate (as illustrated Case 4), and simultaneously satisfy the requirement that only the target tag be detected by the radio.

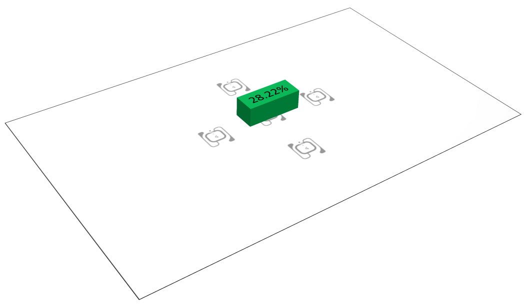


Figure 10.3: Tags Identification at "IC Center" with 0° from Single Skyetek Loop

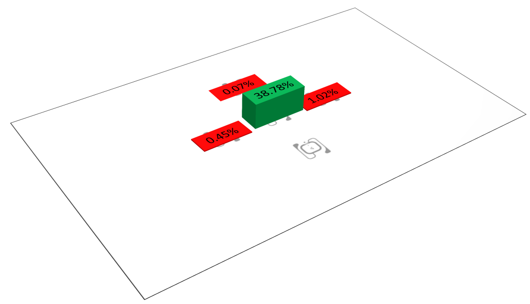


Figure 10.4: Tags Identification at "Tag Center" with 0° from Lexmark Loop

Chapter 11 Conclusion and Contribution

To the objective of this study was to investigate and identify, if possible, optimal configuration of multiple proximal tags, which maintains a high throughput rate of uniquely encoded tags. The first two cases discussed in Chapter 6 and 7, laid a solid foundation to understand the key factors that affect multi-tag programming in the static environment. Design factors such as tag spacing, power level , tag orientation and air gap were confirmed to be the significant factors based on the 2^k factorial design. But factors like the number of proximal tags were found not to be significant at the levels investigated. Though a decent target tag read rate be achieved, at certain conditions a few non-targeted tags were identified, which was counter to our experimental objectives. Case 3 and Case 4 (Chapter 8 and 9) were introduced to study the root causes for detecting non-targeted tags. Also, to further improve the system performance in the target tag read rate, the critical levels of key design factors were further investigated while comparing different antenna configurations and types. By using the “Single Loop Antenna”, no non-targeted tags were identified. However, the target tag read rate was compromised. In order to compensate for the loss in the target tag read rate, we consider a new antenna, which had a double loop wire. The results from this new antenna in Case 5 (Chapter 10) showed a significant increase for the target tag read rate at the cost of detecting non-targeted tags during the reading process.

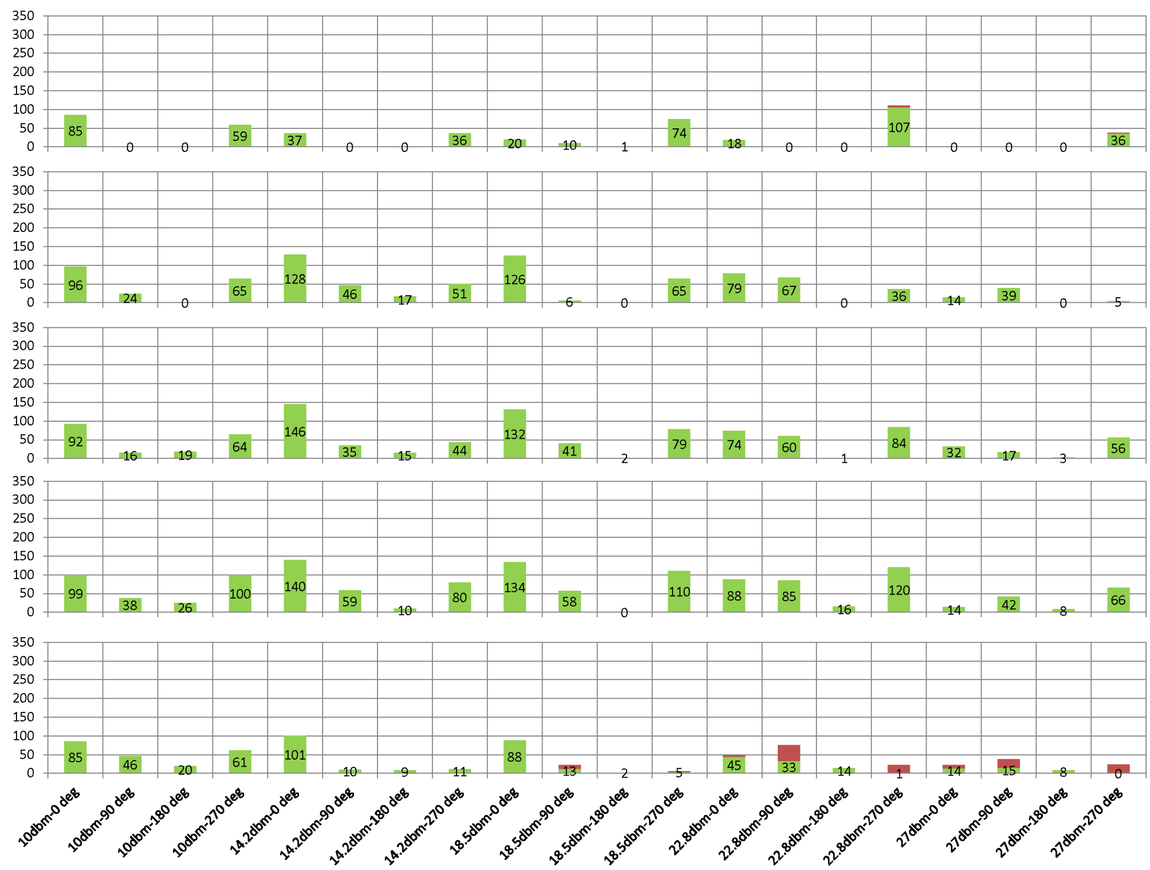
The main contribution of this study is to offer a new solution, by physically varying the configuration of tag placement, antenna position and RFID radio parameters to accurately and effectively read a single tag in a multi-tag environment. As the tags are too close together for localization to be reliable employed. The studies included in this thesis suggest configurations which maximize effective reading of tags, while eliminating (or significantly reducing) the detection of non-targeted tags.

