EVALUATION OF PASSIVE UHF RADIO FREQUENCY IDENTIFICATION TRANSPONDER PERFORMANCE USING DIFFERENT PACKAGING MATERIALS

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ABSTRACT

EVALUATION OF PASSIVE UHF RADIO FREQUENCY IDENTIFICATION TRANSPONDER PERFORMANCE USING DIFFERENT PACKAGING MATERIALS

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Radio Frequency Identification (RFID) technology plays an important role in supply chains by providing possibilities of improved security, efficiency and visibility of item tracking and management. In order to achieve the expected functionality of RFID technology, it is critical to understand factors that influence RFID transponder performance.

The objective of this research was to determine the effect of packaging materials on the performance of passive UHF RFID transponders in a simulated manufacturing environment. Three general-purpose passive transponders were tested when they were attached to four packaging materials. Performance parameters of read range, which is the maximum distance the transponder can be detected by the interrogator, and orientation read rate, which is the percentage of orientations in which the transponder was read, out of the randomly chosen set of orientations evaluated based on rotation, tilt, or incline of the transponder within three-dimensional space, were quantified and analyzed. The results showed that packaging materials had a consistent effect on read range and orientation read rate across different antenna designs of passive dipole antenna transponders. Transponder antenna designs had a significant effect on read range and orientation read rate. Interrogator antenna polarizations had a significant effect on transponder read range but did not have a consistent effect on transponder orientation read rate.

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KEY TO ABBREVIATIONS

AIC	Akaike Information Criterion
AIDC	Automatic Identification and Data Capture
AIRTC	Auto-Identification Research and Testing Center
AM-EAS	Acousto-magnetic Electronic Article Surveillance
ASTM	American Society for Testing and Materials
CANR	College of Agriculture & Natural Resources
CP	Circularly Polarized
CW	Continuous Wave
dBi	decibel isotropic
dBm	decibel milliwatts
DC	Distribution Center
DoD	Department of Defense
DSB-ASK	Double-sideband Amplitude Shift Keying
EIRP	Effective Isotropic Radiated Power
EM	Electromagnetic
EPC	Electronic Product Code
ERP	Effective Radiated Power

ETSI	European Telecommunications Standards Institute
FCC	Federal Communications Commission
HF	High Frequency
IC	Integrated Circuit
IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
IT	Information Technology
LF	Low Frequency
LP	Linearly Polarized
M1	C-flute uncoated corrugataed paperboard
M2	Polyethylene film
M3	Polyethylene corrugated board
M4	PET/Al/polyethylene film
MF	Medium Frequency
MSU	Michigan State University
NPV	Net Present Value
OCR	Optical Character Recognition
O-RDRate	Orientation Read Rate
PR-ASK	Pulse-interval Amplitude Shift Keying

RCS	Radar Cross Section
RF	Radio Frequency
RF-EAS	Radio Frequency Electronic Article Surveillance
RFID	Radio Frequency Identification
RH	Relative Humidity
RSSImx	Maximum Response Signal Strength Indicator
SAP	Superabsorbent Polymer
SAS	Statistical Analysis System
SCC	Statistical Consulting Center
SHF	Super High Frequency
SSB-ASK	Single-sideband Amplitude Shifting Keying
TIPP	Tagged-Item Performance Protocol
TotCnt	Total Count of Reads
UHF	Ultra High Frequency
ΔRCS	Delta Radar Cross Section
3D	Three Dimensional

Chapter 1

Introduction

1.1 Overview

This research topic began with an evaluation of a passive ultra-high frequency (UHF) radio frequency identification (RFID) transponder's three-dimensional read range in a simulated manufacturing environment within the Michigan State University Auto-Identification Research and Testing Center (MSU AIRTC). The MSU AIRTC, directed by Dr. Robb Clarke, focused on research topics related to applications of automatic identification and data capture (AIDC) technology in process control, logistics and transportation, and inventory management, as well as the effects of packaging and products on the performance of AIDC technology [1]–[8]. Results from testing the passive UHF RFID transponder's three-dimensional read range led to an interest in evaluating passive UHF RFID transponders' performance while the transponder is attached to different packaging materials.

RFID, as one type of AIDC technology, is a means to identify an object using radio frequency (RF) transmission. RFID consists of an interrogator, transponder and host computer installed with middleware. The interrogator receives a request for information from the host computer through the middleware, and sends the request to the transponder within its interrogation zone via RF signals. The transponder processes the request and sends a response containing the requested information to the interrogator. The interrogator then sends the collected information to the host computer [9]. RFID technology acquires an item's information from a relatively far distance compared to the short distance possible with the commonly known barcode technology. With RFID, the communication can be achieved even without a line-of-sight to the object. RFID technology enables visibility, efficiency and security of automatic data collection processes within supply chains [9].

There are many factors that influence the performance of a UHF RFID system, including the sensitivity of the interrogator and the transponder, the transponder's orientation, interference from the operational environment, a product's packaging materials, a product's material and the operation processes [2], [3]. Many researchers have developed different methodologies to evaluate the performance of RFID transponders from varying approaches: some methodologies required anechoic chambers to conduct tests (e.g. [10], [11]); some focused on transponder performance tests in real world environments (e.g. [12], [13]); and some explored the effect of packaging materials and product contents (e.g. [1], [2]), environmental noise [3], and practical conditions of operation processes (e.g. [7], [8]) on the performance of a RFID transponder. Although the effects of packaging materials on transponder performance have been somewhat documented [2], [8], [14], [15], there are still many questions in this area that are worth exploring.

This thesis focuses on the evaluation of RFID transponder performance with different packaging materials in a simulated manufacturing environment. The transponder performance was quantified and analyzed by means of read range and orientation read rate. In this research, the read range was interpreted as the maximum distance from which a transponder can be read by the interrogator. A new term named orientation read rate was introduced and defined as the percentage of orientations in which the transponder was read, out of the randomly chosen set of orientations evaluated based on rotation, tilt, or incline of the transponder within three-dimensional space. This research provides an unbiased testing methodology to measure RFID transponders' read range and orientation read rate. It thus contributes insights into the packaging materials' effects on RFID transponder performance.

1.2 Research Goals

The primarily goal of this research was to investigate the effect of packaging materials on the performance of passive UHF RFID transponders in a simulated manufacturing environment. To fulfill this goal, three general-purpose passive UHF RFID transponders, courtesy of Impinj, were evaluated when attached to four commonly used packaging materials, including uncoated corrugated paperboard, polyethylene film, polyethylene corrugated board and PET/aluminum/polyethylene laminated film. The three transponders were all dipole antenna transponders. These evaluations were conducted in a machinery lab at the MSU School of Packaging. A testing methodology consisting of two sub-tests was developed based on the results of pilot testing. In the first test, the transponder's read range at given orientations was measured. In the second test, the transponder's orientation read rate at a given distance from the interrogator was evaluated. Both linearly polarized and circularly polarized interrogator antennae were used in each test. Statistical analysis for each test was conducted using Statistical Analysis System (SAS) software.

The hypotheses of this study are as below:

- Hypothesis 1: Packaging materials will NOT have a consistent effect on read range across different antenna designs of general-purpose dipole antenna transponders.
- Hypothesis 2: Packaging materials will NOT have a consistent effect on orientation read rate across different antenna designs of general-purpose dipole antenna transponders.

1.3 Thesis Summary

Chapter 2, *Literature Review*, presents an RFID primer, application examples of RFID technology in supply chains, and principles of RFID communication, as well as relevant research about evaluation of RFID system performance and development of methodologies for evaluation. Chapter 3, *Methodology*, describes the testing equipment, specimen preparation, and testing location. Then the procedures for each sub-test contained in the methodology are presented. Chapter 4, *Results*, presents the data collected during this research. Chapter 5, *Analysis and Discussion*, explains the statistical model for each test and discusses the results. Chapter 6, *Conclusions and Future Research*, summarizes the new learned results, proposes avenues for future study, and discusses the limitations of this work.

Chapter 2

Literature Review

2.1 Automatic Identification and Data Capture Technologies

AIDC technologies come in a wide variety of functionalities, all targeted towards automatically identifying a physical object with associated data contained within an information-technology (IT) system [16]. Barcodes, optical character recognition (OCR), biometric procedures (e.g. voice identification), smart cards, and RFID are some of the common forms of AIDC [17]. AIDC technologies are often combined together in practical applications to provide a more reliable base of information flow [2]. To date, among all the methods of AIDC, by far the most commonly used one is barcode technology---- a machine-decipherable bar code on an object, scanned using an optical laser scanner to extract identifying information [18].

RFID is the use of radio communication to identify a physical object [9]. Compared to barcodes, RFID operates at a much greater distance with higher rates, can carry more information than just the ID, and may also identify an object without line-of-sight [19]. In addition, it provides faster processing, increased security and accuracy of information, as well as better anti-counterfeiting function with minimal or no manual intervention [16], [20].

2.2 History of RFID

RFID has existed for more than half a century, but its widespread application has had to wait for inexpensive integrated circuits to enable small, low-cost transponders. Since the mid-1990's, the application of RFID in supply chain management had drawn a lot of attention. In 1999, MIT launched the Auto-ID Center, supported by various parties in the industry. After research on various alternative approaches, the Auto-ID Center concluded that 900-MHz regime is the best operating frequencies for RFID transponders in consideration of cost, read range and capability [18].

In 2003, EPCglobal Inc. was founded as an independent and non-profit organization to develop industry-driven standards to support the adoption and implementation of RFID and the Electronic Product Code (EPC, a code system) technology. In 2004, the Generation 2 protocol was developed by EPCglobal and in 2006 was endorsed by the International Organazation for Standardization (ISO) as ISO 18000-6 [18].

At the same period of time, Wal-Mart and the US Department of Defense (DoD) began to mandate the use of RFID to track shipping cases, containers and pallets. By 2010, it was fair to conclude that RFID technology is an appropriate data carrier technology for tracking goods [18].

2.3 Components of RFID

In a basic backscatter RFID system, three fundamental components are required for data to travel: transponder, interrogator with antenna, and host computer with middleware.

2.3.1 Transponder

A transponder, also called a tag, generally consists of a chip, which is an integrated circuit (IC) made of silicon, an antenna that is made of metal or metal-based material, and a substrate that houses the chip and the antenna. A transponder is programmed with information that can identify itself uniquely [9]. Tags/transponders fall into three broad categories based on power source: passive tags, active tags, and semi-passive tags.

Passive tags have no independent source of electrical power. They depend on the power transmitted from an interrogator to drive the circuit and modify their interaction with the transmitted power in order to send information to the interrogator. Depending on the operation frequency, passive tags can be read up to 20 meters (about 65 feet). They are inexpensive, with a cost of a few cents to a dollar, and can be used for tracking consumer goods [18]. Passive tags dominate supply chains for cost reasons [1].

Active tags have a local power source such as a battery, as well as a conventional transmitter. They are able to initiate communication by sending their own signal. Active tags have a much greater operational distance compared to passive tags, and are priced from 20 to over 100 dollars. They are used for expensive objects with long useful lifetimes [18].

Semi-passive tags have a local battery but only for turning on the tag circuit. Similar to the passive tags, semi-passive tags require energy transmitted from an interrogator for the tag-to-reader communication. They can achieve ranges as much as 100 meters (up to 320 feet), and are often used in tracking high-value reusable assets such as airplane parts. A semi-passive tag usually costs about 20 to 30 US dollars [18].

2.3.2 Interrogator

An interrogator, also called a reader, is the RFID component that transmits RF signals to the tags, receives information from the tags, and sends information to a host system. It is composed of an RF module, a signal processing and control unit, and a coupling element, which is essentially an antenna. Interrogators can be categorized by the location of use as fixed-mount interrogators, handheld interrogators, and vehicle-mount interrogators [9].

Antennas are often classified by their polarization----either linearly polarized (LP) antennas or circularly polarized (CP) antennas. From the basic principles of the oscillation and propagation of electromagnetic (EM) fields, one can know that the electric field direction is perpendicular to the wave propagation direction. If the direction of the electric field is constant in time, the wave is linearly polarized, and if the electric field rotates around the propagation direction and keeps constant magnitude, the wave is circularly polarized [18]. LP antennas can be further classified into two kinds: horizontally polarized and vertically polarized, depending on the plane on which the wave travels relative to the earth [9].

In theory, if the LP transmitting antenna that generates a horizontal electric field, and a receiving antenna are vertically polarized, the power transfer will degrade considerably. However, with the same LP transmitting antenna, a CP receiving antenna will receive some radiation no matter what angle the receiving antenna inclines within the plane perpendicular to the EM wave propagation direction [9], [18], but in every case only half the transmitted power can be received [18]. The reader and the tag antennas should have the same polarization in order to achieve the maximum power transfer efficiency [9].

2.3.3 Host Computer and Middleware

The host computer installed with middleware provides two functions: 1) to send requests and receive responses from the interrogator, and 2) to filter, store and forward the received data to other systems [9], [21].

2.4 RFID Standards, Regulations and Protocols

2.4.1 RFID Standard Bodies

RFID standards help to ensure products from different manufacturers operate together and provide guidelines for manufacturers to develop complementary products [22]. There are four main types of RFID standards: technology standards, data standards, conformance standards, and application standards [23].

ISO and EPCglobal are two main international RFID standards bodies. ISO set up a joint committee with the International Electrotechnical Commission (IEC) to look at standardization for RFID technology since 1996 [24], and EPCglobal was founded in 2003 [18], as mentioned previously in this chapter.

In the US, the organization that develops and issues RFID standards is the Federal Communication Commission (FCC). In Europe, it is the European Telecommunications Standards Institute (ETSI) [22].

2.4.2 Frequency Allocation

The frequency used by an RFID system determines many of the characteristics of the system [25]. Regulatory bodies allocate different frequency bands as follows, and RFID systems are available in all the radio frequency ranges [9], [25]:

- 125 -134.2 kHz and 140-148.5 kHz, Low Frequency (LF)
- 6.765-6.795 MHz, Medium Frequency (MF)
- 13.56 MHz, High Frequency (HF)
- 433 MHz, UHF
- 860 -960 MHz, UHF
- 2.45 GHz, Super High Frequency (SHF).

LF is often used for vehicle identification. HF is typically used for contactless payment, access control, and electronic ticketing. UHF is the only spectral region that does not have uniformly allocated frequency bands around the world. Common use of UHF includes container tracking and asset management. SHF is usually used by an active system for long range tracking [25]. Generally speaking, higher frequency systems provide a larger read range but less tolerance to interference [2]. Table 1 shows an overview of UHF regulations for passive RFID systems within the 860 to 960 MHz band in several countries and regions, along with the maximum power allowed [26]. The Tags discussed hereinafter refer to passive UHF RFID tags if not specified.

In Table 1, the maximum power was expressed as EIRP (equivalent isotropic radiated power) or ERP (effective radiated power). EIRP and ERP are measured by different methods, and approximately, 2 Watts ERP is equal to 3.2 Watts EIRP [26].

Table 1 UHF Regulations for Passive RFID Within the 860 to 960 MHz Band in Different Countries and Regions

Country	Frequency in MHz	Maximum Power
Brazil	902-907.5	4 W EIRP
	915-928	4 W EIRP
Canada	902-928	4 W EIRP
China	920.5-924.5	2 W ERP
Europe	865.6-867.6	2 W ERP
India	865-867	4 W ERP
Japan	916.7-920.9	4 W EIRP
	916.7-923.5	0.5 W EIRP
Korea	917-920.8	4 W EIRP
	917-923.5	200 mW EIRP
Mexico	902-928	4 W EIRP
South Africa	865-867.6	2 W ERP
	915.4-919	4 W EIRP
	919.2-921	4 W EIRP
United States	902-928	4 W EIRP

2.4.3 RFID Protocols

Protocols are of importance for the communication of RFID systems. They define the physical layer and the tag-identification layer of the communication between RFID components [27]. For passive RFID systems which operate at 860 - 960 MHz, the most common and globally accepted protocol is the *EPC™ Radio Frequency Identity Protocols, Class-1 Generation-2 UHF RFID Protocol for Communications at 860 MHz – 960 MHz.* It is often referred to as the Gen 2 protocol.

In a passive RFID system compliant with the Gen 2 protocol, the reader sends a modulated RF signal that contains information to one or more tags. The tag is powered up by this modulated RF signal. The reader receives a response from the tag by transmitting a continuous-wave (CW)

RF signal that does not contain any information to the tag while listening for a backscattered reply. The tag responds by backscatter modulating the amplitude and/or phase of the RF signal. The modulation methods used in the Gen 2 compliant systems include double-sideband amplitude shift keying (DSB-ASK), single-sideband amplitude shift keying (SSB-ASK), and phase-reversal amplitude shift keying (PR-ASK) [27]. In addition to the Gen 2 protocol, EPCglobal also issued documents about conformance requirements and interoperability test systems for certifying UHF RFID devices' compliance to the Gen 2 protocol [28], [29].

2.4.4 The Electronic Product Code

The Electronic Product Code (EPC) is syntax for unique identifiers assigned to any entity that is identifiable in business processes and applications [30]. RFID is a main carrier technology for the use of EPCs [31]. When used with RFID tags, EPCs are encoded in binary forms that carry information within RF signals. By accessing the database, EPCs can be represented in text form and are suitable for data sharing among enterprise information systems [30].

2.5 Applications of RFID

The use of RFID in supply chain covers a large part of RFID applications. RFID in the supply chain delivers better security, increased efficiency and visibility, increased process and data accuracy, better counterfeit detection, and easier product recall. As a result, members of the supply chain can potentially benefit from the implementation of RFID systems [20]. In this section, examples of RFID applications in the transport and logistics industry, as well as in the retail store environment, will be discussed, followed by a successful RFID application case.

2.5.1 RFID in the Transport and Logistics Industry

A cargo consists of various layers: item level (layer 0), package level (layer 1), case level (layer 2), pallet level (layer 3), container level (layer 4), and vehicle level (layer 5). Shippers will focus more on layers 0, 1 and 2, and warehouse operators will pay more attention to layer 3. Port terminal operators will focus on layer 4. Different RFID readers and tags should be used for different layers to achieve optimum results. However, for the majority of applications within the logistics industry, passive RFID systems are adequate [32].

For different layers of cargo, tags are read at different points. First, for warehouses and shippers, items and cartons are usually read at the tag commissioning. Pallet tags are read when the cartons have been loaded in the case that the pallet has already been equipped with a tag (e.g., a returnable pallet embedded with RFID tags). If the pallet does not have a tag, the tag will be attached and read at the tag commissioning. Pallets are also read at the dock door when being loaded onto the vehicle. Typically, the conveyance is read at gate in and gate out, as well as when it arrives at the dock door. Second, for carriers, tags are read at the loading and unloading process. And last, for terminal operators, tags are read at gate in and gate out. [32].

The use of returnable pallets, or other forms of returnable transport items (e.g. returnable totes and bins) is a trend in the modern supply chain. It offers reduced costs, increased handling efficiency, as well as improved environmental sustainability. Integrating RFID tags into returnable pallets brings benefits from both product logistics and asset management points of view. To assume a minimal level of process security, at least two tags are suggested to be attached on a pallet. For wooden pallets, one tag should be attached on the longer side and one on the shorter side of the pallet. For plastic pallets, it is recommended that the two tags be placed on either pair of the diagonal corners [33].

Cargo container security and tracking revenues were expected to grow at a compound annual growth rate (CAGR) of 27 percent from 212 million in 2011 dollars to 690 million dollars in 2016 [34]. However, the customs inspection process at international borders, especially in maritime ports, is inefficient, time consuming, costly, and only manually operated [35]. Electronic seals (e-seals) are a solution to increase efficiency, security and visibility, as well as decrease costs of importing and exporting goods. Cargo containers with e-seals can be automatically inspected without opening the container doors, since all the content information can be accessed through reading the e-seal. RFID based e-seals, compared to the e-seals based on other technologies, have been estimated to provide greater Net Present Value (NPV), higher Return On Investment (ROI) and a lower payback period [36].