Appendices

A

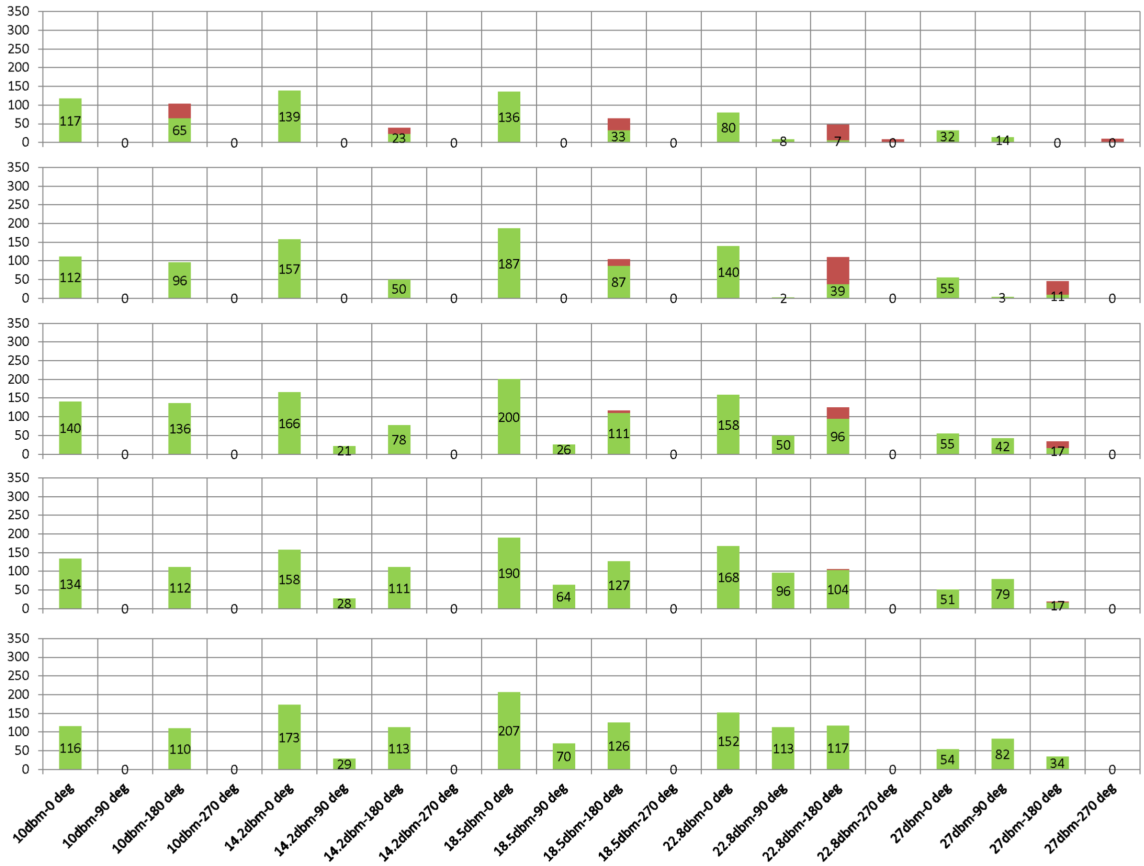
“Dogbone” Pattern Charts (Foundation Tests)

Factors and their levels: 5 power levels, 3 tag numbers, 5 air gaps, 4 tag orientations and 4 tag spacings.

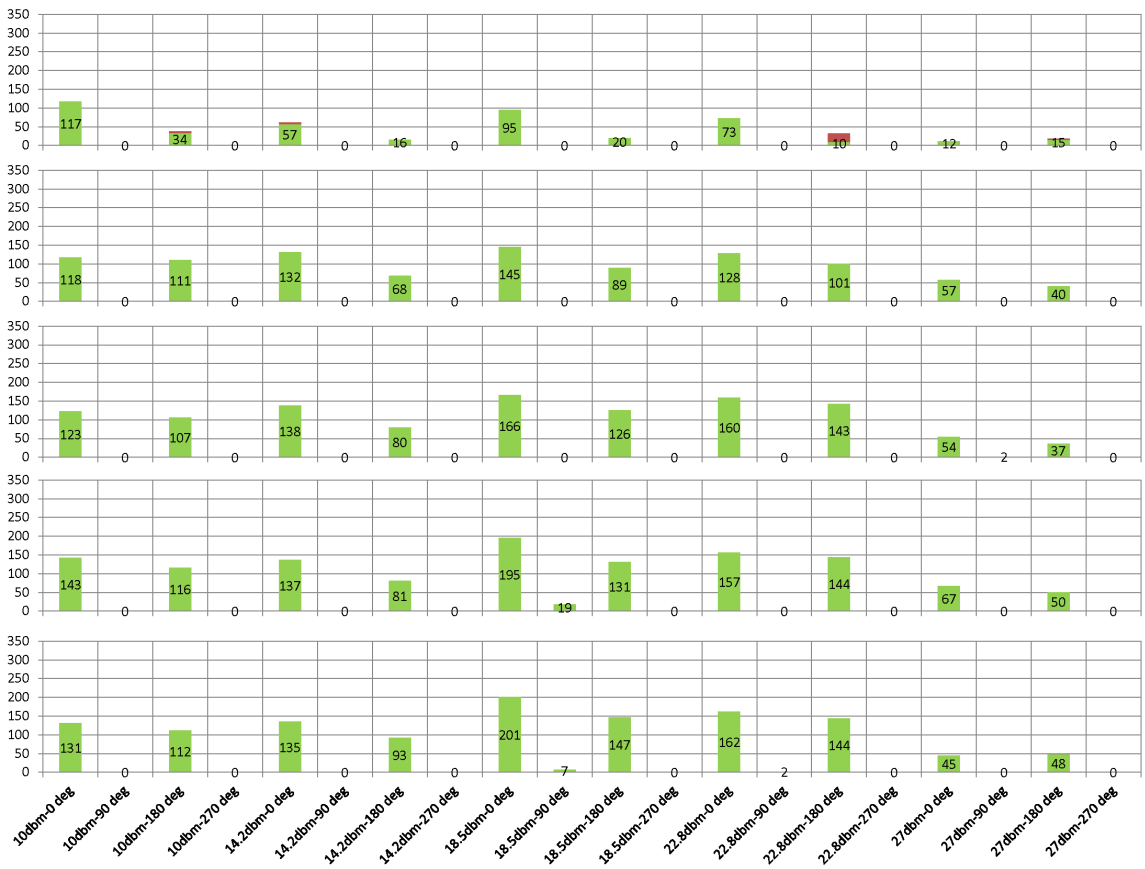


3Tags AirGap5mm

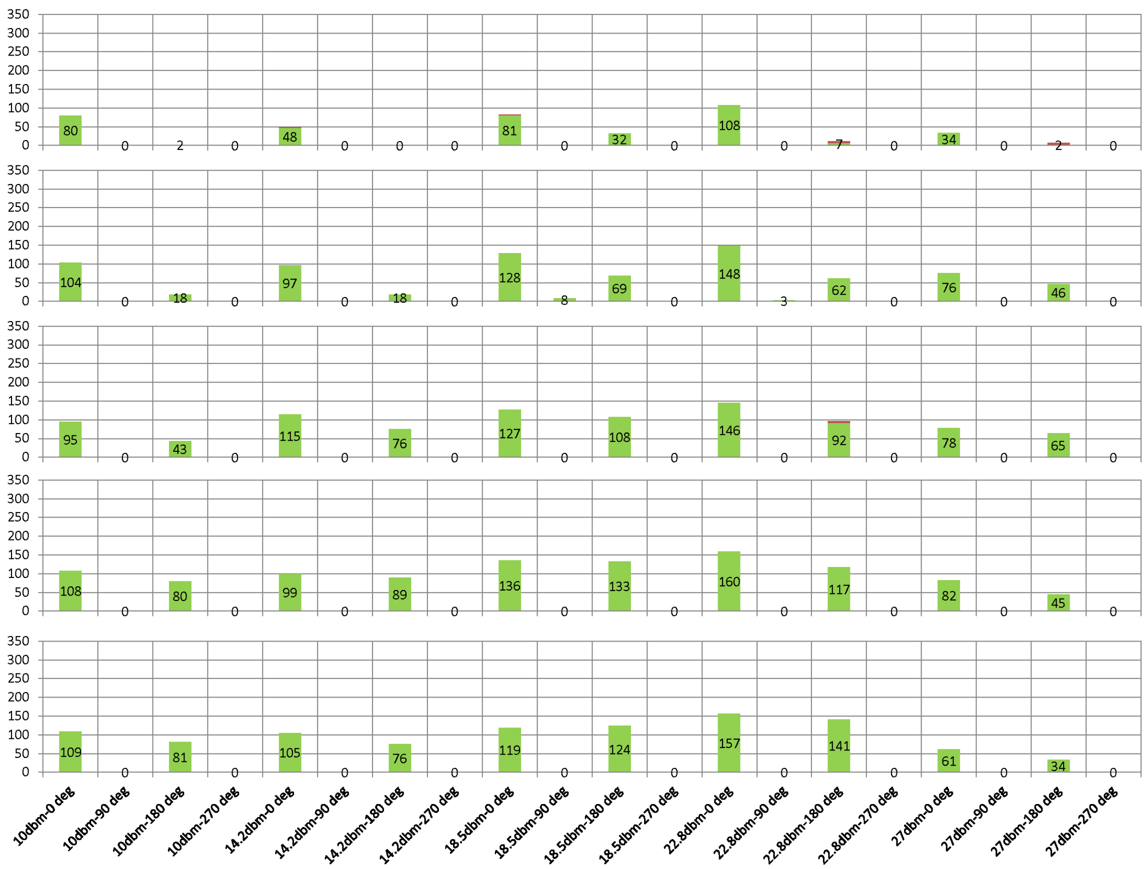
Read non-target tag
Read target tag



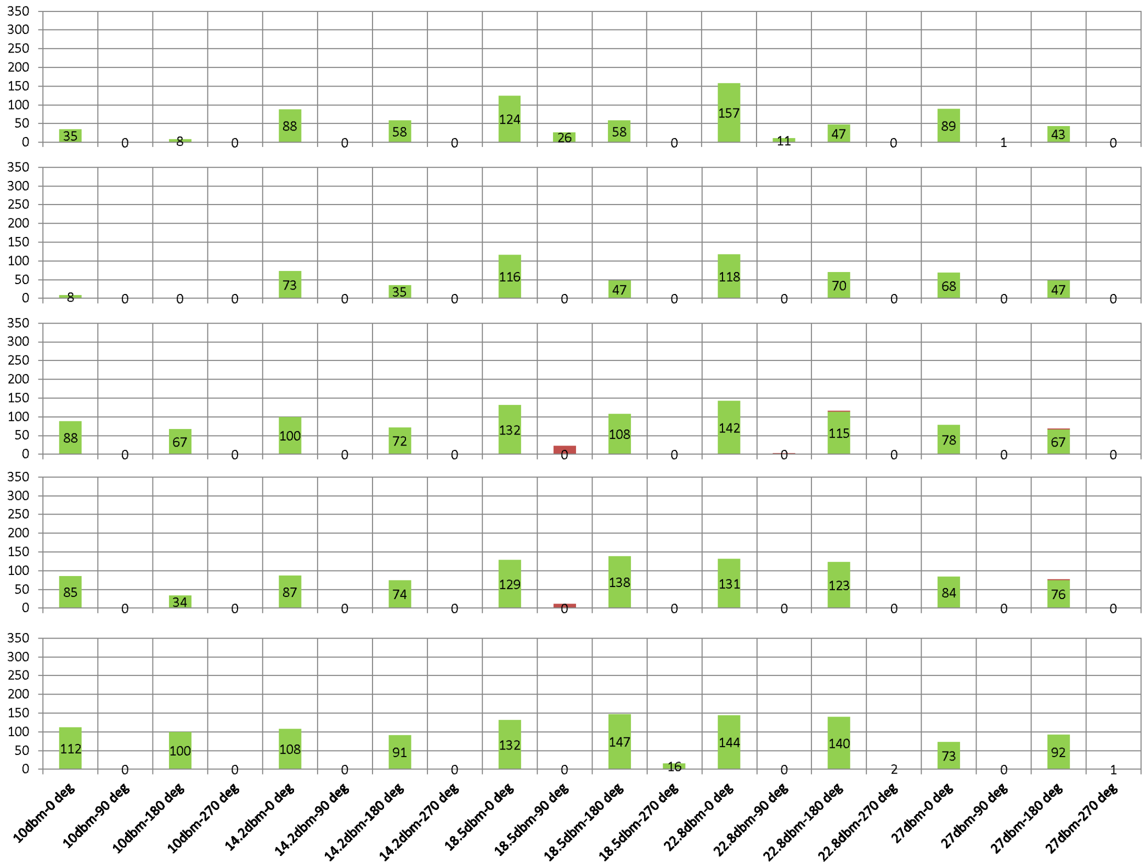
3Tags AirGap10mm