2.5.2 RFID-based Electronic Article Surveillance (EAS) System in the Retail Store

EAS at retail stores is used for loss prevention and detection to reduce theft including shoplifting. Compared to RF based (RF-EAS) and Acousto-magnetic based (AM-EAS) systems, which are two dominant EAS technologies currently, an RFID based system adds additional benefits by reducing out-of-stock merchandise, automating replenishment, eliminating manual processes and enhancing the consumer buying experience [37], [38].

A typical implementation of an RFID-based EAS system in the retail store environment would be: 1) items are received in the back room, and the EPC number that is encoded on the RFID tag for each item is read at the door and added to the EAS database; 2) when the merchandise is brought to the retail area, the RFID tags can be read at the entry from the back room to the retail area; 3) staff are able to use handheld readers to locate and manage merchandise in the retail area as well as in the back room; 4) at the point of sale, the EPC numbers are removed from the EAS database after purchase, and consumer notification occurs; 5) at the point of exit, the RFID-based EAS system automatically verifies sales and activates alarms if unsold items are detected [39].

2.5.3 Successful Case of Benefiting from RFID in Supply Chain

Levi Strauss & Co. started a pilot test of integrating EPC-enabled RFID technology into operations in its Mexico facilities in 2005. With the initial success of the pilot test, in 2007, the company decided to sequentially implement the EPC-enabled RFID solution in its remaining stores. Highlights of the positive business benefits that Levi Strauss experienced from the integration of EPC/RFID technology are listed below:

- Reduced inventory in stores from a four-month to a two-month supply;
- Improved inventory accuracy and better inventory details;
- Increased sales by 11 percent;
- Reduced lost sales by 40 percent because of reduction in out-of-stock merchandise;
- Increased efficiency in distribution center (DC) and reduced logistics costs;
- Enabled fully automated replenishment management [38].

2.6 Principles of RFID

In order to investigate passive UHF RFID tags' performance, understanding the physics of passive UHF RFID systems is critical. This section will illustrate communication principles of a passive UHF RFID system in free space under ideal condition. The system is compliant to the EPCglobal Gen 2 protocol.

2.6.1 Near Field and Far Field

In an EM field, there is a distance from the antenna that defines the *near field* and the *far field*. Inside this distance, the zone is called the near field, and systems operating in the near field depend on inductive coupling between the reader and tag antennas. Outside of this distance, the EM field separates from the antenna, and propagates into free space as a plane wave. Typically, LF and HF systems operate in the near field, while UHF systems operate in both the near field and far field, depending on the distance between the transponder and the interrogator [40].

For small antennas in which the maximum dimension D of the radiating structure is considerable smaller than the wavelength λ ($D \ll \lambda$), the approximate distance where the far field starts is

$$r = \frac{\lambda}{2\pi} \tag{1}$$

where r is the distance from the antenna. For any antenna, the zone inside $r = \frac{\lambda}{2\pi}$ can be defined as the *reactive near field*, where the electric field E and magnetic field H are not orthogonal. In the case when $D > \lambda$, the far field is estimated to start from

$$r = \frac{2D^2}{\lambda} \tag{2}$$

The region between a reactive near field and a far field is called the *radiating near field,* as given below [40]:

$$\frac{\lambda}{2\pi} < r < \frac{2D^2}{\lambda} \tag{3}$$

The signal power produced by an antenna within the near field region, according to the solution of Maxwell's equations, drops off with distance $1/r^3$ [15].

2.6.2 Forward Link Communication

The forward link in an RFID system is defined as the signaling from the reader to the tag [41]. Assuming it has an isotopic antenna that radiates power in all directions uniformly, the power flux density S, at a distance r from the antenna can be expressed as follows:

$$S = \frac{P_{R,TX}}{4\pi r^2} \tag{4}$$

where $P_{R,TX}$ is the power produced by the reader's transmitting antenna. However, for an antenna in the real world, the power flux density is directional with a gain of G_R, so the actual power flux density, which is called the directional power flux density, transmitted by a reader antenna is [40]

$$S_D = \frac{P_{R,TX}}{4\pi r^2} \cdot G_R \tag{5}$$

Then the amount of power received by a tag's receiving antenna when the tag is placed at a distance r from the reader's transmitting antenna can be expressed as

$$P_{T,RX} = S \cdot A_e = \frac{P_{R,TX} \cdot G_R}{4\pi r^2} \cdot \frac{\lambda^2}{4\pi} \cdot G_T = P_{R,TX} G_R G_T \left(\frac{\lambda}{4\pi r}\right)^2 \tag{6}$$

where the A_e is the effective area of the tag antenna given by an isotropic antenna's aperture multiplied by the gain of the actual tag's antenna G_T [42],

$$A_e = \frac{\lambda^2}{4\pi} \cdot G_T \tag{7}$$

When the $P_{T,RX}$ exceeds the minimum required power ($P_{Turn-on}$) for the tag IC to be switched on, the tag is activated. Thus, the maximum distance to activate the tag in the forward link r_{max-F} can be calculated by substituting $P_{T,RX}$ with $P_{Turn-on}$ in equation 6 and is expressed as

$$r_{max-F} = \frac{\lambda}{4\pi}\sqrt{\frac{P_{R,TX} G_R G_T}{P_{Turn-on}}} \tag{8}$$

2.6.3 Reverse Link Communication

The reverse link in an RFID system is defined as the signaling from the tag to the reader [41]. From the tag design's point of view, the factors that affect the tag's performance include: 1) the impedance match between the tag antenna and the chip [43]; 2) the minimum required power for the IC to be turned on, i.e. $P_{Turn-on}$; 2) the capability of the tag antenna to collect wireless energy, i.e., the tag's energy harvesting ability; and 4) the differential radar cross section (ΔRCS) of the tag that determines the clarity of the tag's backscattered signal [44].

Typically, $P_{Turn-on}$ of a tag is -10 dBm to -15 dBm [44]. When the tag is turned on by the reader's transmitting signal, the tag sends data back by modulating its reflection coefficient, then backscattering the signal containing information to the reader [41]. A tag's power reflection coefficient $|s|^2$ is interpreted as

$$|s|^2 = \left|\frac{Z_A - Z_C}{Z_A + Z_C}\right|^2 \tag{9}$$

where the $Z_A = R_A + jX_A$ is the complex antenna impedance, and $Z_C = R_C + jX_C$ is the complex IC impedance [45], and s is defined as the power wave reflection coefficient [43]. When modulating the backscattered signal, the tag switches its input impedance between two states. In order to have a clearly modulated backscatter, usually one state is high impedance and the other one is low [42].

Antenna impedance is typically made to match the high impedance state of the chip for maximizing the power transfer efficiency [42]. The power transfer efficiency, or the power transfer coefficient, can be expressed in IC and antenna impedance as

$$\tau = \frac{4R_A R_C}{|Z_A + Z_C|^2} \tag{10}$$

If $R_A = R_C$, and $Z_A = Z_C$, then τ=1 and the maximum power is transferred. The sum of the power transfer coefficient and the power reflection coefficient is 1 [43].

$$\tau + |s|^2 = 1 \tag{11}$$

The radar cross section (RCS) is defined as *"a measure of the ratio of backscatter power per steradian in the direction of the radar (from the target) to the power density that is intercepted by the target"* [46]. Each of the tag's impedance states represents an RCS [42], and the difference between the two RCSs, i.e. ΔRCS, identifies the quality of the ASK modulation of the tag [44]. The ΔRCS can be expressed as [44],

$$\Delta\sigma = \frac{{G_T}^2 \lambda^2}{16\pi} |s_1 - s_2| \tag{12}$$

where s_1 and s_2 are the power wave reflection coefficients of the two impedance states, and G_T is the tag antenna gain.

By understanding the factors of the tag, the amount of power the reader antenna receives $P_{R,RX}$ can be calculated as

$$P_{R,RX} = P_{T,RX} \cdot (1 - |s|^2) G_T G_R \left(\frac{\lambda}{4\pi r}\right)^2 \tag{13}$$

Substituting equation (6) in equation (13), then $P_{R,RX}$ is

$$P_{R,RX} = P_{R,TX} \cdot (1 - |s|^2) {G_T}^2 {G_R}^2 \left(\frac{\lambda}{4\pi r}\right)^4 \tag{14}$$

Finally, by defining the minimum signal power for demodulation at the reader as P_{R-min}, the maximum range in the reverse link r_{max-R} can be obtained [18]:

$$r_{max-R} = \frac{\lambda}{4\pi} \sqrt[4]{\frac{P_{R,TX} {G_R}^2 {G_T}^2 (1 - |s|^2)}{P_{R-min}}} \tag{15}$$

Generally, the read range of a passive UHF RFID system depends on the forward link, as the reader sensitivity is much higher than the tag [47], i.e., $P_{R-min} \ll P_{Turn-on}$.

2.7 Transponder Performance in the Real World

An ideal RFID system, in which the reader and tag's performance perfectly and strictly follows its designed functionality, has the following characteristics:

1) Orientation of tags does not affect the tag performance;
2) The object to which the tag is attached does not affect the tag performance;
3) The environment in which the system is operated does not affect tag performance;
4) The interrogation zone produced by the reader has a clear boundary;
5) All and only the tags in the reader's interrogation zone can be read;
6) Relative motion between the tag and the reader does not affect the tag performance;
7) The system performance is not affected by the presence of multiple readers and/or multiple tags [19].

However, an ideal RFID system is unrealizable. The performance of a tag while in a reader's interrogation zone can be influenced by the object the tag is attached to, the orientation and relative motion of the tag, as well as the environmental interference.

2.7.1 Product and Packaging Materials

The packaging and the product inside of the packaging have a significant effect on the performance of RFID systems [1], [2], [8]. When a RFID tag is attached to a packaged product, the tag's readability may degrade considerably, depending on what materials the packaging and the product are made of. There are five main categories of packaging materials: wood, paper, plastic, glass, and metal [15]. Materials can be also classified into three categories: dielectric, conductor, and magnetic materials [43]. Since magnetic materials are relatively rare, and barely used for packaging, they will not be discussed in this section.

Dielectric materials can be characterized through two properties: the dielectric constant, also called the permittivity, and the loss tangent [43]. The permittivity ε is a complex, frequency-dependent quantity expressed as

$$\varepsilon = \varepsilon_1 \pm j\varepsilon_2 \tag{16}$$

The loss tangent is the ratio of the imaginary part Im(ε) to the real part Re(ε), and is usually written as tan δ [15]. Dielectric materials have a tan δ less than 0.01, and conductors have tan δ larger than 100. Materials that have a tan δ between 0.01 and 100 are defined as semi-conductors [48].

Dielectric materials are basically electrical insulators. They resist the electric field when in the presence of an electric field. The permittivity of a material can be interpreted as the amount of counteraction the material has to the electric field. The relative permittivity ε_r is often used to characterize a material. ε_r of a material is defined as $\varepsilon/\varepsilon_0$, where ε is the material's permittivity and ε_0 is the permittivity of a vacuum. When a wave travels in a dielectric material with relative permittivity ε_r, the velocity of the propagating wave is

$$\mathrm{v} = \frac{c}{\sqrt{\varepsilon_r}} \tag{17}$$

where c is the speed of light in a vacuum. The wave slows down in the material, and its wavelength decreases by a factor of $1/\sqrt{\varepsilon_r}$ [43].

If an RFID tag is completely immersed in a dielectric material that has a relative permittivity ε_r, the tag antenna is larger by a factor of $\sqrt{\varepsilon_r}$, compared to the wavelength in the material, and the resonant frequency of the tag antenna will be decreased by a factor of $1/\sqrt{\varepsilon_r}$. Changes of the resonant frequency normally result in a considerable impedance mismatch between the tag antenna and IC, therefore influencing the tag's performance [43]. The interference that affects a tag's performance by changing its impedance is called *detuning* [47].

In reality, RFID tags are typically on some objects rather than immersed in materials. Thus, the tag can be regarded as partially surrounded by the object and partially by the air, if the object is relatively thick compare to the size of the antenna, then the effective relative permittivity can be estimated as

$$\sqrt{\varepsilon_{eff}} \approx \frac{\varepsilon_r + \varepsilon_{air}}{2} \tag{18}$$

Although this estimation may be not appropriate for substances with large ε_r, it works well for small ε_r [43]. The ε_r of commonly used packaging materials, such as polypropylene, polyethylene and polyethyleneterephthalate (PET), is relatively small (see Table 2). Paper and corrugated board also have small ε_r when they are dry, but the ε_r will change if moisture is absorbed.

The loss tangent tan δ determines how much energy is lost to the material per wavelength. The larger the loss tangent of a material, the poorer the wave propagates in the material, and the more energy is converted into heat [43]. Some of the common materials' relative dielectric constants and loss tangents are listed in Table 2 [49], [50]. It should be mentioned that the dielectric property of many substance changes not only with frequency and temperature, it changes even with specimens made from the same material but with different manufacturing processes, different amounts of oxidation, and many other factors. Thus, the numbers listed in Table 2 only serve as an indication, and are not precise data that are repeatable for a particular specimen [49].

The dielectric property of water, specifically, when tested at 20 °C with frequency of 1 MHz and 3 GHz, shows a relative permittivity about 80 at both frequencies, and a loss tangent 0.04 at 1 MHz, while the loss tangent is 0.157 at 3 GHz [50]. The challenge of RFID around water comes from the resulting change in the antenna impedance, and the modification to the radiation pattern, as the antenna tends to radiate more energy into the water [43].

Table 2 Dielectric Properties of Materials Tested at Certain Frequencies and Temperatures

Material	**Temperature °C**	**Frequency f**	**εr**	**10^4× tan δ**
Glass (borosilicate)	20	1 kHz /1 MHz	5.3	50 /40
Paper (kraft, tissue, unimpregnated, dry)	20/90	1 kHz	1.8~3.0	10~35
Wood (balsa, 0% water content)	20	50 Hz/3 GHz	1.4 /1.2	40 /140
Wood (scots pine, 15% content)	20	1 MHz/100 MHz	8.2 /7.3	590 /940
Polyethylene	20	50 Hz/1 GHz	2.3	2 /3
Polypropylene	20	50 Hz/1 MHz	2.2	5
Polystyrene	20	50 Hz/1 GHz	2.6	2 /5
Polyethyleneterephthalate (PET)	20	50 Hz/100 MHz	3.2 /2.9	20 /150
Polyvinylchloride (PVC)	20	50 Hz/100 MHz	3.2 /2.8	200 /100
Polytetrafluoroethylene (PFTE, Teflon)	20	50 Hz/3 GHz	2.1	2
Water	20	1 MHz/3 GHz	80	0.04/0.157

Metals are RF reflective materials and result in distortions of the field homogeneity [47]. If a passive tag is directly attached to a metal, it is expected to have poor performance. The easiest solution for reading tags on the metal is to try to provide some spacing from the metal objects [43], usually by an offset of 3 mm to 5 mm from the material surface [15]. However, this solution still performs poorly [43]. Tags that are specifically made for metals are typically based on microstrip antennas. Compared to common passive tags that are usually based on dipole antennas, microstrip antenna tags tend to be relatively expensive [43].

2.7.2 Research on the Effect of Packaging and Product on Transponder Performance

Although the effect of materials on RFID systems is already complicated, it becomes more complicated when taking a packaging/product system into account. The materials used for different layers of packaging, the compounds of the packaged product, the water content and water forms of the product, the operating processes of the packaging/product system may all affect the performance of the RFID system [15]. While the effects of packaging and product on the RFID are still not completely known [15], many researchers have made efforts to investigate the effects:

Tazelaar evaluated the effect of tag orientation and package content on the readability of an RFID system and concluded that orientation and product type have a significant effect on tag readability. In Tazelaar's research, RFID tags were attached to empty cases and cases that were filled with foams, empty PET bottles, rice or water bottles. 48 of the tagged cases with the same contents were stacked onto a pallet with the RFID tags facing in a certain orientation. The tags were then read by running the pallets through a simulated portal installed with reader antennas. 100% of the tags were read in experiments using empty cases, foam-in-place filled cases, and cases filled with empty PET bottles while the tags were facing outward, forward, and upward. For cases filled with rice and with water bottles, certain orientations of the tags resulted in significantly degraded tag performance. In particular, in the test of downward tag orientation using water bottle filled cases, no tags were read at all. In addition, Tazelaar's research showed that case location on the pallet played a role in the tag's performance, but the effect of case location on performance was not consistent across all product types. Thus, in order to maximize the tag's performance for a product/package system, the pallet patterns, and tag orientation and location should all be tested [2].

Falls investigated the effect of conveyor speed, packaging materials, and product on the tag's performance. In Falls' research, the tag on a case of potato chips in plastic tubs and that on a case of chips in a metalized spiral wound fiberboard container were tested to evaluate the effect of the package type; the tag on a case of metal cans, a case of metal bottles and that on a case of metal tins were tested to evaluate the effect of the package shape; and the tag on a case of bottled ketchup and that on a case of bottled motor oil were tested to compare the effect of the product type. Tags were read when the cases were on a conveyor with a speed of 300 feet per minute and of 600 feet per minute to investigate the effect of conveyor speed. Additionally, two generations of tags were used in the research. The results showed that conveyor speed, package type, package shape and product type all had a significant effect on the average amount of tag reads per trial. The two tag types used in the research were found to have a significant effect on the average number of reads per trial for product effect and package shape effect, but did not have a significant effect when testing the package type effect [8].

Onderko evaluated tag's performance on refrigerated and frozen beef loin muscle packages. The result showed that RFID systems in 13.56 MHz frequency range performed well with no loss of data while reading the tag on a package of refrigerated or frozen beef. However, systems operating in the 915 MHz frequency range could read tags on frozen beef packages, but experienced difficulty with the refrigerated beef package [6].

Zhang investigated the influence of water content in products on dielectric properties, antenna radiated power, and tag readability. Hydrated superabsorbent (SAP) polymer was used in Zhang's research to simulate products with water content from 45% to 90%. Permittivity of the hydrated SAP was measured, and then the effect of water content on tag performance was evaluated. The results showed that tags could barely be read when evaluated with the hydrated SAP sample that had water content more than 75%. The conclusion was that product content and packaging operations are important factors to the success of employing RFID system in supply chains [1].

Crawforth investigated the effect of antennae configuration, product and tag type on the tag performance when tagged cases were stretch wrapped on a stretch wrapper. Results of Cawforth's research showed that the antenna configurations with a combination of antennas both on top of the pallet load facing downward and on the side of the pallet load resulted in the greatest read rate of tags, while the configuration of only antennas on the side had a lower read rate, and that of antennas mounted only above the pallet had the worst read rate. No significant difference was found between 1 and 2 antennas, or 3 and 4 antennas. In addition, Cawforth found that empty cases had no effect on the readability of tags, rice filled jars degraded the tag performance, and water bottle filled cases decreased the tag readability considerably. The tag type was not found to have a significant effect on the tag's total reads, but differences were observed with specific combinations of variables [7].

Ukkonen and Sydänheimo developed a testing methodology to measure a passive UHF RFID tag's radiation pattern based on the tag's $P_{\mathrm{Turn-on}}$ and compared a tag's radiation patterns when the tag was attached on a case of six-pack metallic cans to that in free space. Results of the measurements showed that the tag's in-free-space radiation patterns of the E plane and the H plane are both symmetrical and agreed with the expected antenna radiation pattern, while distortions and change in direction were observed on the tag's radiation patterns tested with the case of metallic cans [14].