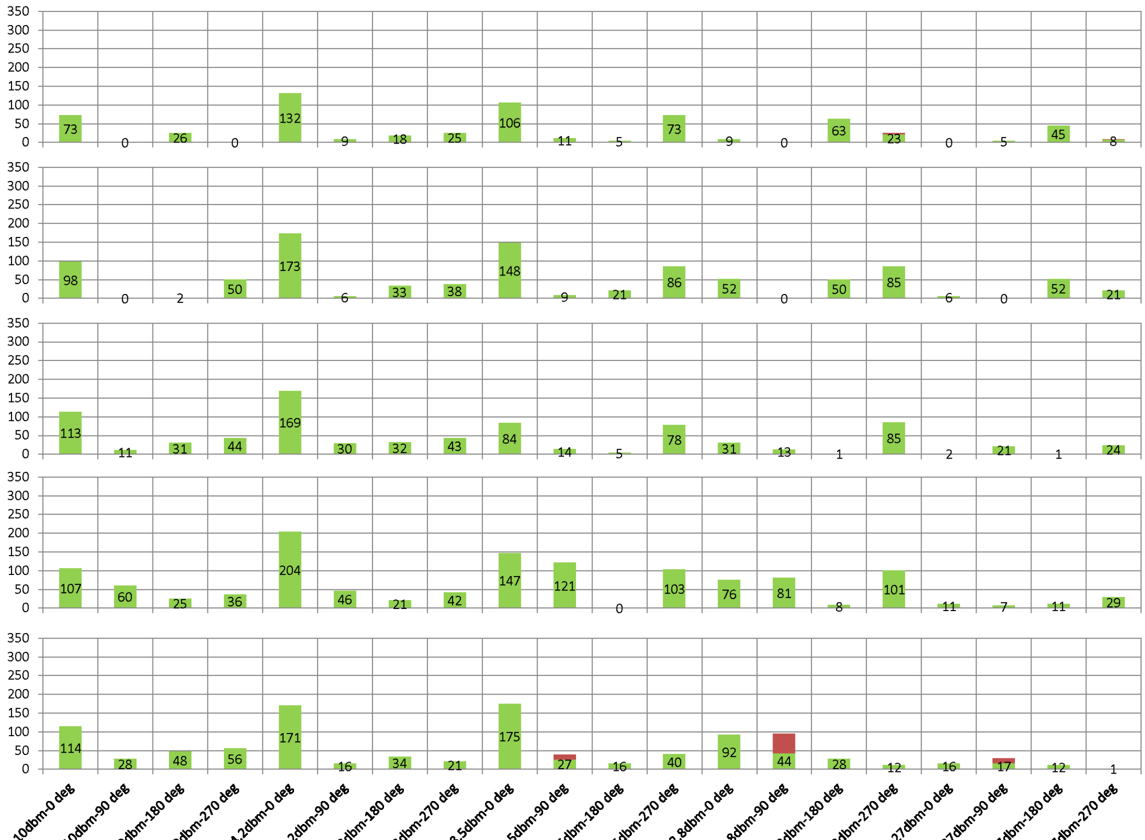
3Tags AirGap15mm



3Tags AirGap20mm



3Tags AirGap25mm



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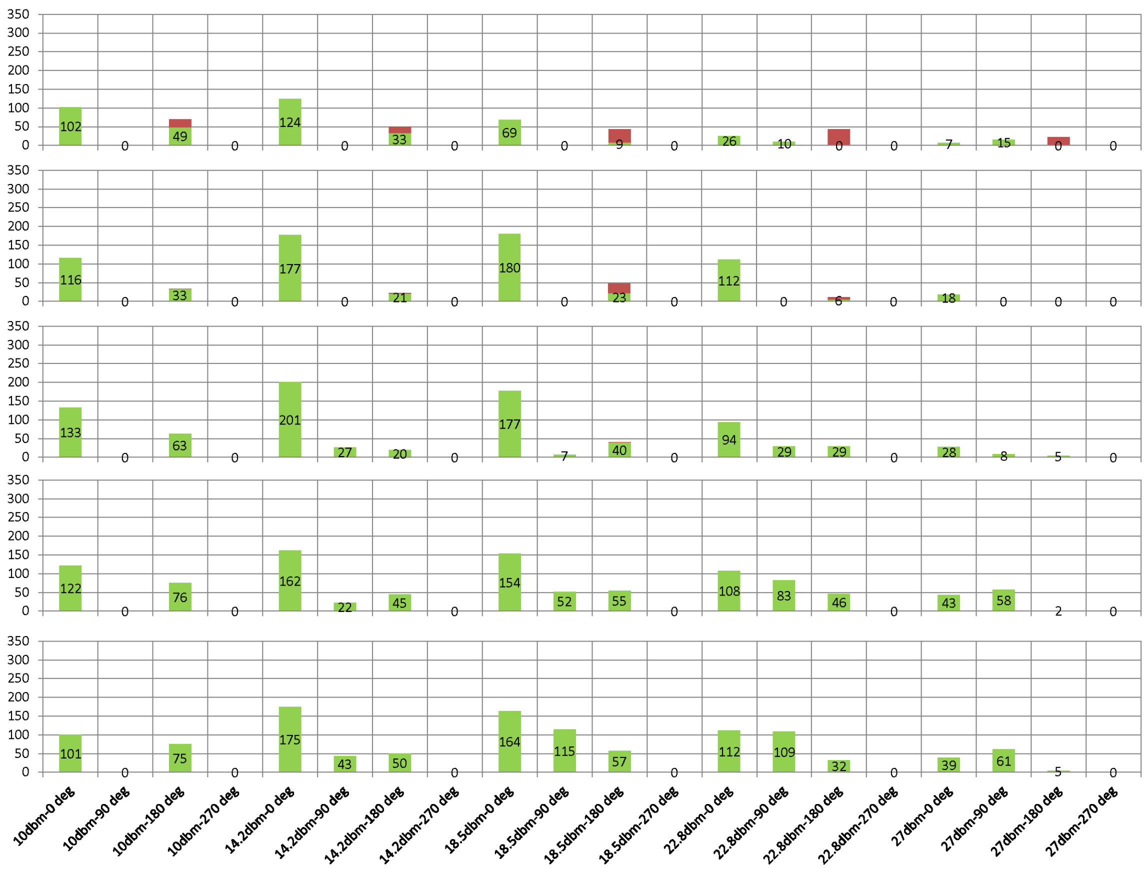