Last but not least, Suwalak and Phongcharoenpanich found that when a UHF passive tag was attached to an elliptical curved surface, the angles of the curvature of the tag antenna affected the tag performance. The tag performance change was interpreted as the tag's input impedance changed with changing elliptical curved surface's axis dimensions [51]. Yang et.al tested UHF RFID tag performance in various simulated dielectric backgrounds. The results showed that the tag antenna's resonant frequency was proportional to $1/\sqrt{\varepsilon_r}$ when attached on a material with a relative permittivity of ε_r, and the resonant frequency decreased with the increasing thickness and increasing size of the material [52]. Bolton et.al performed a study to test 10 different multisurface tags on three mediums (air, metal, and cardboard) at 6 distances (5 ft, 10 ft, 15 ft, 20 ft, 25 ft, and maximum distance) with four tag orientations (0, 45, 90, and 180 degrees). The results showed that no tag had 90% or higher readability or precision. Blind spots were observed at various distances and orientations in different mediums, and the authors concluded that this was mainly because of the polarity of the antenna used in the study [53].

All of the research above demonstrated that understanding and evaluating the effects of packaging, products, and packaging related processes on RFID system performance is critical to the success of implementing a RFID system.

2.7.3 Operating Environment Effect on Transponder Performance

The practical environment in which an RFID system is deployed affects the system's performance considerably [3]. A pre-installation site analysis is necessary before implementing RFID technology at a location, as the surrounding physical environment may deviate the performance of a RFID system from the expected [2]. RF waves travel from the transmitter to the receiver can be affected by a variety of factors related to the practical environment, including absorption, dielectric effects, diffraction, reflection, refraction, scattering, noise and interference [9].

Absorption occurs if a part of the RF energy is absorbed when the RF wave strikes an object in the field. The amount of energy absorbed by an object depends on the dielectric property of the object, as mentioned in the *Product and Packaging Materials* section. Water and liquid products absorb RF waves. Wood, paper and paperboard, and food that contains a certain amount of water may also absorb RF waves [9].

Dielectric effects, also mentioned in the *Product and Packaging Material* section, refer to the material's capability to resist the electric field. As a result, the velocity of a wave is reduced, and the signal is detuned. Diffraction happens when a wave strikes sharp edges or when it passes through narrow gaps. Reflection occurs when a wave strikes a surface that has much larger dimensions compared to the wave. Refraction is the phenomenon of the wave changing its direction when it travels through two substances. The wave direction changes at the boundary of the two mediums. Scattering refers to an object absorbing a wave and then reradiating it in a different direction [9].

Noise is defined as an unwanted electrical wave or energy present in a signal [9]. Electronic motors, light switches, and thermostats are some of the common sources of noise [3]. Interference is the interaction of two or more waves while they are traveling along the same medium. There are two forms of interference: constructive interference and destructive interference. Constructive interference occurs when the resultant wave has a larger amplitude compared to the original waves, and destructive interference is the case when the resultant wave has a smaller amplitude compared to the original waves [9].

2.8 Research on Testing Methodology

Besides the research mentioned in the section of *Research of the Effect of Packaging and Product on Transponder Performance*, testing methodologies for evaluating various aspects of RFID tag performance have also been developed by many other researchers and organizations.

EPCglobal issued a document titled *Tag Performance Parameters and Test Methods* to provide a systematic means to evaluate tag performance. The current version of this document was released in 2008. The document addresses testing procedures for determining read range, orientation tolerance, frequency tolerance, interference tolerance, backscatter range, write time and tag proximity of a passive UHF RFID tag. Procedures for testing read range and orientation tolerance are the most relevant to this research. Figure 1 shows a side view of the test set physical block diagram for tests in the EPCglobal Tag Performance Parameters and Test Methods [41].

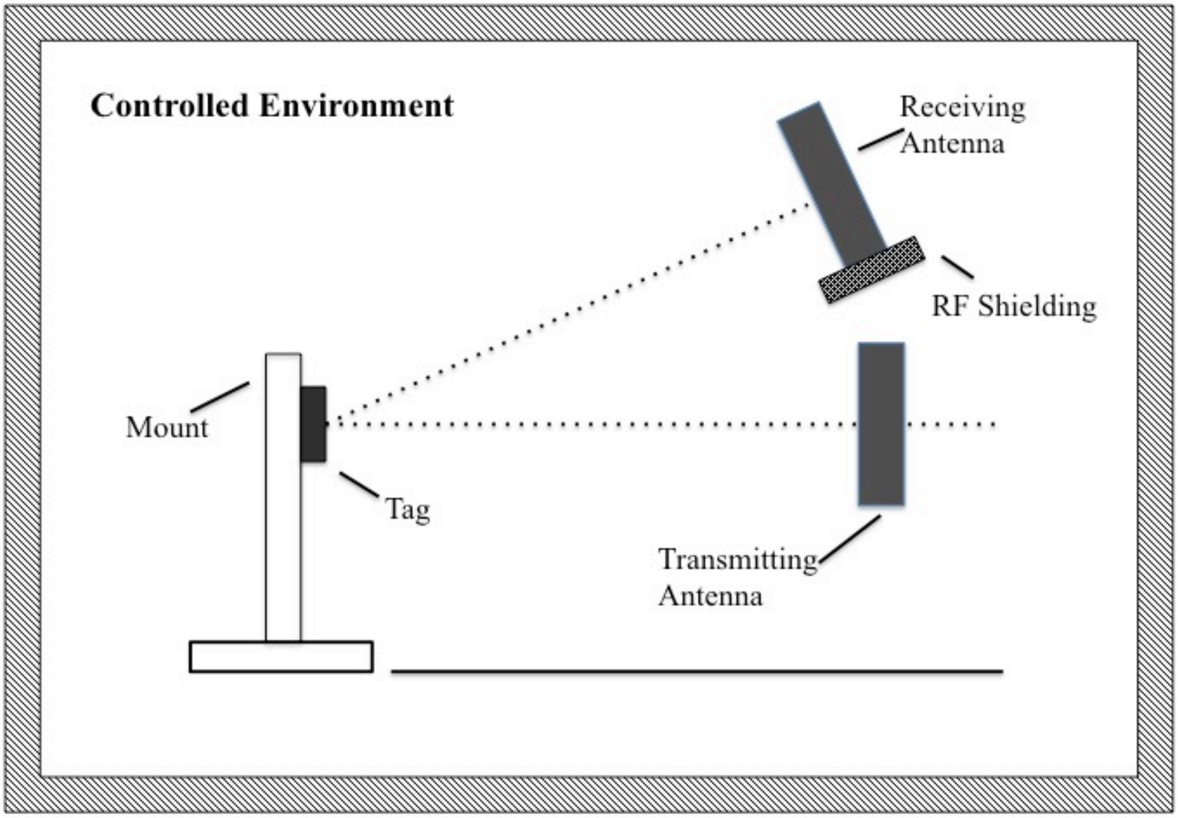


Figure 1 Side View of the Test Set Physical Block Diagram for Tests in the EPCglobal Tag Performance Parameters and Test Methods

All tests should be conducted in a controlled environment, such as an anechoic chamber. The material on which the tag is attached should be tailored to the approximate dimensions of the tag. An RF-inert, styrene foam block is desired while evaluating the tag's free space performance. Other materials may be used to evaluate the tag's performance on the material [41].

Specifically, the read range of a tag is measured by positioning the tag in the far field of the transmitting antenna, and then varying the transmitting power until the tag reaches a 50% read rate. The free space read range is reported under the assumption of a 35 dBm transmitting EIRP. The orientation tolerance is defined as the percentage of tag positions where the range is at least half of its maximum read range. It is measured by rotating the tag from −90° to +90° on its horizontal centerline and on its vertical centerline, and varying the transmitting power until the tag reaches a 50% read rate. The result of the orientation tolerance of a tag is again reported under the assumption of a 35 dBm transmitting EIRP [41].

EPCglobal also developed a testing methodology for measuring the readability of an RFID tag when the tag is applied to a case and the case travels through convey portals. In this test methodology, one antenna on each side of the portal is required, and an antenna on the top or bottom of the portal is optional, but no more than four antennas shall be used. The suggested conveyor speed is 625 feet/minute [54].

In addition, EPCglobal's *Static Test Method for Applied Tag Performance Testing* acts as a low-cost alternative compared to tests such as the convey portal test that was mentioned above. The main goal of the static test method is to evaluate the tag's read rate when the tag is placed on an item, case, or pallet. An anechoic chamber is preferred, but when not available, an open area test site with well-defined RF characteristics is acceptable [55].

Last but not the least, GS1 issued a document defining the testing methodology guideline used for the Tagged-Item Performance Protocol (TIPP) tagged-item grading. The TIPP prensents a grading system to classify the RFID performance of a tagged item. This document provides the method and criteria for validating if a TIPP tagged-item meets a specified grade level [56].

ASTM International issued three standard test methods for tag performance evaluation. They are intended for use in laboratory settings that simulate the practical distribution environment of the product being tested [57]–[59] . *ASTM D7435-08 Standard Test Method for Determining the Performance of Passive Radio Frequency Identification (RFID) Transponders on Loaded Containers* is the standard that gave enlightenment to the development of the test methodology used in this research. Two types of transponder distance are defined by the ASTM standard, depending on how they are tested. The *critical transponder distance* is "*the distance between the transponder and the interrogator antenna at which a transponder becomes undetectable by an RFID system, when moving the RFID transponder out of the read field*", and the *transponder acquisition distance* is defined as "*the distance between the transponder and the interrogator antenna at which a transponder is first detected by an RFID system, when moving the transponder into the read field*" [57].

The ASTM D7435-08 method first determines the read performance of a RF system by measuring the critical distance read field and the transponder acquisition distance read field with a transponder attached to an empty container. Both types of transponder distance shall be measured along every 15° radian within two of the two-dimensional quadrants in front of the antenna. So a total of 13 radii should be tested at a horizontal plane. The height of the interrogator antenna shall be fixed, and the height of the transponder shall be adjusted from 1 foot to 6 feet from the floor with an increment of 1 foot, and be adjusted to the height of the interrogator antenna, if this height is not included in every 1 foot from 1 to 6 feet. All the 13 radii on each horizontal plane shall be tested. After all the tests, the radiation pattern of the interrogator antenna in a three-dimensional space in front of the interrogator is given. Then the transponder readability in the established read field of the RF system while the tag is attached to a product-filled container is determined by following the same procedures of measuring critical distance and acquisition distance at each plane. In the end, the performance of the transponder when it is attached to the product-filled container is compared to that of the empty container [57].

ASTM D7434-08 evaluates RFID system performance while the tag is attached to a unit load. The testing procedures are similar to ASTM D7435-08 with measuring the critical distance and acquisition distance of a transponder affixed to a pallet load by moving the pallet load towards or away from the interrogator antenna. The transponder's height is fixed but not changed compared to the ASTM D7435-8 procedures, as ASTM D7434-08 is intended to simulate the use of a transponder on a pallet load in practical processes [58].

ASTM D7580/D7580M-09 is a rotary stretch wrapper test method for determining transponder performance on homogenous unitized loads. A unitized load is assembled with RFID-tagged cases, and then the tags on the load are read in a stationary RF field while the load being stretch wrapped by an automated rotary stretch wrapping machine [59].

Other than the test methods issued by standards bodies, many researchers have developed different test methods to evaluate transponder performance under different settings. D'Mello, Mathew, McCauley and Markham studied the effects of tag's orientation on an asset on the tag performance in a highly controlled environment, and the effect of tag's relative position to the interrogator antenna on the tag performance in a three-dimensional real world environment. Results of D'Mello et al.'s experiment indicated that orientation of a tag has an enormous impact on readability. The authors questioned the applicability of RFID technology in the real world based on the generally poor performance of the tested RFID tags in both tests, and emphasized that understanding the tag performance under different orientations is critical for real world applications of RFID [13].

Derbek, Steger, Weiss, Preishuber-Pfügl, Pistauer presented an UHF RFID measurement based on a modular hardware system for evaluating designs of tags and ICs, and provided means to quantitatively analyze tag performance in various applications. With tests of 20 tag types, the authors made conclusions including: different ICs have huge differences on tag performance; different tag types have large variance in performance consistency; not all tags are applicable to global operations; tag types have large difference between orientation sensitivity; read ranges of more than 10 meters were measured, and the read range of different tag types is limited by the forward link; some tags have problems at higher power levels [47].

Choi, Kim, Cho, Joo and Lee performed a study to determine the minimum requirements for ISO/IEC 18046-3 *Information technology - Radio frequency identification device performance test methods test methods for tag performance – Part 3: Test Methods for tag performance* [11]. Luh and Liu developed a test method based on IC's $P_{\mathrm{Turn-on}}$ to measure the read distance of UHF RFID passive tags in a mini anechoic chamber [10]. Poque conducted performance analysis of UHF passive RFID tags with respect to read range and orientation in a real world environment setting. The tag was placed on a cardboard box. Little or no read points were found within the tag's read range [60]. Ayyer developed methodology to evaluate tag performance in a trauma resuscitation bay setting that is dynamic and time critical [12]. Lu, Chen and Ye created a 3D model to estimate the interference between tags, while each tag was attached to a box and the boxes stacked in a 3×3×3 pile [61]. Zou, Wu and Zhao proposed an automatic testing system with hardware and software architectures for investigating tag performance [62]. Huo, He, Li, She, Zuo and Zhu presented a software-defined test method for measuring RFID system signal transmission and evaluating tag performance [63]. Kosuru and Devours developed a theoretical model for evaluation of the tag performance when the tag is immersed in a dielectric medium [64]. Colella, Catarinucci, Coppola and Tarricone presented a UHF RFID tag performance evaluation platform that can automatically calculate a tag's sensitivity, working range, and radiation pattern based on a theoretical formulation of the tag's minimum $P_{Turn-on}$, which was derived from testing with varied frequencies and tag orientations [65].Stasa, Svub and Benes developed a RFID measurement chamber that can automatically evaluate the performance of tags on objects, and greatly reduced human labor involvement as well as manual operation errors [66].

2.9 Relevancy

Literature discussed in this chapter provided essential knowledge and insights to prepare, design, and conduct this research. This thesis focused on the evaluation of the performance of general-purpose transponders in a working environment using packaging materials. Performance parameters of read range and orientation read rate were quantified by procedures described in Chapter 3 Methodology. Creative analysis models will be provided in further chapters.

Chapter 3

Methodology

3.1 Test Environment

The testing took place at the machinery lab in the School of Packaging at Michigan State University. This room has a large amount of space filled with equipment made from metal (Figure *2*). Robinson of MSU AIRTC evaluated the RF noise of this room and concluded that this room showed a clear disturbance in communication capabilities of passive tags due to the RF noise and the reflective surfaces present in this room. Possible signs of both constructive and destructive interference were present in this room [3].

This room was chosen to investigate RFID transponder performance in a simulated manufacturing environment. Tests were conducted along an open aisle close to the centerline of the room. Figure *3* shows the layout of the machinery lab and the test location in the room.

Figure 2 The Machinery Lab in the School of Packaging at Michigan State University

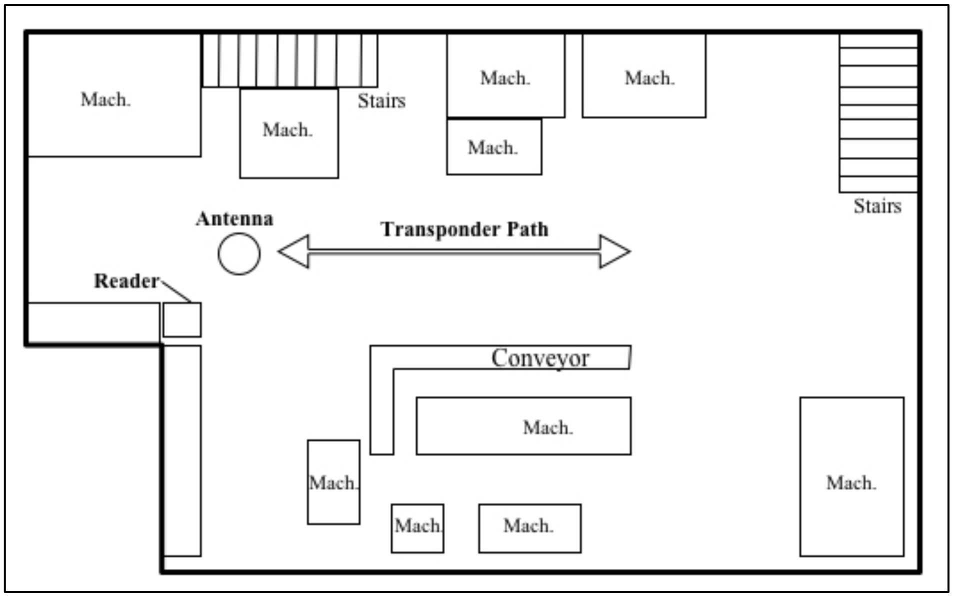


Figure 3 Layout of the Machinery Lab and the Test Location in the Room

The room temperature and the relative humidity (RH) were measured and recorded throughtout the entire testing period (late spring to fall). A VaisalaHMI41 humidity and temperature indicator was used (Figure 4). The temperature and RH were measured at three spots around the testing area in the room every two hours. The average values of the temperature and the RH of the three spots were calculated and recorded each time. The average temperature throughout the entire testing period was 22.41 °C, with the maximum value of 25.60 °C, the minimum value of 19.03 °C, and a standard deviation of 1.69 °C. The average RH thoughout the testing period was 34.23%, with the maximum of 55.03 %, the minimum of 16.70%, and a standard deviation of 8.98%.

Figure 4 Vaisala HMI41 Humidity and Temperature Indicator

3.2 RFID Equipment

The RFID equipment used in this thesis utilizes waves in the 915 MHz region. Impinj IPJ-R1000 was used as the interrogator (Figure 5). It was configured with Impinj MultiReader version 4.2.0. middleware in this research.

Figure 5 Impinj IPJ-R1000 Reader

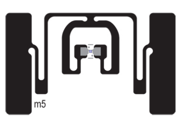
The LP antenna used in this thesis was Alien ALR-9610-AL with a 5.9 dBi antenna gain. The CP antenna used was Alien-9610-BC with a 6.0 dBi antenna gain. The antenna was mounted on a vertical PVC pipe as shown in Figure 6. The height of both the CP and LP antennas was 4 feet 4 inches measured from the floor to the center of the antenna.

Figure 6 Circularly Polarized Antenna on the PVC Pipe.

The passive transponders used in this research were manufactured by Avery Dennison Inc. Table 3 shows the size, chip and memory, as well as the common applications suggested by the manufacturer [67]. AD-227m5 (Tag 1), AD-233m5 (Tag 2) and AD-381m5 (Tag 3) all have

Impinj® Monza® 5 chips, 128 bits memory and were made for similar applications, but with different sizes and antenna designs as Table 3 shows. The Impinj® Monza® 5 chip has a $P_{Turn-on}$ as low as -20 dBm with a dipole antenna, according to Impinj [68]. One tag for each tag design was chosen from three packs of sample tags to use in this research. Figure 7 shows the actual tags.

Table 3 Transponder Descriptions by the Manufacturer

Name	Size (in)	Chip	Memory	Common Applications
AD-227m5 	3.74×0.33	Impinj® Monza® 5	128 bits	• Supply chain, inventory and logistics • Apparel and other item-level retail • Returnable transport units
AD-233m5 	2.76×0.57	Impinj® Monza® 5	128 bits	• Supply chain, inventory and logistics • Apparel and other item-level retail
AD-381m5 	1.97×1.18	Impinj® Monza® 5	128 bits	• Supply chain, inventory and logistics • Apparel and retail • Library, media, documents and files

[Source: Avery Dennison RFID Solutions]

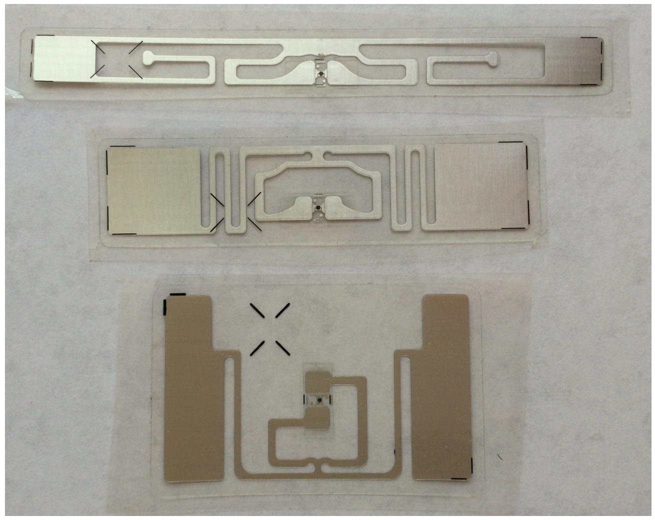


Figure 7 Transponders used in this thesis

3.3 Packaging Materials

Packaging materials used in this research were C-flute uncoated corrugated paperboard (M1), polyethylene film of 0.5 mil thickness (M2), polyethylene corrugated board (M3) and PET/Al/polyethylene film (M4). Materials were cut to 7×7 inch square samples (Figure 8). Uncoated corrugated paperboard was used to frame the films. One sample for each material type was used in this research.

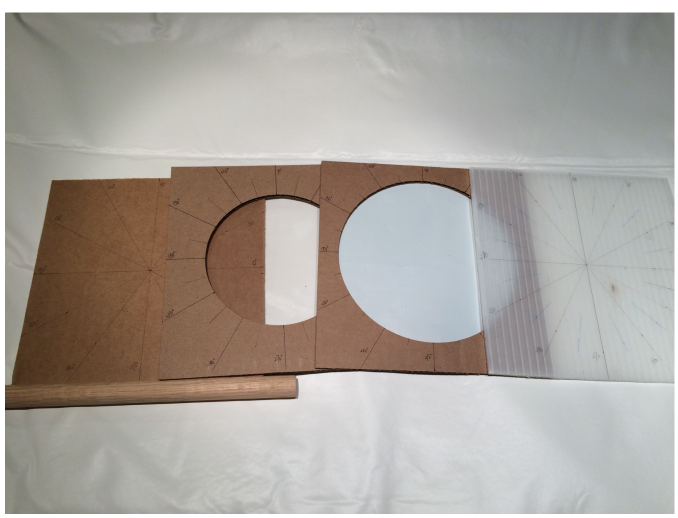


Figure 8 Packaging Material Samples

To fulfill the purpose of evaluating tag performance using packaging materials, a transponder support was made specifically for this research (Figure 9 and Figure 10). Material samples could be plugged into the slot of the transponder support. The tag attached to the material sample could be rotated, tilted and inclined to any angle in three-dimensional space using this transponder support. The center of the material sample was 4 feet 4 inches above the ground when the sample was placed vertically on the transponder support. Tags were attached to the center of the material sample.

Figure 9 Transponder Support, Front View

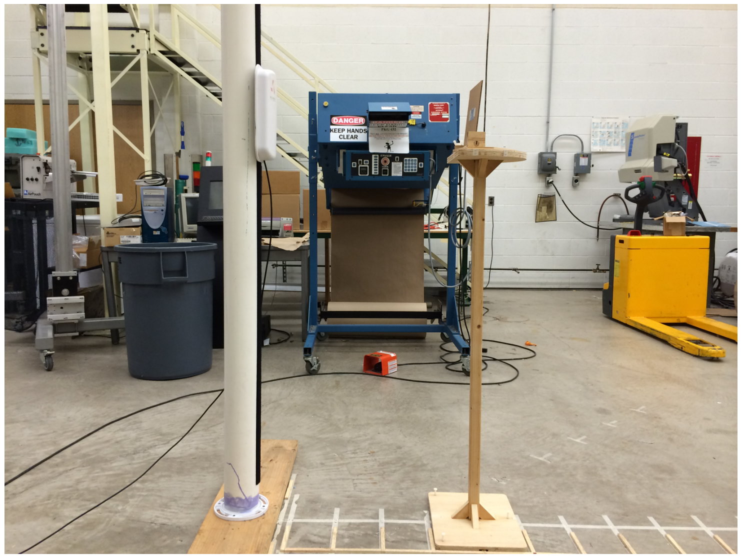


Figure 10 Transponder Support, Front View

In addition, distance marks were glued on the floor as Figure 9 and Figure *10*. These distance marks were made from wood sticks and have thickness, in order to position the transponder support accurately each time. Distance marks were 6 inches apart.

The parameters for the transponder support are shown in Figure 11. Written descriptions follow.

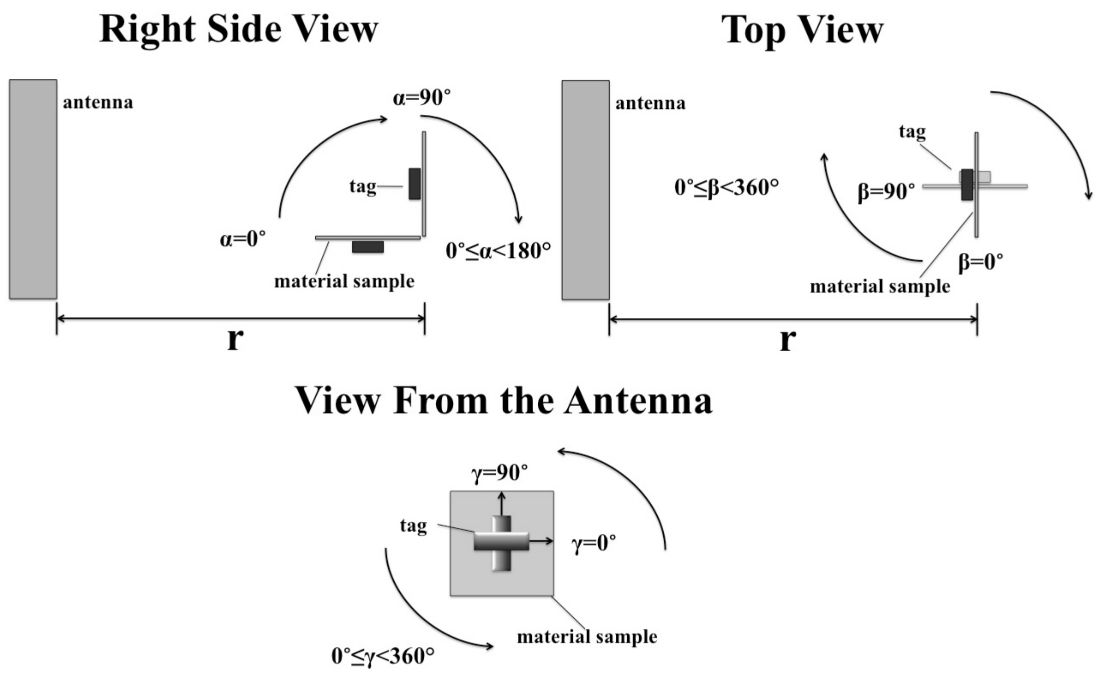


Figure 11 Parameter Definitions

- Angle α: the angle achieved by turning the material sample clockwise around the horizontal axis located at the bottom of the sample. When α=0°, the packaging material sample is horizontal and the tag on the sample is facing downward. When α=90°, the sample is vertical. $0° \leq \alpha < 180°$.
- Angle β: the angle achieved by spinning the material sample clockwise along the vertical axis. When α=90° and β=0°, the tag is facing the antenna. $0° \leq \beta < 360°$.
- Angle γ: the angle achieved by spinning the tag on the material sample counter clockwise around the axis that is perpendicular to the material sample and through the center of both the tag and the material sample. When α=90°, β=0° and γ=0°, the tag is in its preferred orientation to the antenna.
- Distance r: the distance between the center of packaging material sample's bottom edge to

the vertical plane that the antenna surface is on. The transponder support was always moved along the line that ran across the center of the antenna and perpendicular to the antenna surface.

3.4 Procedures

The testing procedures used in this research were developed from two pilot tests. Details of the pilot tests are provided in Appendix 1 and 2. Conclusions of the pilot tests that contributed to the development of the testing methodology in this chapter include: 1) critical distance and acquisition distance of a transponder are statistically the same, in other words, the maximum read distance of a tag measured by moving the tag towards or outwards from the reader's interrogation zone does not significantly differ; 2) angle α does not have a significant effect on the read range of a tag; 3) angle γ may influence the read range of a tag, whether the tag communicates with a CP reader antenna or an LP reader antenna; and 4) material may have inconsistent effects on a tag's performance, that is to say, tag A's read range tested with material A is greater than that of with material B, but tag B's read range tested with Material A is smaller than that with material B. Based on the above conclusions, tests for this research were conducted using with following procedures.

3.4.1 Read Range Test

The purpose of this test is to measure the transponder's read range using different packaging materials. Angle α and angle γ were at fixed values of α=90° and γ=0° throughout the entire read range test. Packaging material samples and transponders were conditioned in the machinery room for at least 48 hours prior to the test. After conditioning, procedures of the read range test were as follows:

1) Assemble the LP antenna to the reader, and configure the reader to a transmitting power of 20 dBm, and a receiving sensitivity of -70 dBm;
2) Assemble the packaging material to the transponder support and set the angle α to 90°, keep α=90° for all the procedures;
3) Attach Tag 1 to the material sample M1 at γ=0° using a small piece of masking tape. The center of the tag is aligned with the center of the material sample. Angle γ is kept as 0° for all the procedures;
4) Rotate angle β to 0°, and move the transponder support to the distance r=0.5 foot;
5) Turn on the reader to automatically read the tag 3 times, 5 seconds each time. Delay between two runs is 5 seconds. Each 5-second run was considered as one trial of the measurement;
6) Save the data file with information of reader antenna polarization, tag number, material number, angle β and distance r in the filename;
7) Move the transponder support to 1 foot and repeat steps 5 and 6;
8) Move the transponder support outwards from the antenna with an increment of 0.5 foot each time, until the tag cannot be detected by the reader for 5 consecutive increases in distance;
9) Record the last distance r the tag could be read as R_0. R_0 is defined as the the maximum read distance for the tag at β=0°;
10) Move the transponder support back to r=0.5 foot, turn the angle β=30° and repeat steps 5 to 9;
11) Increase the angle β by 30° each time until β=330°;
12) Repeat step 2 to step 11 for all three tags using samples of four packaging materials;

13) Assemble the CP antenna to the reader and configure the reader the same, repeat step 2 to step 12.

3.4.2 Orientation Read Rate

The purpose of this test is to determine how well the tag is read when it is rotated away from its preferred orientation, which is $\alpha=90°$, $\beta=0°$, and $\gamma=0°$ for the transponders evaluated in this research. 60 sets of random angle combinations α-β-γ were generated using Python and listed in Table 4. Angles used in generating the random α-β-γ were integer multiples of 15° within the ranges shown in Figure *11*. Packaging material samples and transponders were conditioned in the machinery room for at least 48 hours prior to the test. The test procedures to determine the orientation read rate were:

1) Assemble the LP antenna to the reader, and configure the reader to a transmitting power of 20 dBm, and a receiving sensitivity of -70 dBm;
2) Locate the transponder support at the distance r=2 feet for the entire test;
3) Attach Tag 1 to material M1 at $\gamma=345°$ using a small piece of masking tape. The center of the tag is aligned with the center of the material sample;
4) Assemble the material sample with the tag to the transponder support and turn the angle α to 0° and angle β to 60°;
5) Read the tag 3 times, 5 seconds each time, and 5 seconds delay between each run;
6) Save the data file with information of reader antenna polarization, tag number, material number, angle combination α-β-γ in the filename;

7) Repeat step 3 to 6 for the remaining α-β-γ in Table 4;

8) Repeat step 3 to step 7 for all three tags using four packaging material samples;

9) Assemble the CP antenna to the reader and configure the reader the same, repeat step 2 to step 8.

Table 4 60 Sets of Random Angle Combination

α°	β°	γ°	α°	β°	γ°	α°	β°	γ°	α°	β°	γ°	α°	β°	γ°
0	60	345	30	315	270	75	105	180	105	255	150	135	300	105
0	165	270	45	45	120	75	135	255	105	255	255	135	300	285
0	255	0	45	135	30	75	165	165	105	270	180	135	315	300
0	300	225	45	165	30	75	195	15	105	315	75	150	45	180
0	345	150	45	195	75	75	300	180	120	135	240	150	120	45
15	15	135	45	225	60	90	105	180	120	165	195	150	120	60
15	135	15	45	300	75	90	180	285	120	195	315	150	120	75
15	135	300	60	60	30	90	255	330	120	315	225	150	150	285
30	105	240	60	195	75	90	285	270	135	75	165	150	240	300
30	195	60	60	240	30	90	330	15	135	180	120	165	30	15
30	210	240	60	300	300	105	30	270	135	240	210	165	135	315
30	300	285	75	90	165	105	165	135	135	270	105	165	180	30

3.5 Data Management

Test data saved each time with the Impinj MultiReader in a comma separated values (.csv) file. The two tests conducted above generated a large amount of .csv files that were difficult to handle for analyzing. Desired information from both the filename and the content of the .csv files was extracted and written into Excel worksheets using Python. Selected outputs were used in this thesis to draw graphs, conduct analysis and compare tag performance:

- Total count of reads (TotCnt): number of times the interrogator read the tag in each 5 second run;

- Maximum received signal strength indicator (RSSImx) in dBm: the maximum signal strength the interrogator received from the transponder;
- R_β and R_{max} in feet: for a given tag and a given material tested with a given polarized antenna in the read range test, the maximum distance the tag could be read at angle β, and the maximum distance the tag could be read among all βs, respectively;
- Orientation read rate (O-RDRate): the ratio of the amount of angle combinations a tag could be read out of all 60 sets of α-β-γ in the orientation read rate test.

Chapter 4

Results

4.1 Results of the Read Range Test

In the read range test, the tag with the material sample was read at a distance r from the reader, and with an orientation of fixed α=90° and γ=0°, but a changing β every 30° from 0°~330°. The measurement at each distance r with angle β was performed as described in section 3.4.1, and the TotCnt and RSSImx were recorded.

Since each measurement consisted of 3 trails, and each trial was a 5-second run of the reader, there were three TotCnt and three RSSImx values recorded for each measurement. The integer of the average TotCnt of three trials, and the value of the maximum RSSImx of three trials were used to represent the TotCnt and RSSImx value of this measurement. Then the following terms were defined:

A *Read Point* was defined as a measurement with an average TotCnt value of at least 1. A *No-read Point* was defined as a measurement with an average TotCnt less than 1. The No-read Points did not have any RSSImx value, since the reader could not detect any signal from the tag.

Tables Table *5* to Table *10* are summaries of the read range tests of the three tags with the four packaging materials using the LP and CP antenna. In the tables, the count of Read Points for a tag with each material is first given, then the maximum, minimum, mean, and standard deviation values of TotCnt and RSSImx were calculated from all the Read Points of the tag with a given material. The R_{max}, the Angle β at where the R_{max} appeared, and the average value of R_{β}s are also provided. Finally, the table shows whether a No-read Point was found within the tag's read range as outlined by the Rβ value and shown in figures from Figure 12 to Figure 29. In this chapter, general discussion of the observed results will be given. Statistical analysis of the results are given in depth in Chapter 5.

Table 5 Summary of the Read Range Test of Tag 1 with Four Materials Using LP Antenna

LP Antenna, Tag 1					
Material		**M1**	**M2**	**M3**	**M4**
Count of Read Points		199	209	211	0
TotCnt of Read Points	**Max**	431	430	428	Not Applicable
	Min	2	5	2	
	Mean	337	344	329	
	Deviation	134.98	124.97	137.67	
RSSImx of Read Points	**Max**	-24	-27	-23	
	Min	-62	-64	-62	
	Mean	-51	-53	-51	
	Deviation	8.53	8.24	8.50	
R_{max} (ft)		14.0	14.5	15.0	
Angle β of R_{max}		0°, 150°, 180°, 330°	0°	0°, 180°	
Average of R_β (ft)		9.0	9.1	9.2	
No-read Point in the Read Range		Yes	Yes	Yes	

Table 6 Summary of the Read Range Test of Tag 1 with Four Materials Using CP Antenna

CP Antenna, Tag 1					
Material		**M1**	**M2**	**M3**	**M4**
Count of Read Points		124	125	127	0
TotCnt of Read Points	**Max**	430	430	431	Not Applicable
	Min	8	5	3	
	Mean	338	332	339	
	Deviation	140.09	139.95	138.33	

Table 6 (cont'd)

CP Antenna, Tag 1					
Material		M1	M2	M3	M4
RSSImx of Read Points	Max	-31	-34	-31	Not Applicable
	Min	-62	-64	-62	
	Mean	-52	-54	-52	
	Deviation	7.97	7.75	8.05	
R_{max} (ft)		9.0	9.0	9.0	
Angle β of R_{max}		0°, 180°	0°, 180°	0°, 180°	
Average of R_{β} (ft)		5.4	5.6	5.7	
No-read Point in the Read Range		Yes	Yes	Yes	

Table 7 Summary of the Read Range Test of Tag 2 with Four Materials Using LP Antenna

LP Antenna, Tag 2					
Material		M1	M2	M3	M4
Count of Read Points		142	157	158	0
TotCnt of Read Points	Max	430	431	431	Not Applicable
	Min	2	3	1	
	Mean	335	328	328	
	Deviation	150.20	147.98	148.63	
RSSImx of Read Points	Max	-30	-32	-29	
	Min	-64	-64	-63	
	Mean	-53	-55	-53	
	Deviation	7.95	7.69	8.02	
R_{max} (ft)		13.5	13.5	14.0	
Angle β of R_{max}		0°	0°, 180°	0°	
Average of R_{β} (ft)		6.6	7.0	7.0	
No-read Point in the Read range		Yes	Yes	Yes	

Table 8 Summary of the Read Range Test of Tag 2 with Four Materials Using CP Antenna

CP Antenna, Tag 2					
Material		**M1**	**M2**	**M3**	**M4**
Count of Read Points		95	96	95	0
TotCnt of Read Points	**Max**	430	430	431	Not Applicable
	Min	3	2	4	
	Mean	326	322	331	
	Deviation	150.87	150.84	145.18	
RSSImx of Read Points	**Max**	-36	-39	-36	
	Min	-64	-65	-64	
	Mean	-55	-57	-54	
	Deviation	7.23	6.94	7.31	
R_{max} (ft)		6.0	6.0	6.0	
Angle β of R_{max}		0°, 30°, 150°, 180°, 210°, 330°	0°, 30°, 150°, 180°, 210°, 330°	0°, 150°, 180°, 210°, 330°	
Average of R_{β} (ft)		4.0	4.0	4.0	
No-read Point in the Read Range		No	No	No	

Table 9 Summary of the Read Range Test of Tag 3 with Four Materials Using LP Antenna

LP Antenna, Tag 3					
Material		**M1**	**M2**	**M3**	**M4**
Count of Read Points		83	94	95	0
TotCnt of Read Points	**Max**	430	430	430	Not Applicable
	Min	3	5	10	
	Mean	341	337	340	
	Deviation	147.55	137.23	139.11	
RSSImx of Read Points	**Max**	-35	-37	-34	
	Min	-62	-64	-62	
	Mean	-53	-55	-53	
	Deviation	7.17	7.03	7.37	
R_{max} (ft)		5.5	6.0	6.0	