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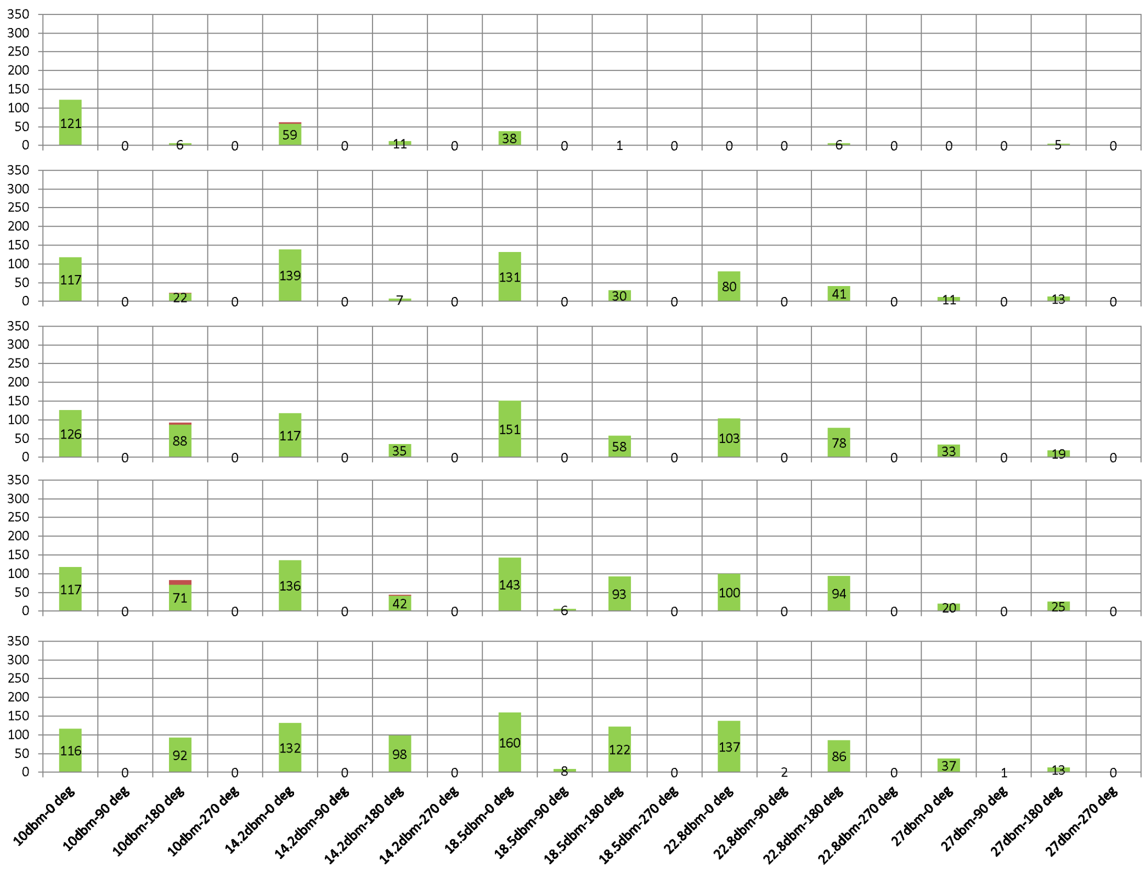

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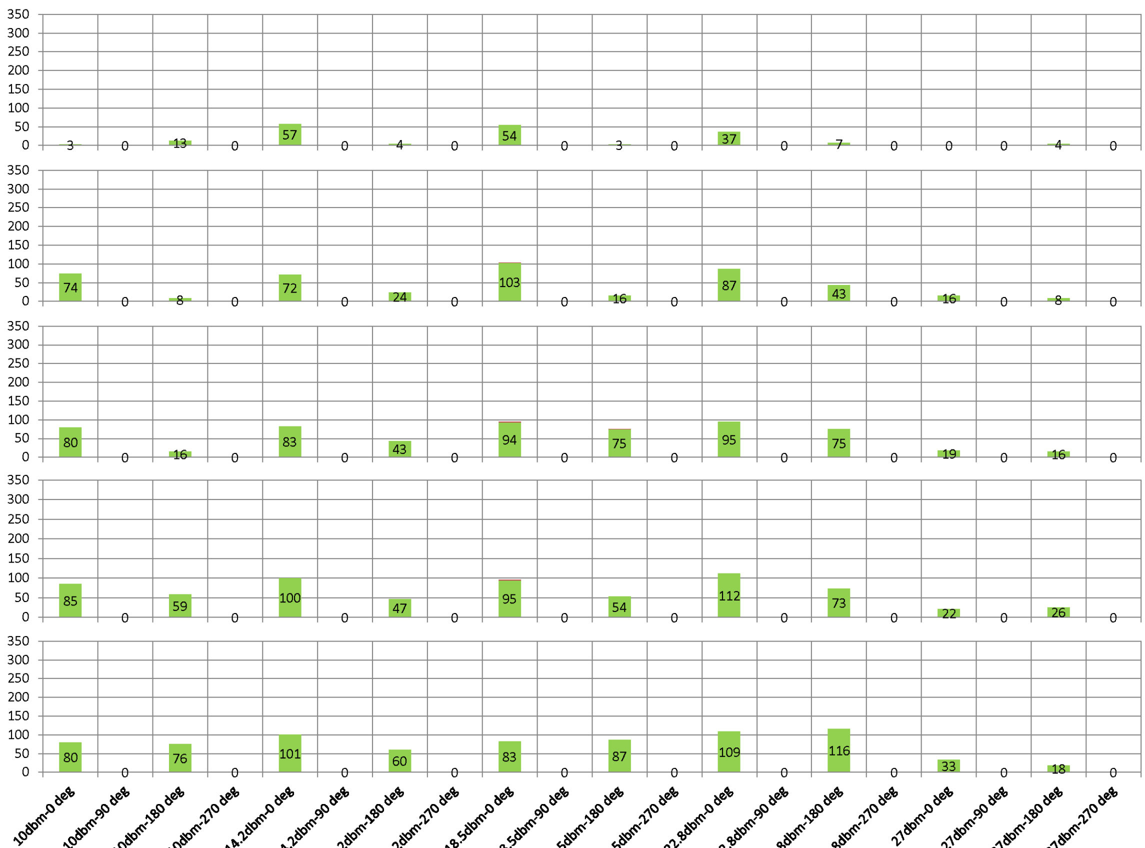

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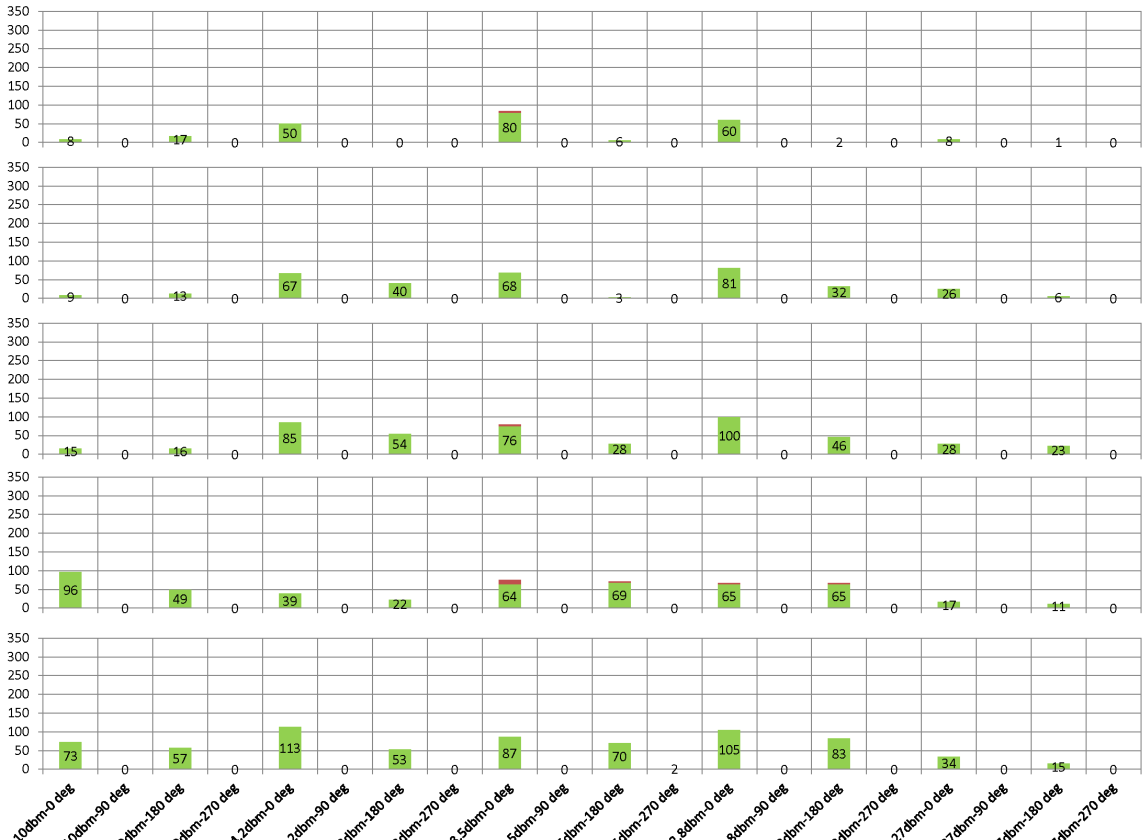