Table 9 (cont'd)

<table>
<tr><th colspan="5">LP Antenna, Tag 3</th></tr>
<tr><th>Material</th><th>M1</th><th>M2</th><th>M3</th><th>M4</th></tr>
<tr><td>Angle β of R_{max}</td><td>0°, 150°, 180°, 330°</td><td>0°, 180°</td><td>0°, 180°</td><td rowspan="3">Not Applicable</td></tr>
<tr><td>Average of R_β (ft)</td><td>3.5</td><td>4.0</td><td>4.0</td></tr>
<tr><td>No-read Point in the Read Range</td><td>No</td><td>Yes</td><td>No</td></tr>
</table>

Table 10 Summary of the Read Range Test of Tag 3 with Four Materials Using CP Antenna

<table>
<tr><th colspan="6">CP Antenna, Tag 3</th></tr>
<tr><th colspan="2">Material</th><th>M1</th><th>M2</th><th>M3</th><th>M4</th></tr>
<tr><td colspan="2">Count of Read Points</td><td>55</td><td>56</td><td>57</td><td>0</td></tr>
<tr><td rowspan="4">TotCnt of Read Points</td><td>Max</td><td>430</td><td>430</td><td>430</td><td rowspan="12">Not Applicable</td></tr>
<tr><td>Min</td><td>4</td><td>8</td><td>10</td></tr>
<tr><td>Mean</td><td>323</td><td>308</td><td>315</td></tr>
<tr><td>Deviation</td><td>153.13</td><td>160.27</td><td>156.31</td></tr>
<tr><td rowspan="4">RSSImx of Read Points</td><td>Max</td><td>-41</td><td>-44</td><td>-41</td></tr>
<tr><td>Min</td><td>-63</td><td>-65</td><td>-63</td></tr>
<tr><td>Mean</td><td>-55</td><td>-57</td><td>-55</td></tr>
<tr><td>Deviation</td><td>6.15</td><td>5.96</td><td>6.27</td></tr>
<tr><td colspan="2">R_{max} (ft)</td><td>3.5</td><td>3.5</td><td>3.5</td></tr>
<tr><td colspan="2">Angle β of R_{max}</td><td>0°, 180°, 330°</td><td>0°, 150°, 180°, 210°, 330°</td><td>0°, 30°, 150°, 180°, 210°, 330°</td></tr>
<tr><td colspan="2">Average of R_β (ft)</td><td>2.3</td><td>2.3</td><td>2.4</td></tr>
<tr><td colspan="2">No-read Point in the Read Range</td><td>No</td><td>No</td><td>No</td></tr>
</table>

Comparing within each table to evaluate the effect of materials on the tag's performance in the read range test, the observations include:

1) There was no read point for M4 for any tags using either antenna;

2) Materials M1, M2, and M3 resulted in similar values of count of Read Points. The greatest difference was obtained in Table 6 between M1 and M3, with M3 having 16 more Read Points than M1;

3) Materials M1, M2 and M3 resulted in similar values of TotCnt. For a given tag with M1, M2, and M3, the maximum values of TotCnt were around 430, the minimum values of TotCnt were in the range of 1 to 10, the mean values of TotCnt were from 308 to 344, and the deviation values were from 124 to 160;

4) M2 showed smaller maximum, minimum and mean values of RSSImx than M1 and M3. The differences were within -3dBm;

5) The R_{max} of a tag with M1, M2, and M3 were either identical or no more than 1 foot difference;

6) The angle β where the R_{max} was measured had subtle difference between materials, but all the β angles of R_{max} with materials M1, M2 and M3 were within the ranges of 0°±30° and 180°±30° (0° −30° is equal to 330°);

7) Materials M1, M2 and M3 had little effect on the average value of R_β with a difference that was no more than 0.4 foot for each tag;

8) Only Tag 3 tested with LP antenna (Table 9) had a difference in the No-read Point in the read range between M1, M2 and M3.

Comparing between Table 5, Table 7, and Table 9, or comparing between Table 6, Table 8, and Table 10, tags with different antenna designs showed the following in the read range test:

1) Tag 1 had more Read Points, larger R_{max} and larger average R_β than Tag 2, and Tag 3 had the

least Read Points, smallest R_{max} and smallest average R_{β};

2) All three tags had very similar values for TotCnt;

3) The maximum and mean values of RSSImx of Tag 1 were greater than those of Tag 2, and Tag 3 had the lowest values of maximum and mean RSSImx. However, the minimum values of RSSImx of each tag were very similar.

4) Different tags did not have much difference in the angle β of R_{max}. For all the tags, the angle β of R_{max} were within the ranges of 0°±30° and 180°±30° (0° −30° is equal to 330°);

5) Tag 1 had No-read Points in its read ranges with materials M1, M2 and M3 measured by both the LP and CP antenna, while Tag 2 had No-read Points with materials M1, M2 and M3 using the LP antenna. Tag 3 showed No-read Points only with M2 while using the LP antenna.

Comparing Table 5 to Table 6, and Table 7 to Table 8, as well as Table 9 to Table 10, the effect of different reader antennas on the tag's performance in the read range test was:

1) The tag tested with the LP antenna always had more Read Points, larger maximum RSSImx, larger mean RSSImx, as well as greater R_{max} and greater average R_{β}, compared to the results tested using the CP antenna;

2) The values in the TotCnt category and the minimum RSSImx were similar between measurements using the LP antenna and the CP antenna;

3) CP antenna readings of the tag resulted in more β angles where the R_{max} was obtained;

6) All three tags read by the LP antenna had No-read Points within their read ranges, while only Tag 1 had No-read Points in the read ranges tested using the CP antenna.

The following figures are created to visually present the data in a detailed and straightforward manner. Figure 12 to Figure 17 show the read ranges of Tag 1 with each material tested by the LP antenna and CP antenna. Figure 18 to Figure 23 show the read ranges of Tag 2. Figure 24 to Figure 29 show the read ranges of Tag 3. No-read Points were marked as × in the read range figures. The trends of TotCnt versus distance and RSSImx versus distance are also shown below. However, only the test results at β=0° are provided in this document as representative examples. Figure 30 to Figure 35 show the TotCnt versus distance and RSSImx versus distance at β=0° with the same tag; Figure 36 to Figure 41 show the TotCnt or RSSImx versus distance at β=0° with the same material; and Figure 42 to Figure 45 show the TotCnt or RSSImx versus distance at β=0° using the same reader anteena. Since there was no read point for M4 for any tags using either antenna, M4 results are all excluded in the figures. TotCnt versus RSSImx figures are provided in Appendix 3 to show how the results were clustered.

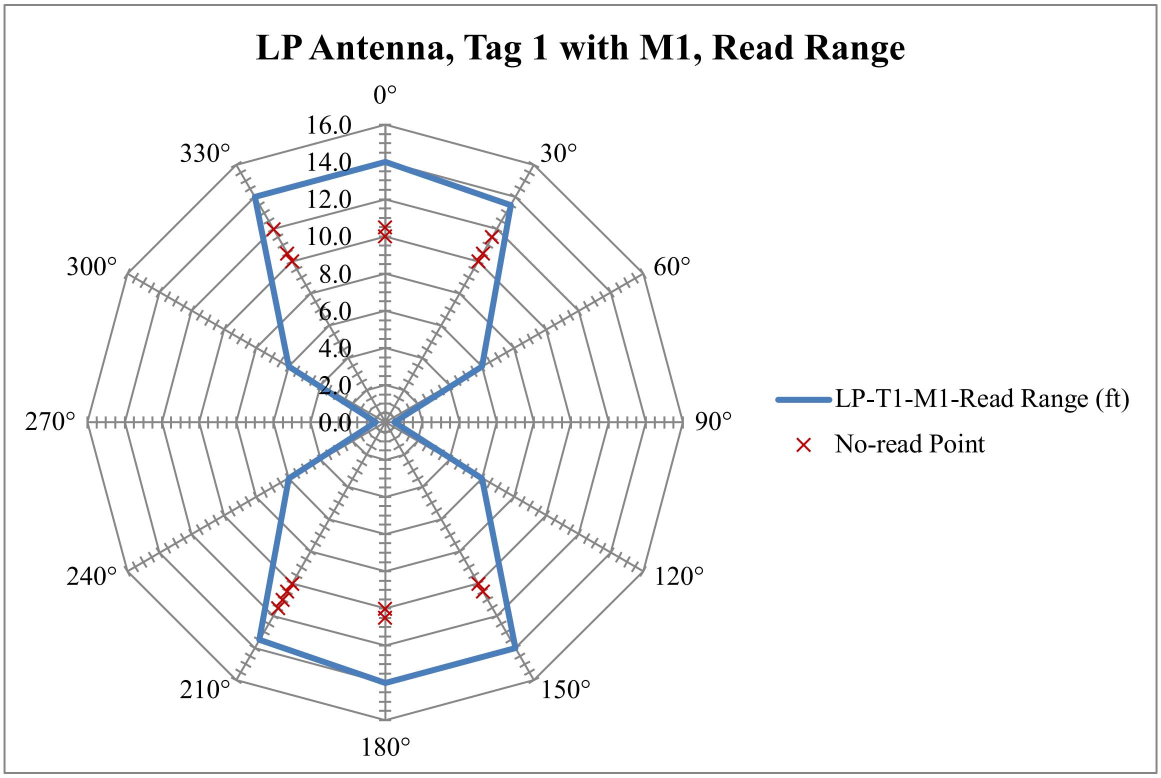


Figure 12 Read Range of Tag 1 with M1 Measured Using LP Antenna

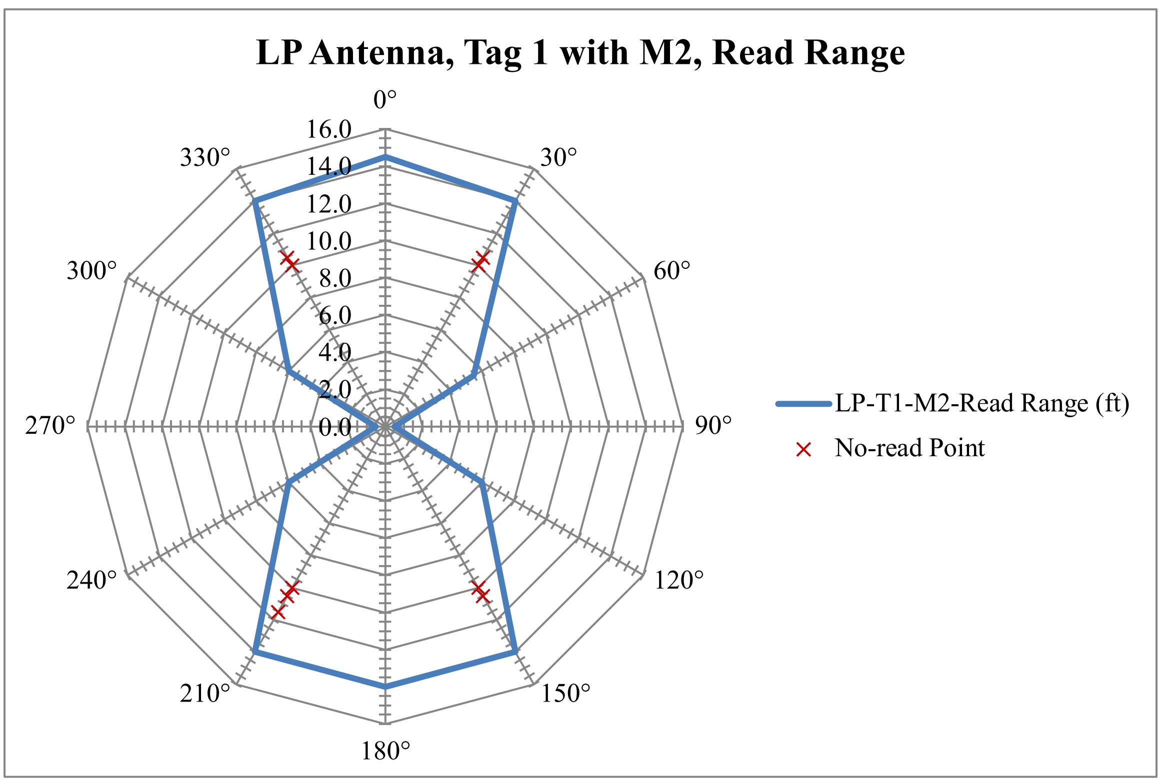


Figure 13 Read Range of Tag 1 with M2 Measured Using LP Antenna

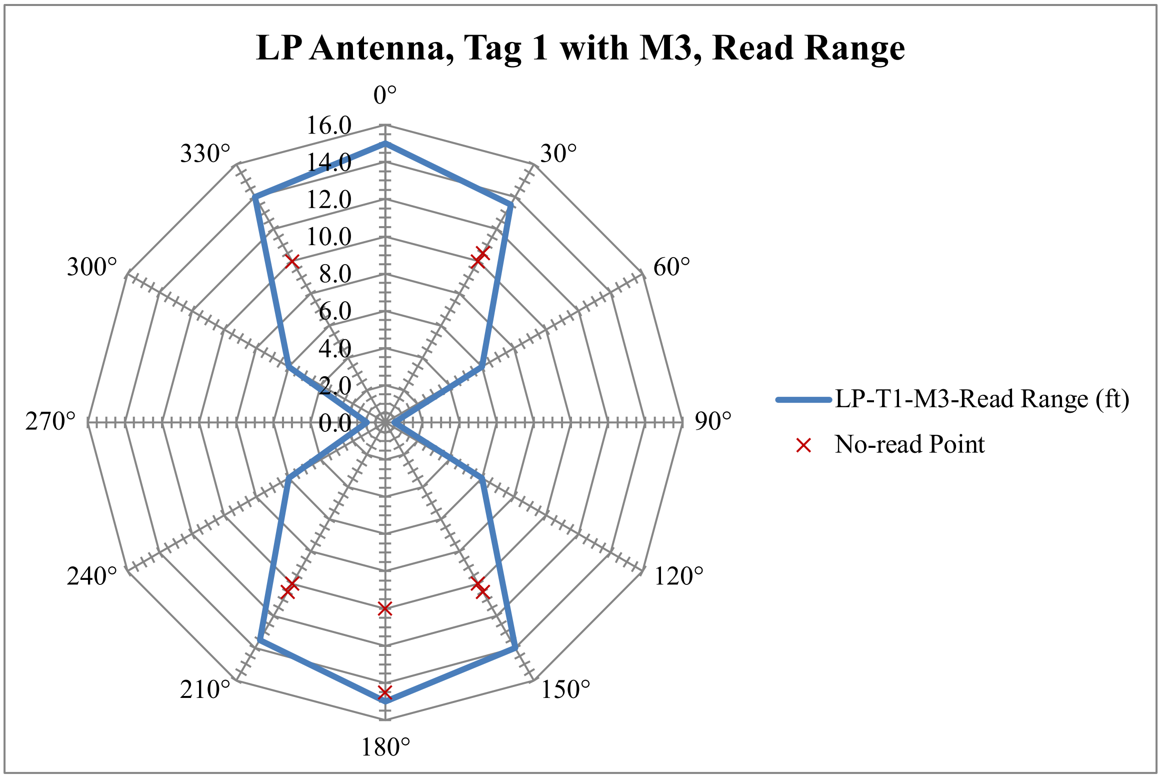


Figure 14 Read Range of Tag 1 with M3 Measured Using LP Antenna

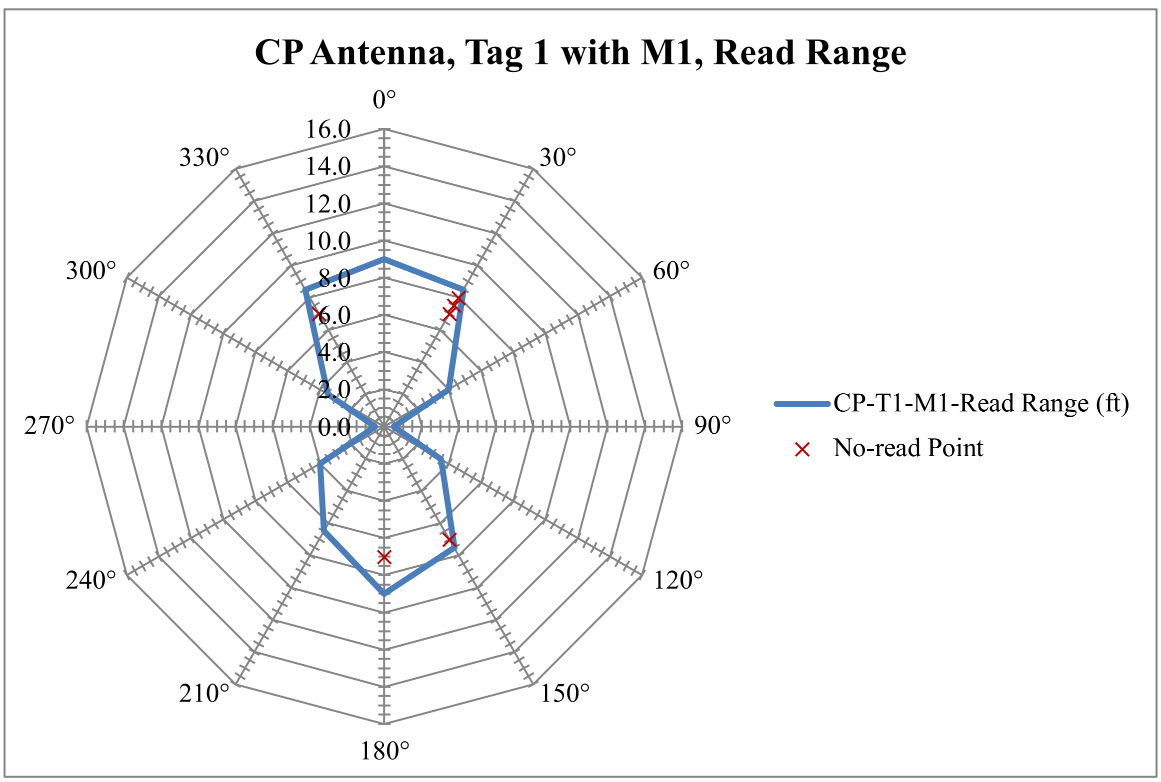


Figure 15 Read Range of Tag 1 with M1 Measured Using CP Antenna

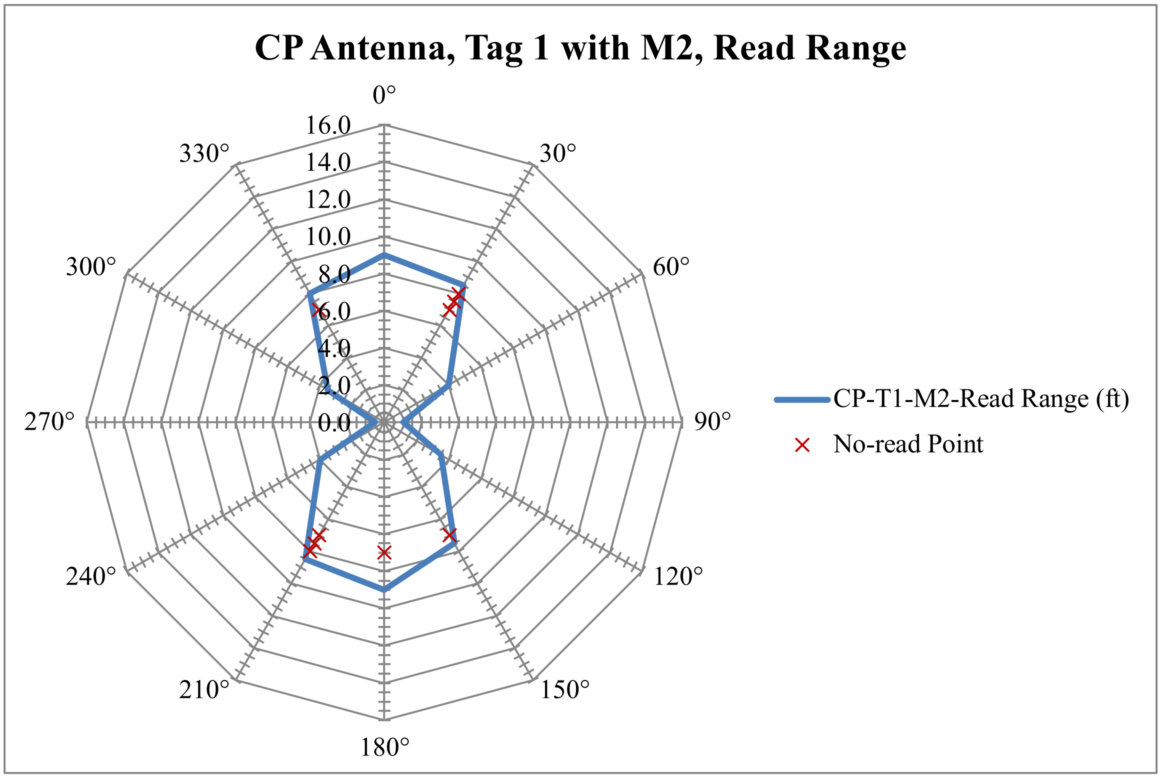


Figure 16 Read Range of Tag 1 with M2 Measured Using CP Antenna

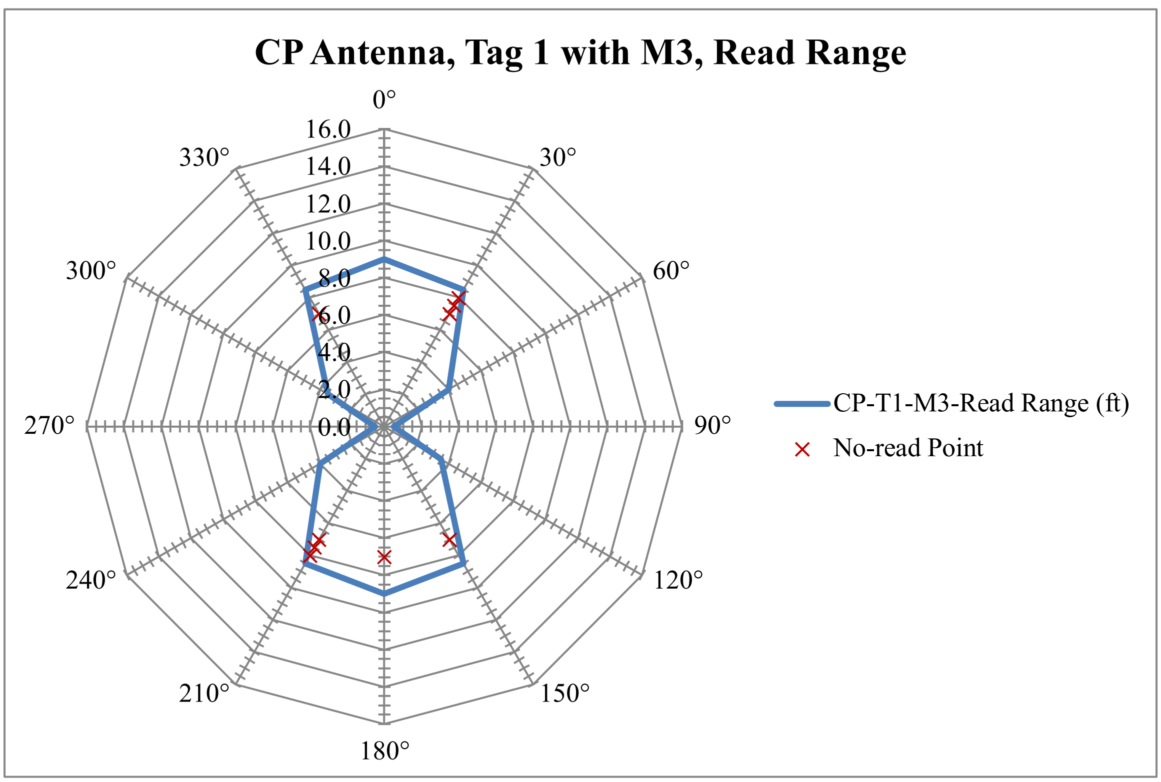


Figure 17 Read Range of Tag 1 with M3 Measured Using CP Antenna

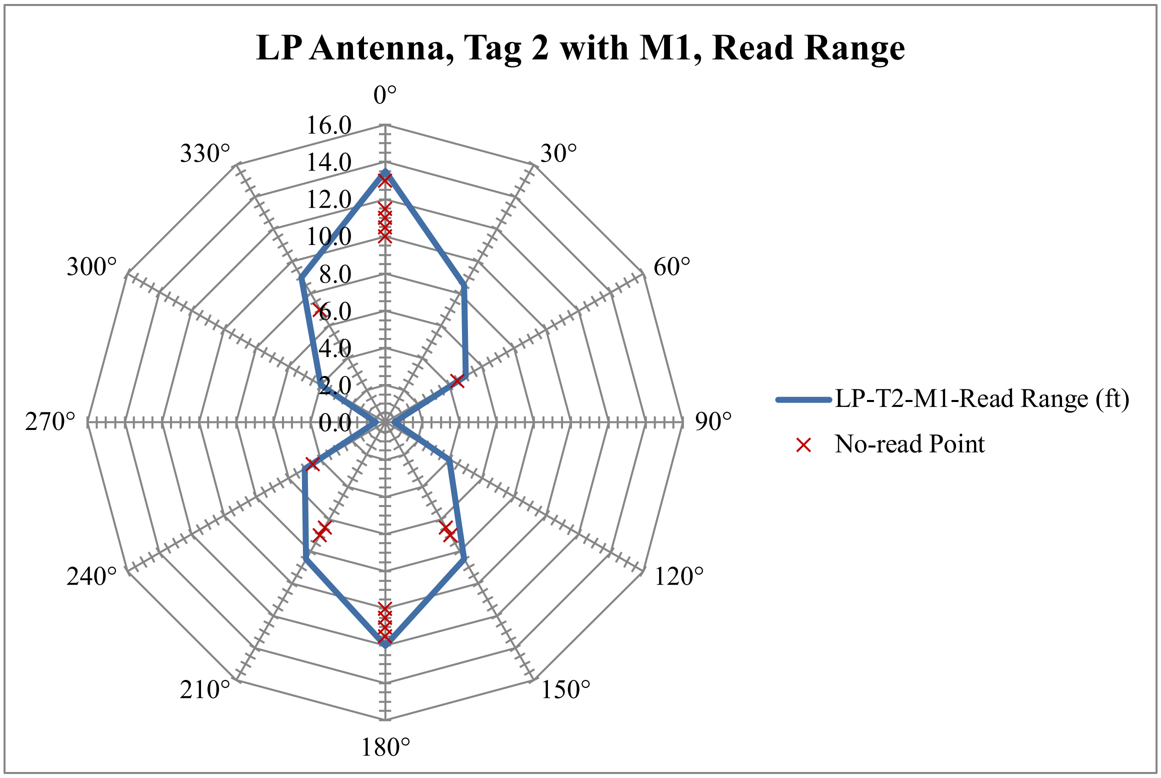


Figure 18 Read Range of Tag 2 with M1 Measured Using LP Antenna

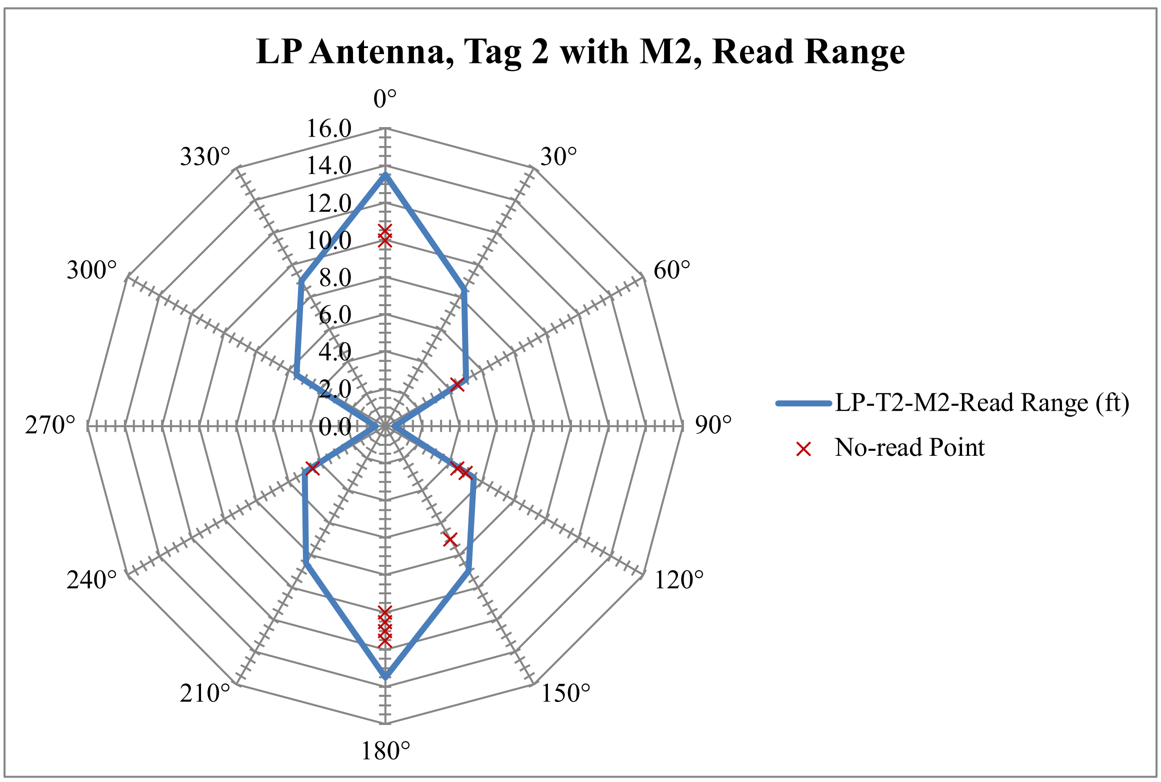


Figure 19 Read Range of Tag 2 with M2 Measured Using LP Antenna