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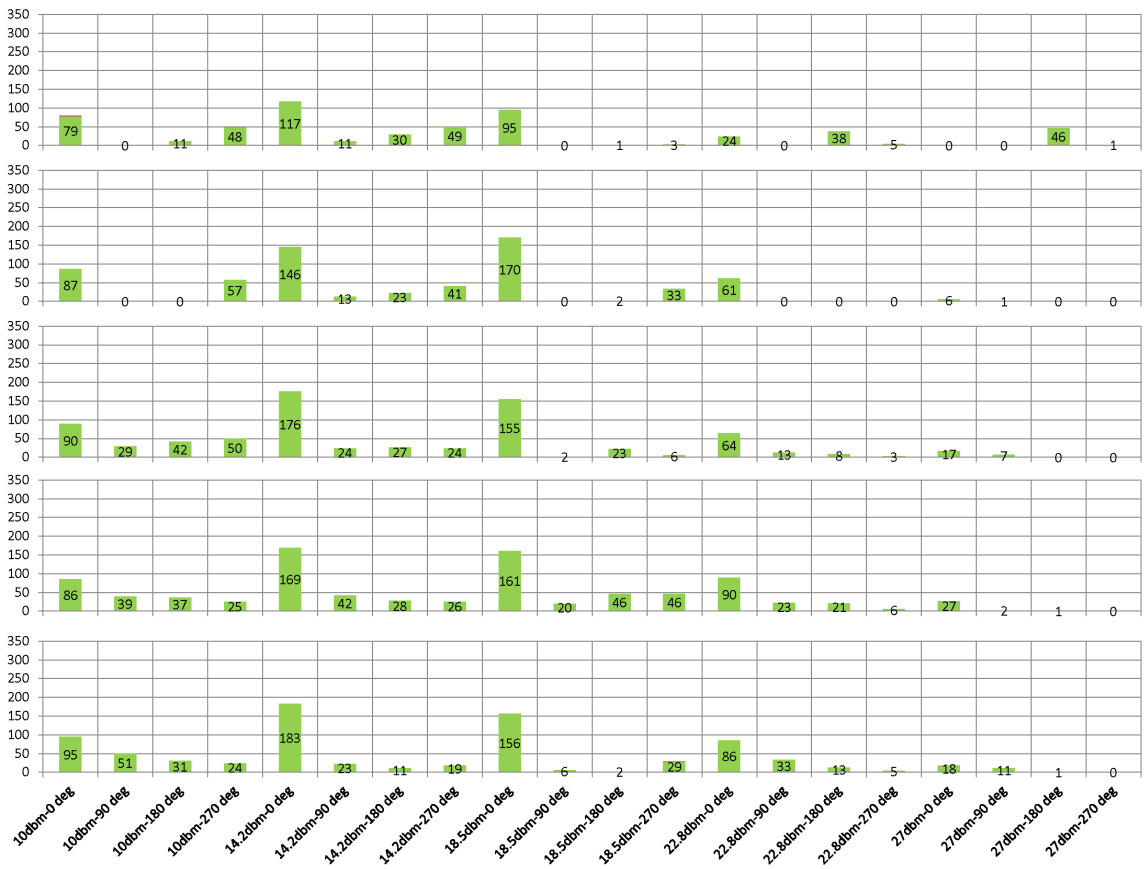

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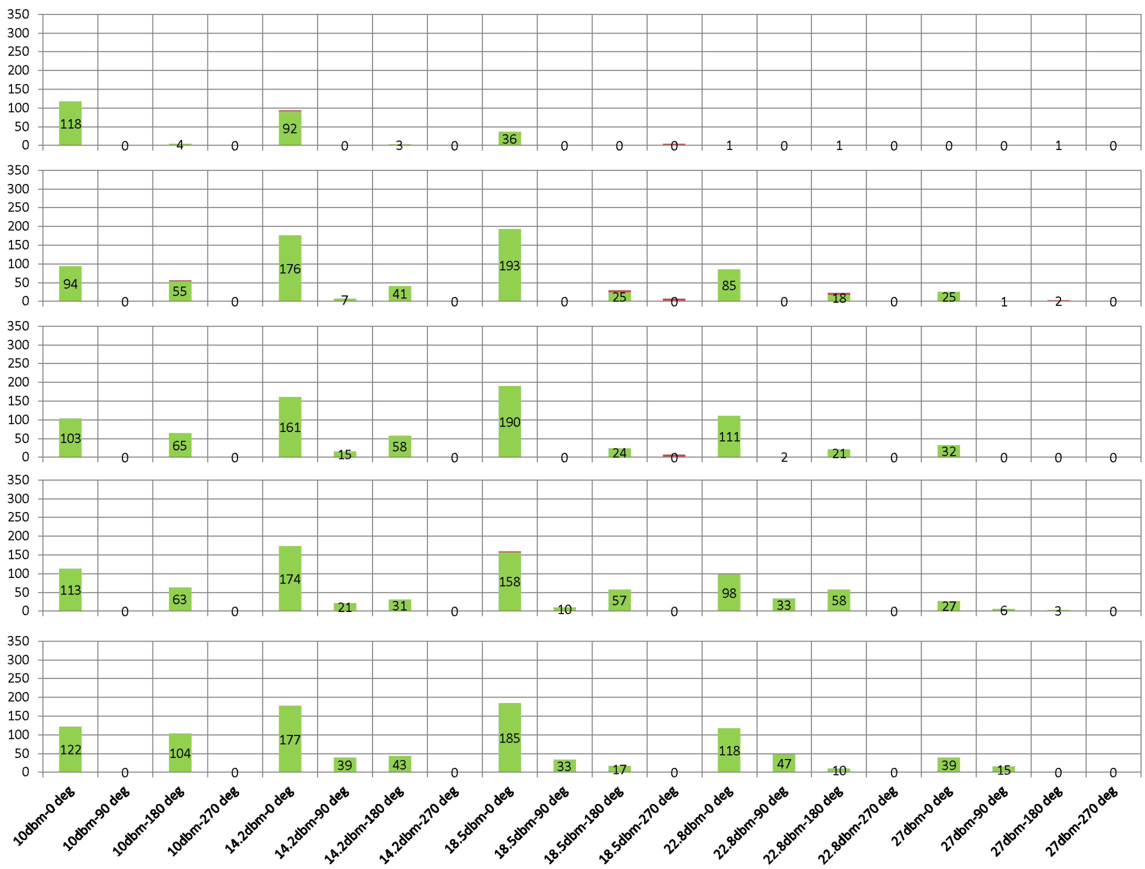