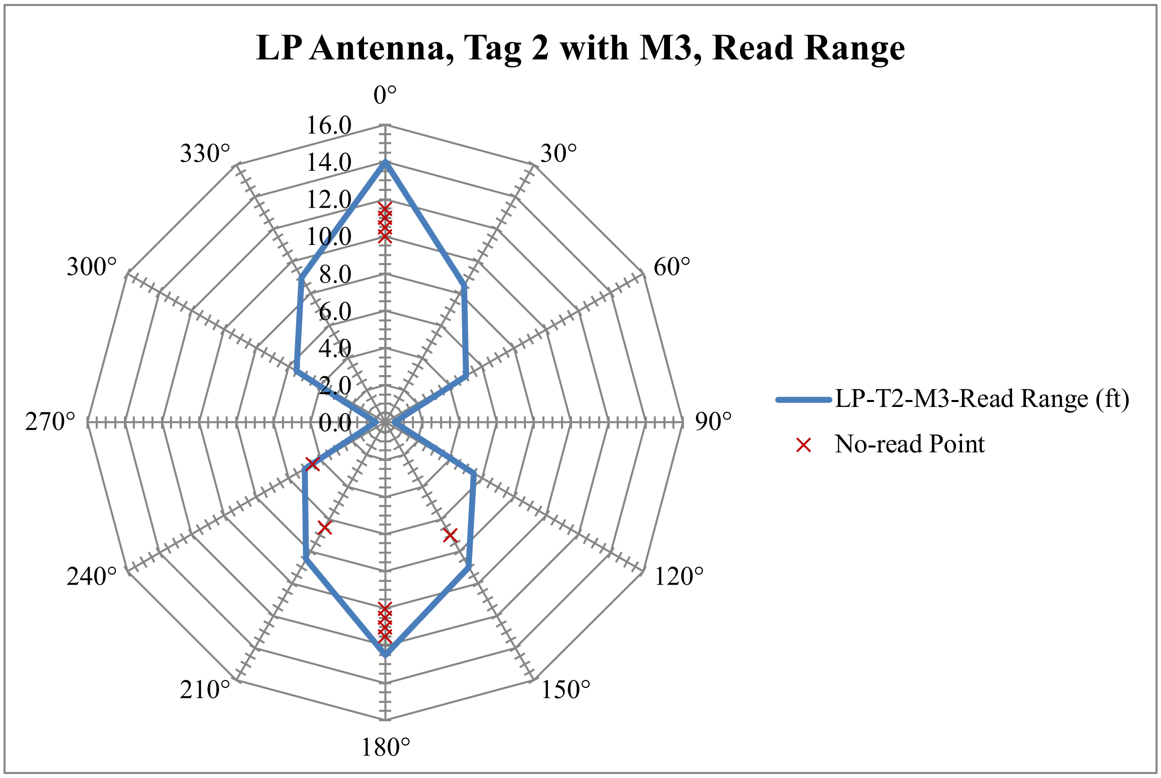


Figure 20 Read Range of Tag 2 with M3 Measured Using LP Antenna

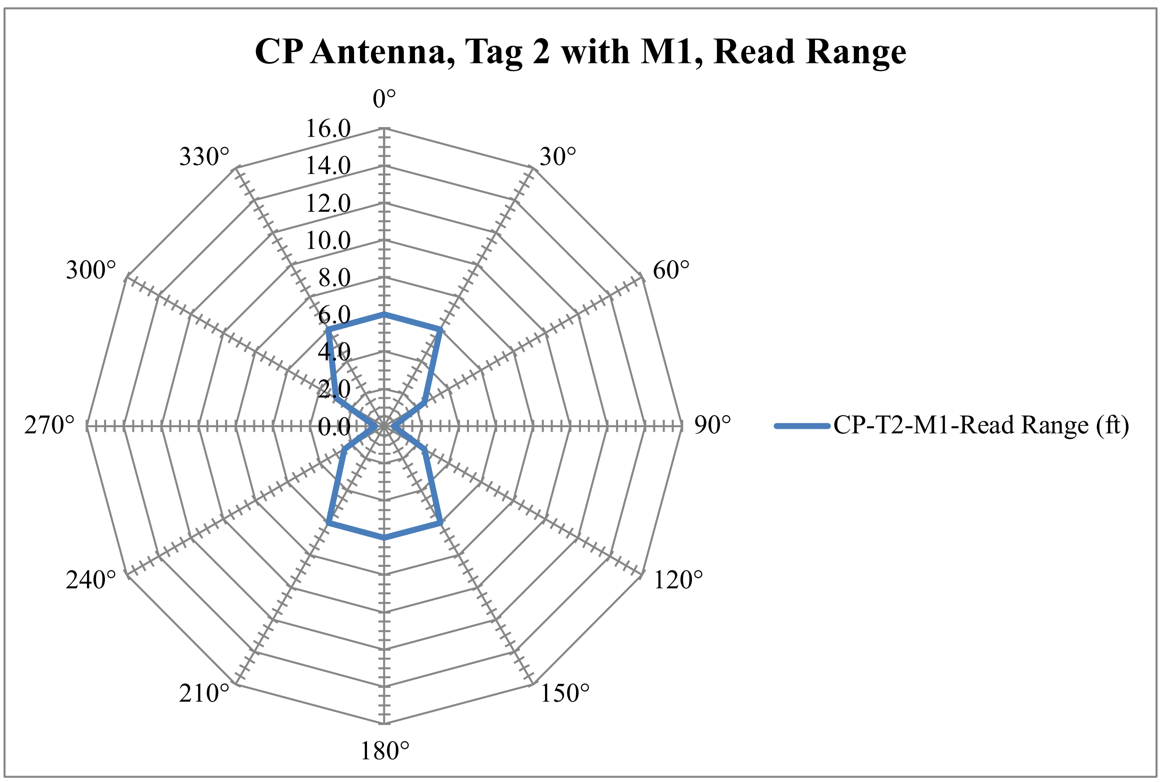


Figure 21 Read Range of Tag 2 with M1 Measured Using CP Antenna

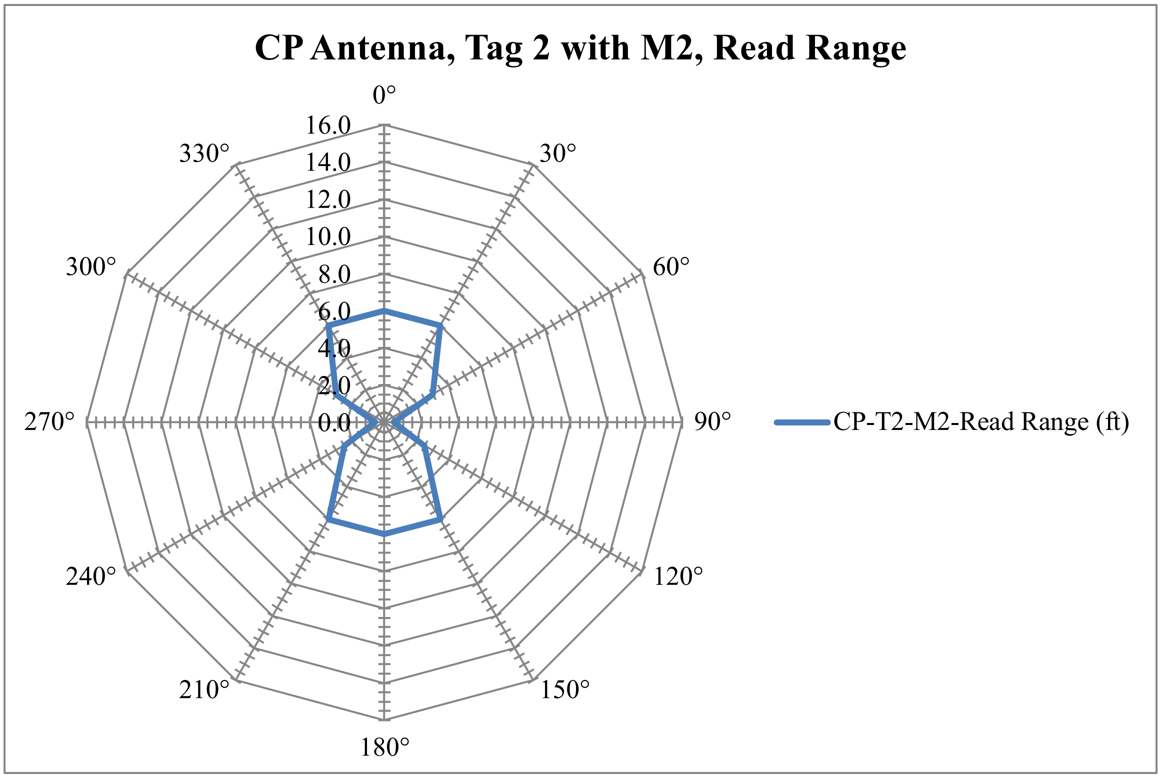


Figure 22 Read Range of Tag 2 with M2 Measured Using CP Antenna

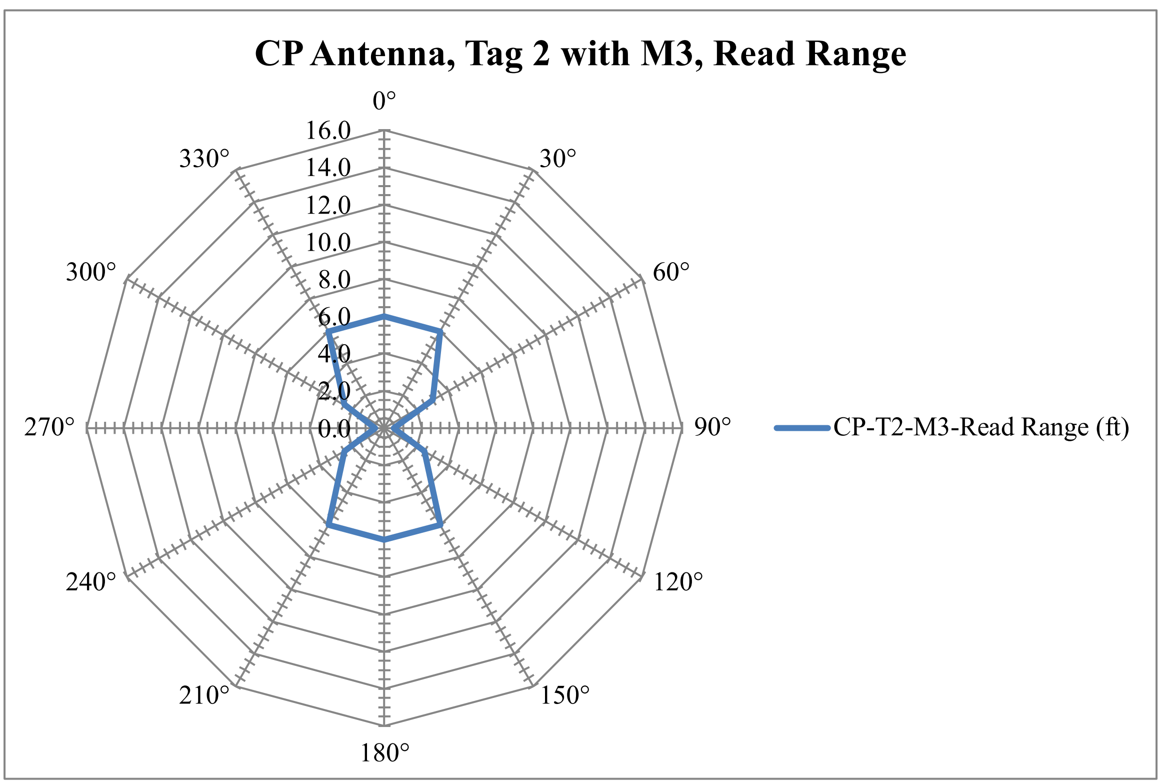


Figure 23 Read Range of Tag 2 with M3 Measured Using CP Antenna

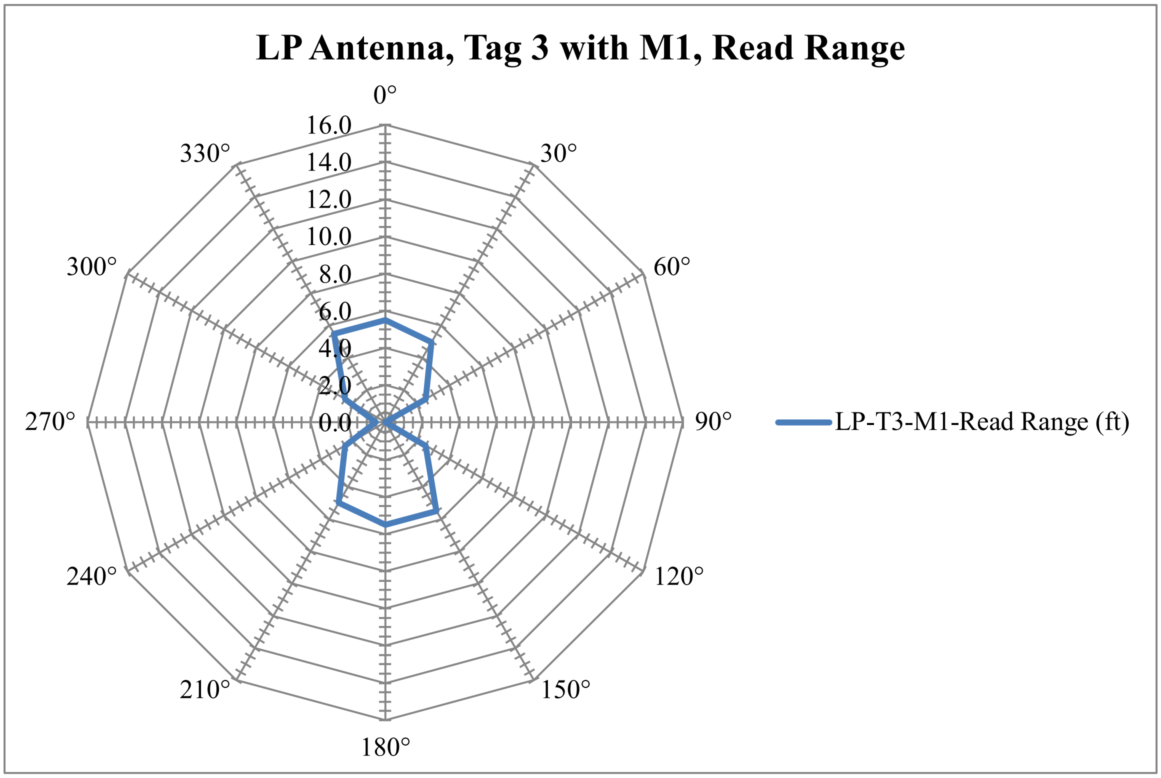


Figure 24 Read Range of Tag 3 with M1 Measured Using LP Antenna

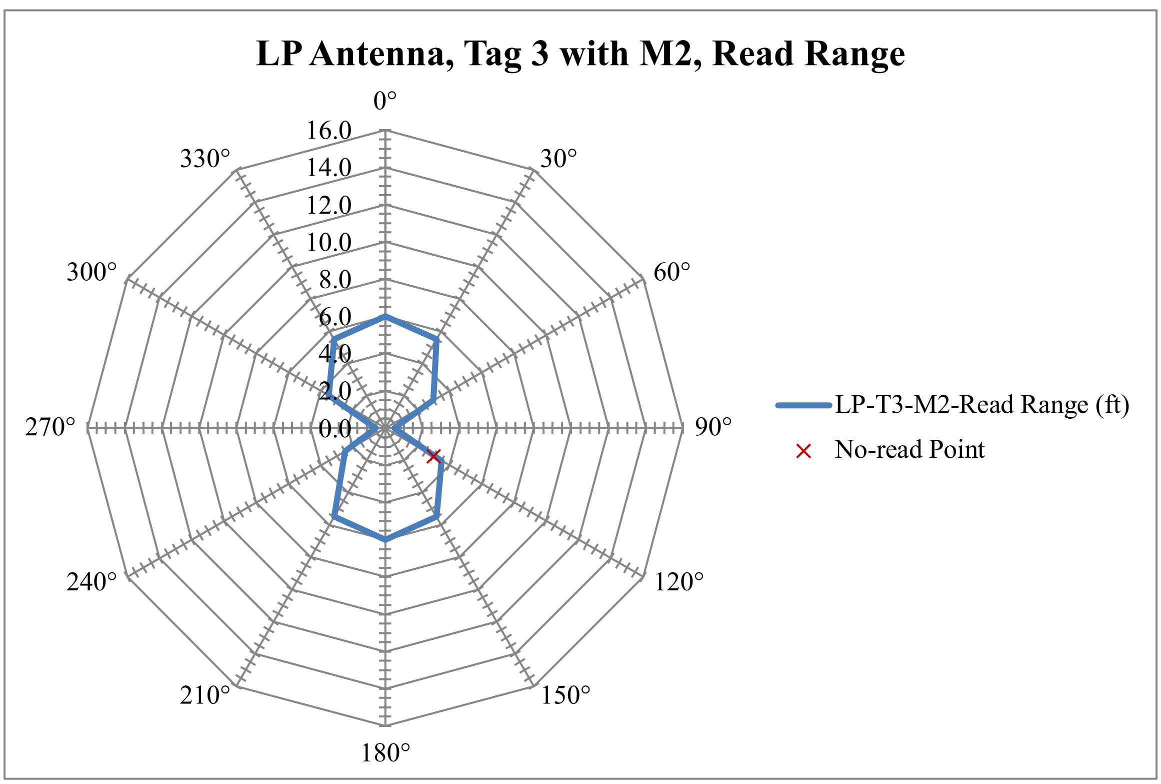


Figure 25 Read Range of Tag 3 with M2 Measured Using LP Antenna

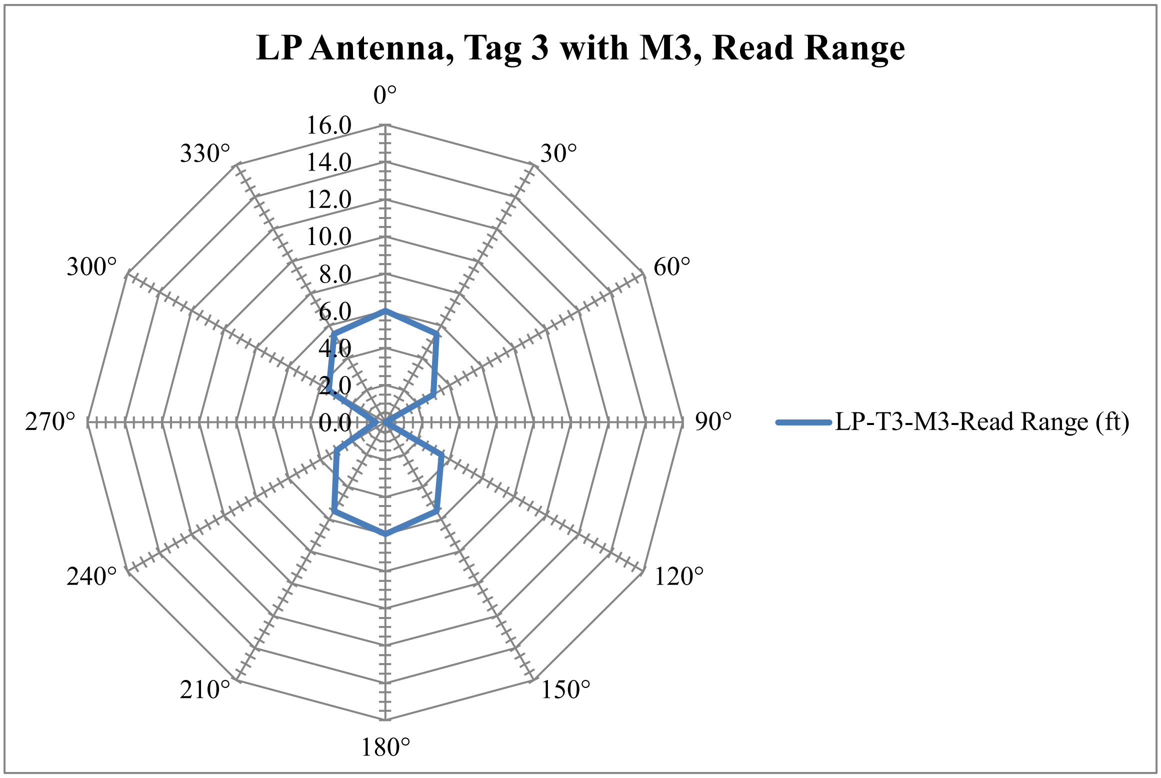


Figure 26 Read Range of Tag 3 with M3 Measured Using LP Antenna

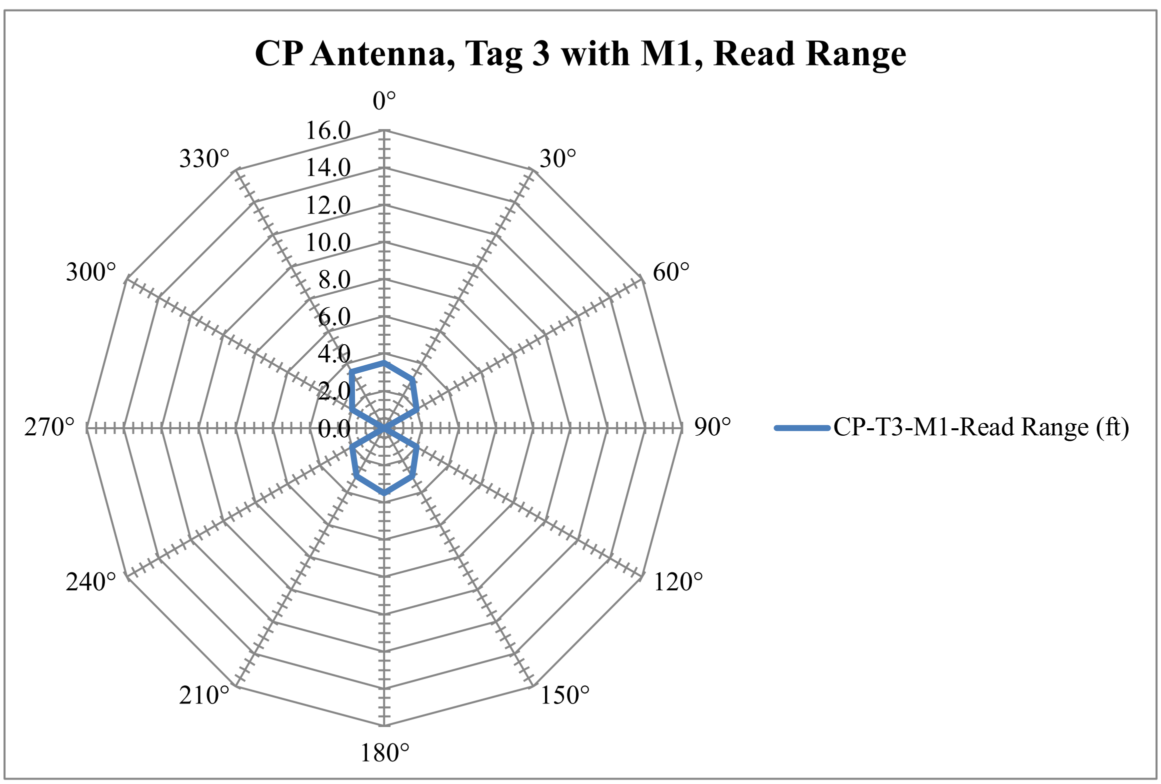


Figure 27 Read Range of Tag 3 with M1 Measured Using CP Antenna

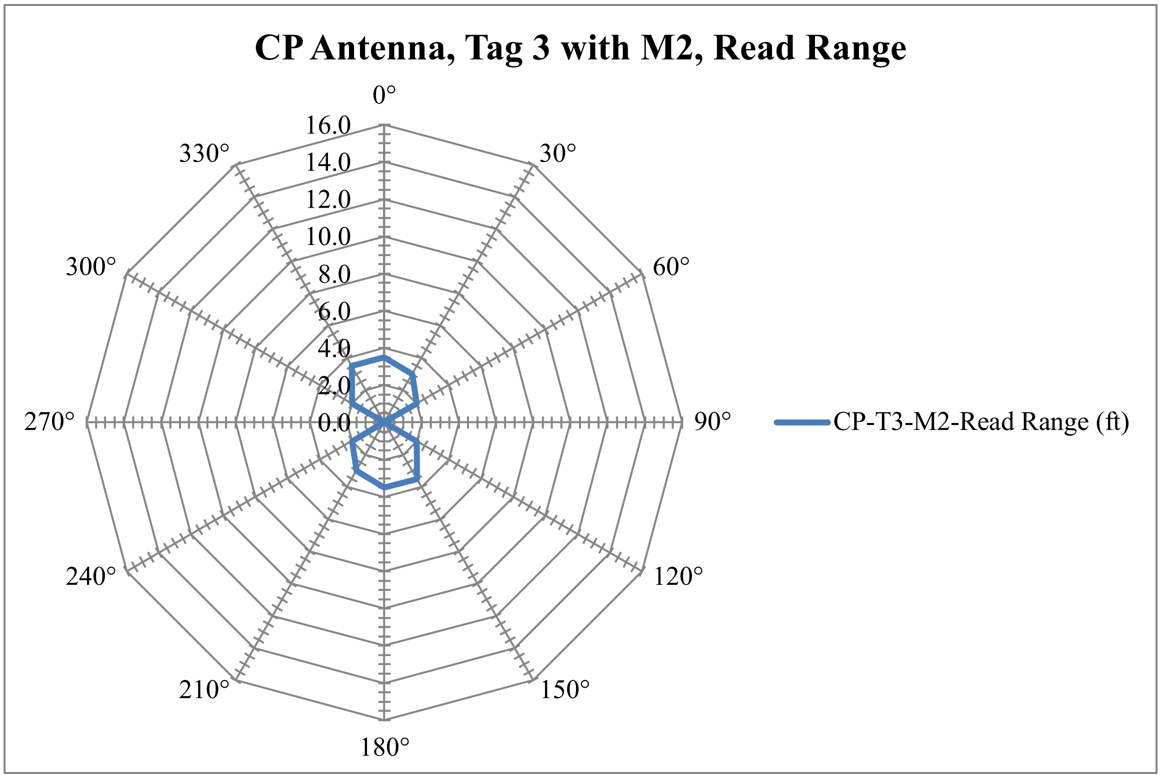