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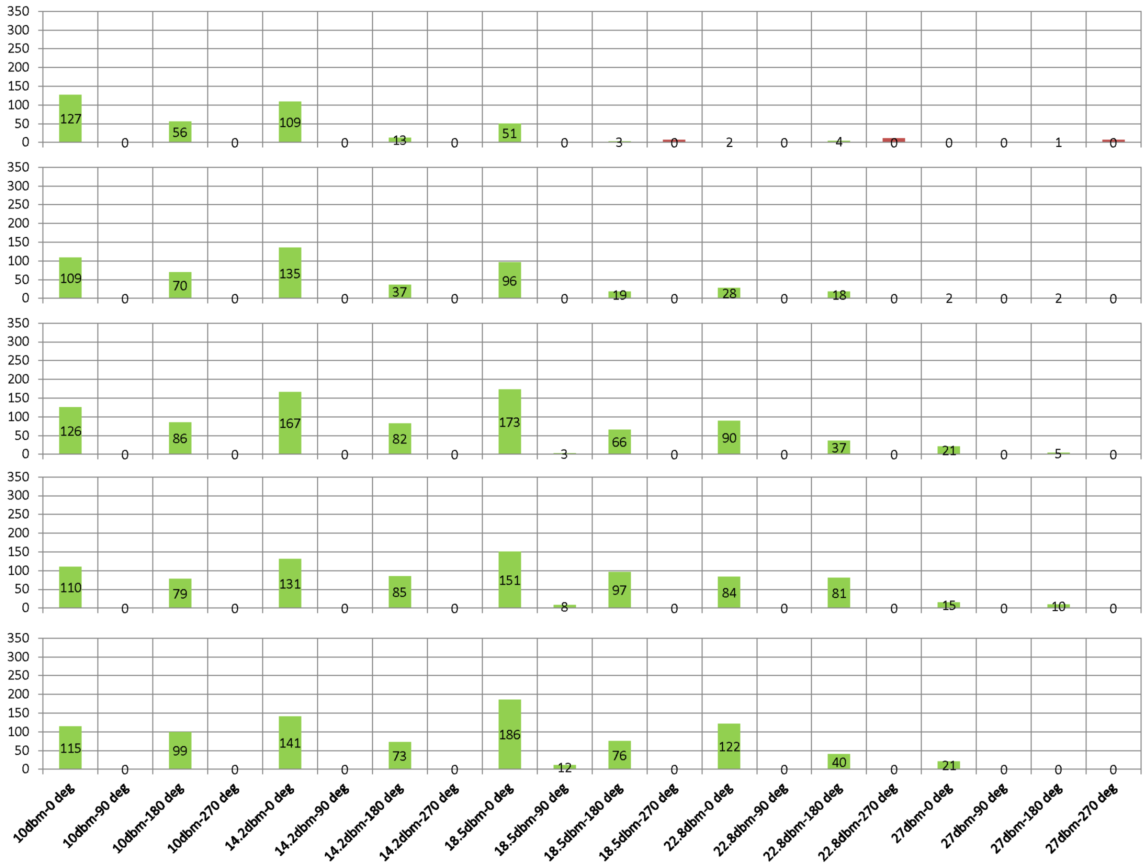

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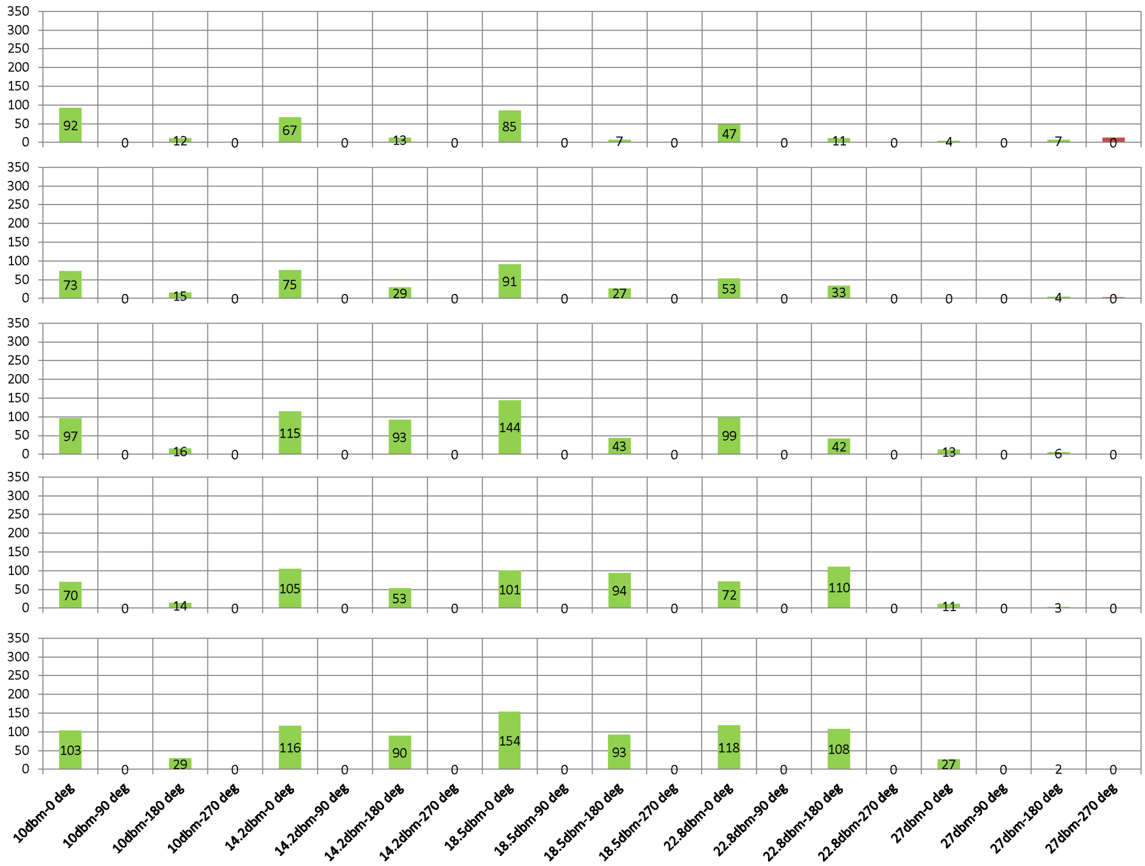
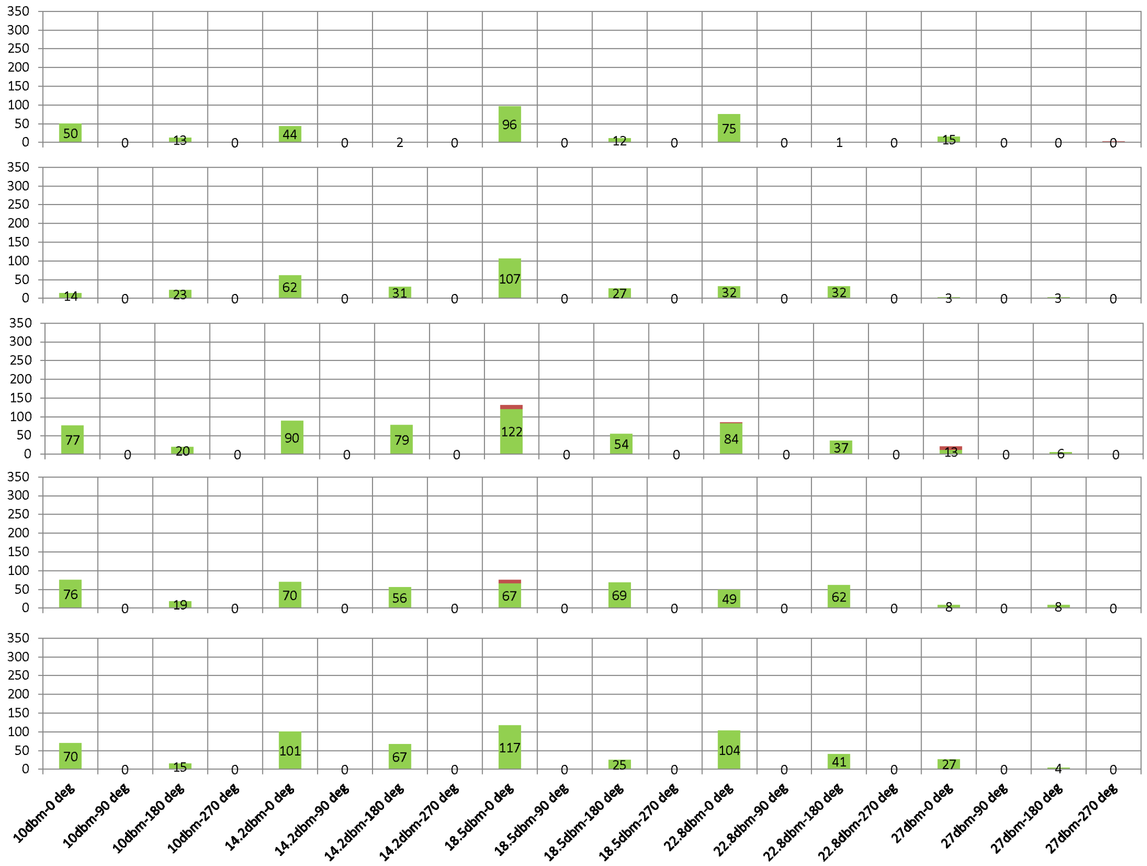


9Tags AirGap20mm



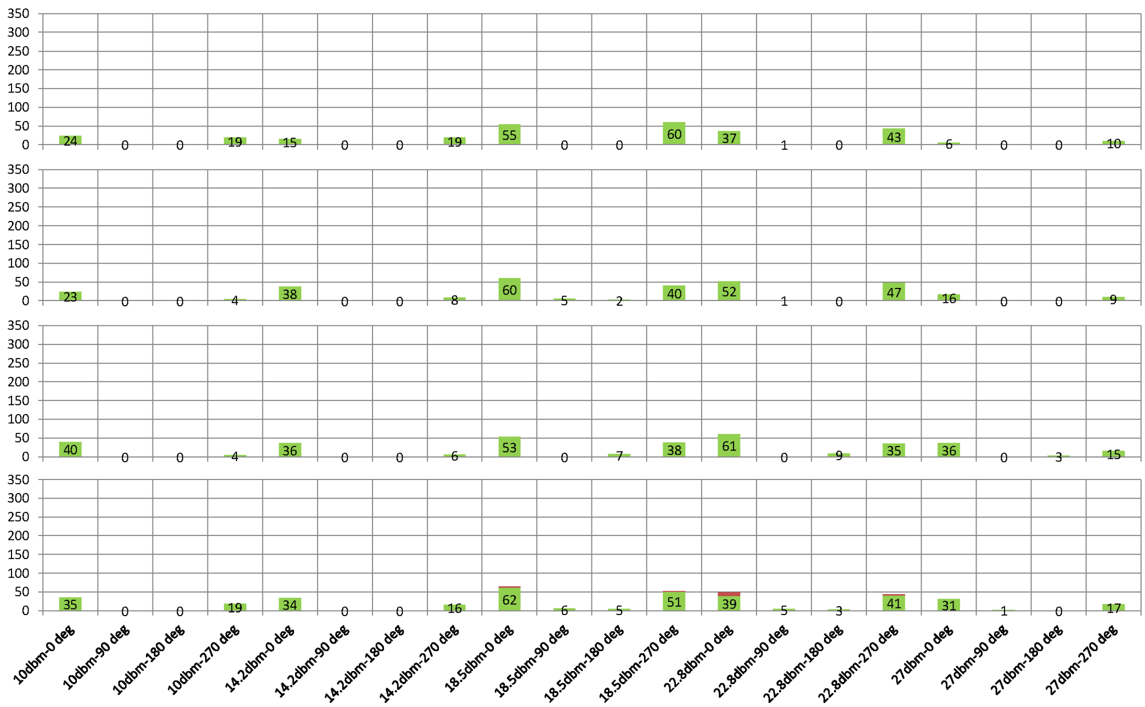
9Tags AirGap25mm

B

Alien "Bio" Pattern Charts (Advanced Tests)

Factors and their levels: 5 power levels, 2 air gaps, 2 tag orientations, 1 tag number and 4 tag spacings.

5Tags AirGap5mm



5Tags AirGap10mm

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Vita

Yi Zhou was born in Anshan, China. He received a bachelor of science degree in applied engineering and management from Eastern Kentucky University in 2012, and a bachelor of science degree in electrical engineering from Liaoning University of Technology in 2011.