Figure 28 Read Range of Tag 3 with M2 Measured Using CP Antenna

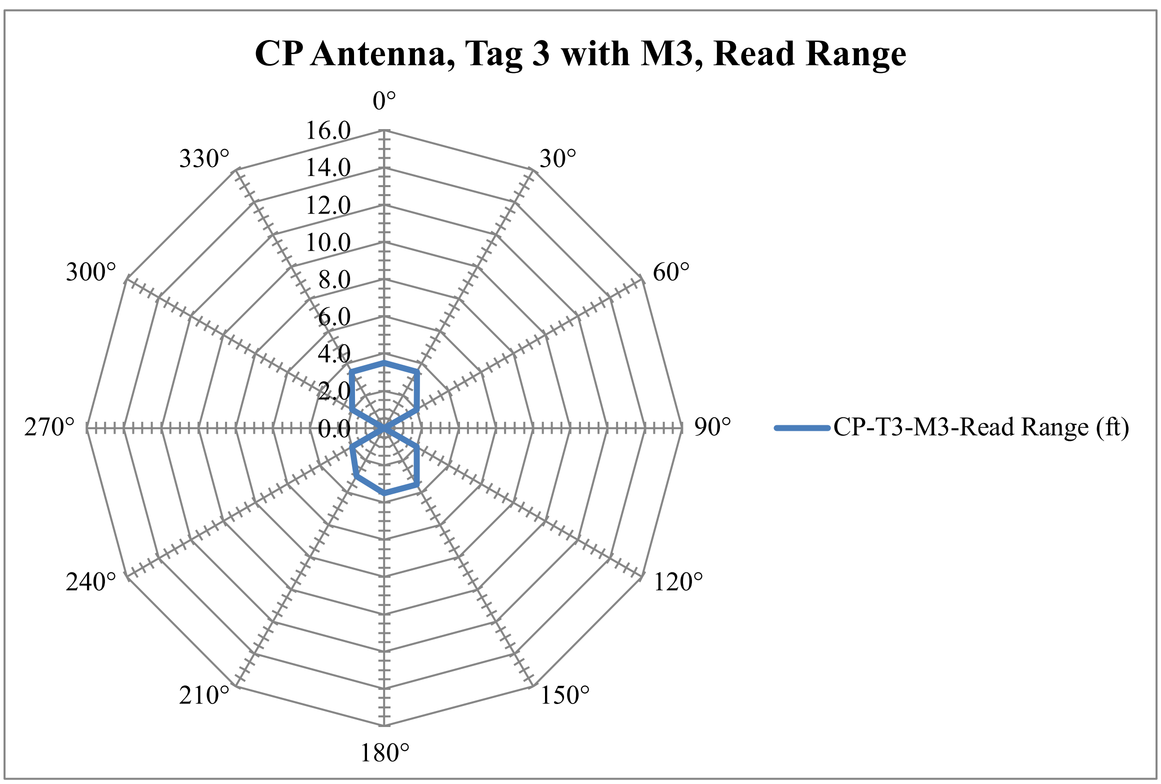


Figure 29 Read Range of Tag 3 with M3 Measured Using CP Antenna

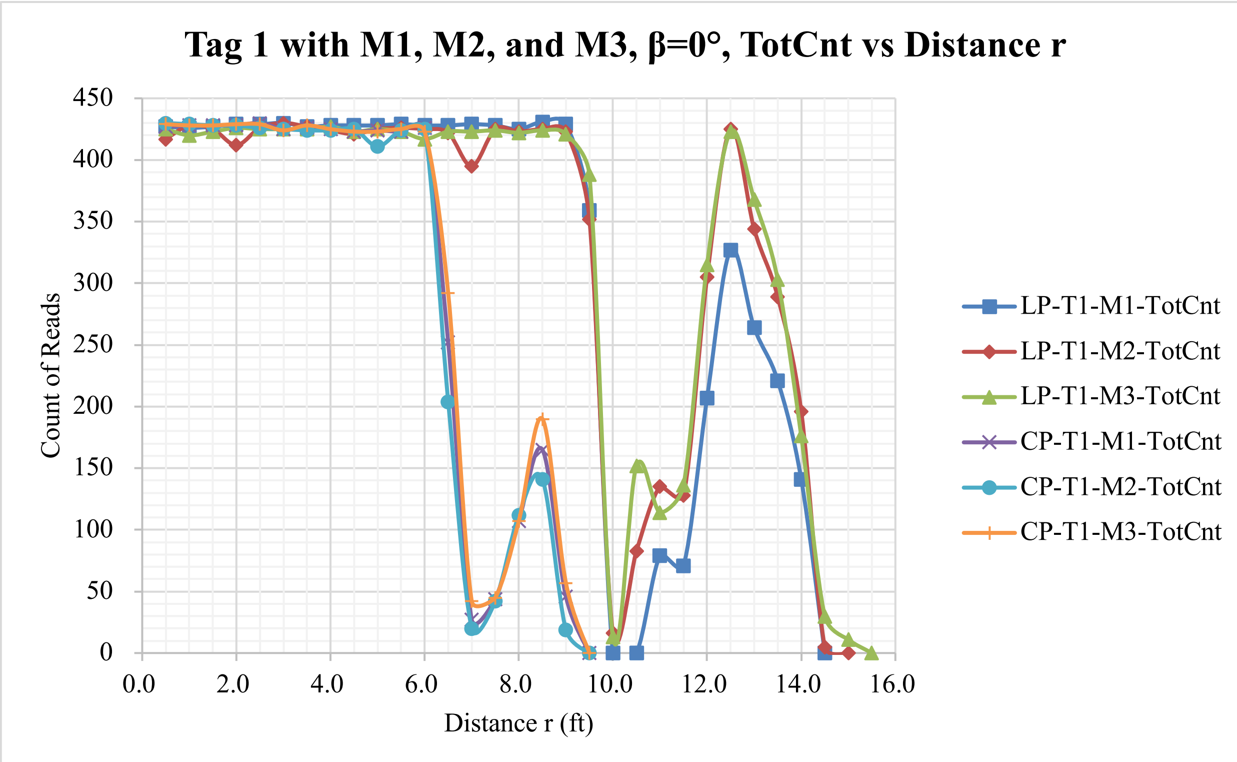


Figure 30 Tag 1 with M1, M2, and M3, TotCnt versus Distance when β=0°

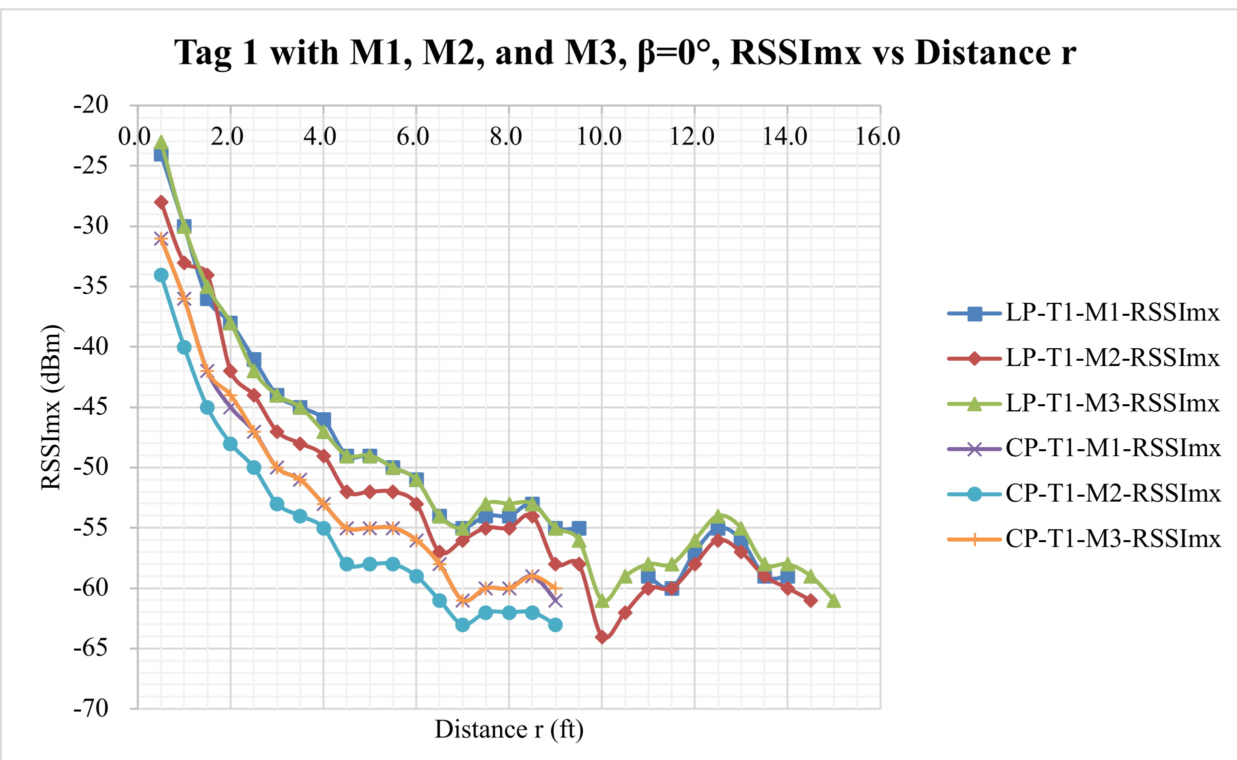


Figure 31 Tag 1 with M1, M2, and M3, RSSImx versus Distance when β=0°

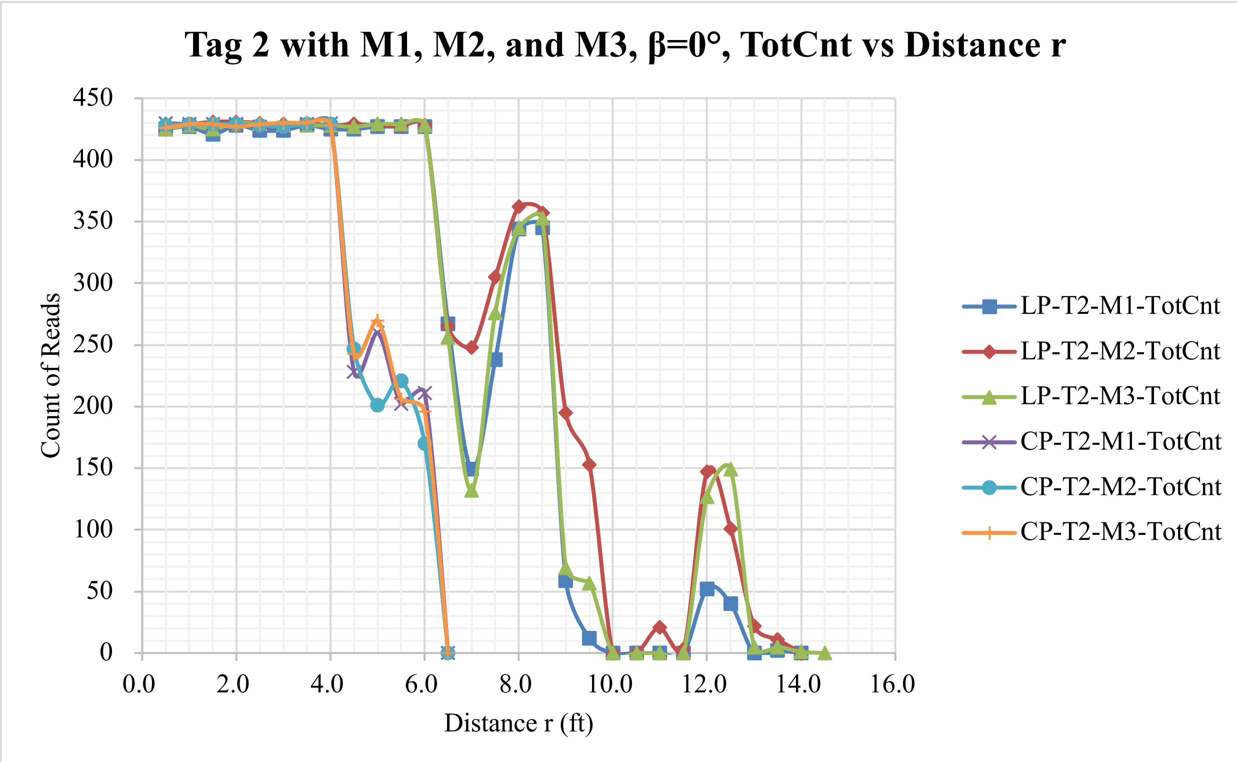


Figure 32 Tag 2 with M1, M2, and M3, TotCnt versus Distance when β=0°

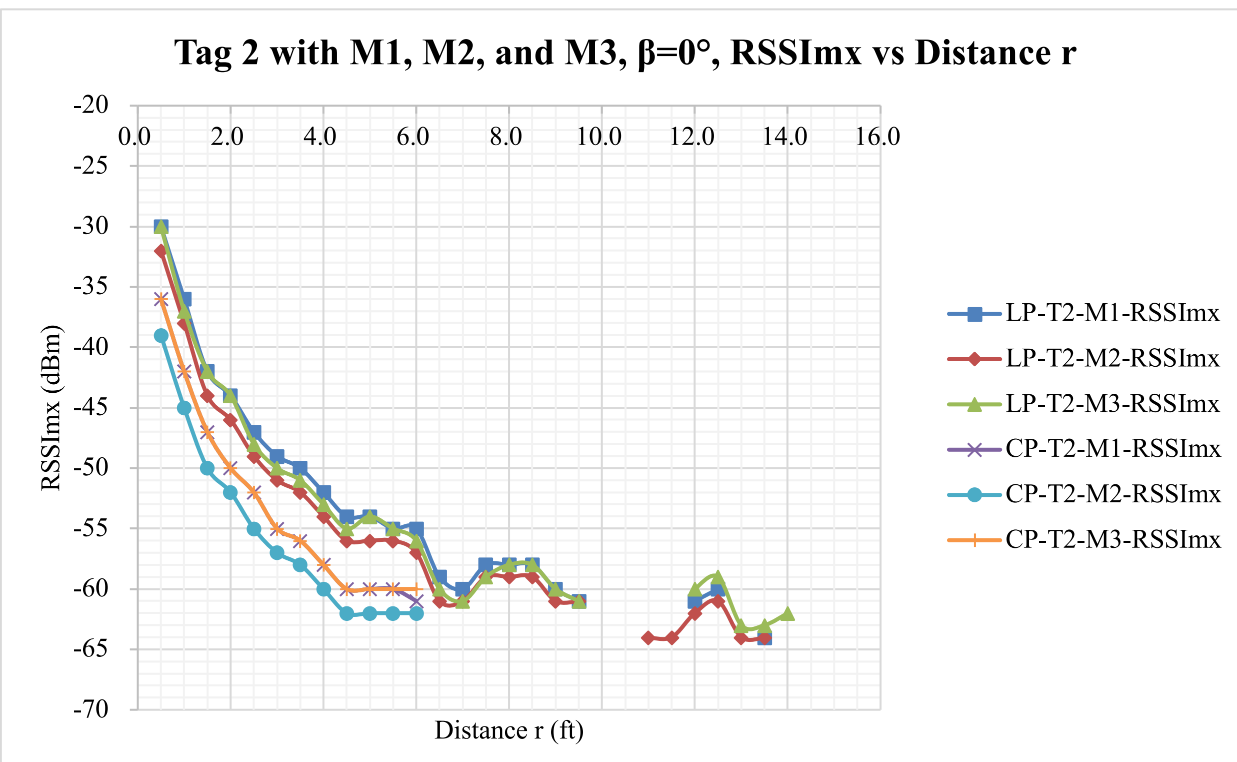


Figure 33 Tag 2 with M1, M2, and M3, RSSImx versus Distance when β=0°

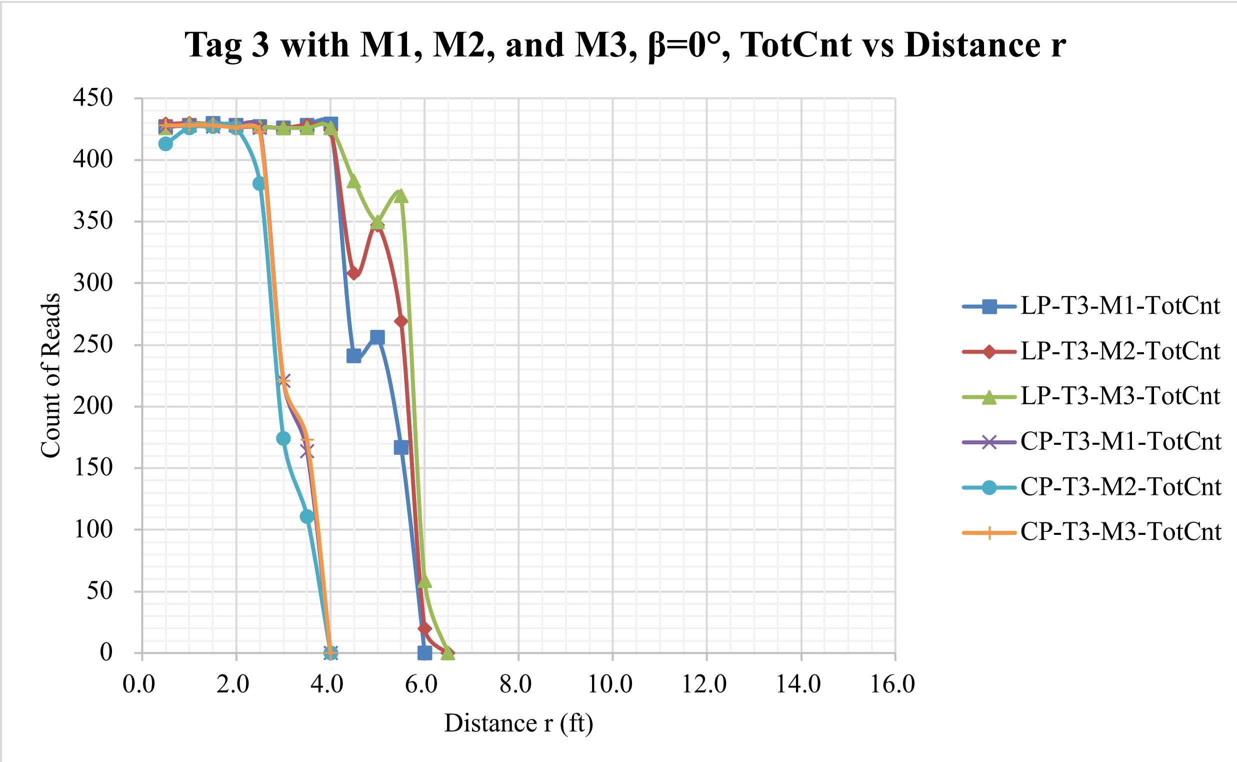


Figure 34 Tag 3 with M1, M2, and M3, TotCnt versus Distance when β=0°

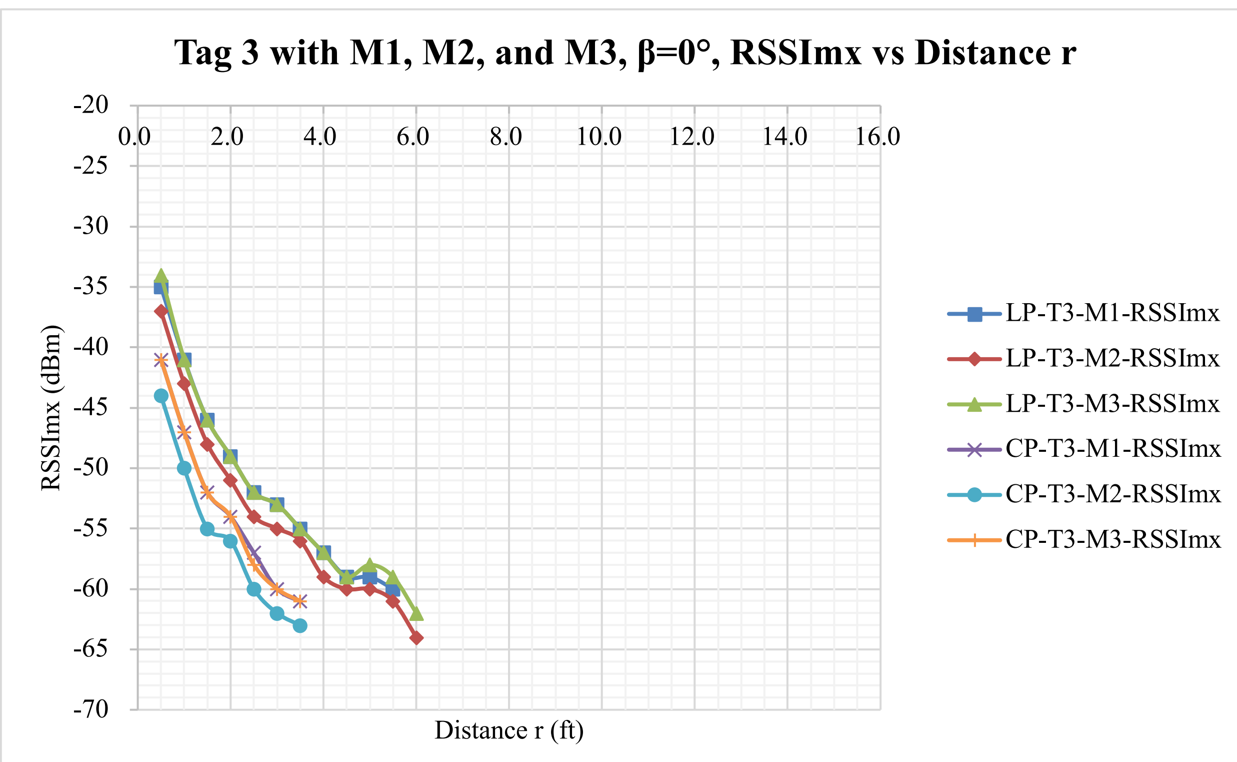


Figure 35 Tag 3 with M1, M2, and M3, RSSImx versus Distance when β=0°

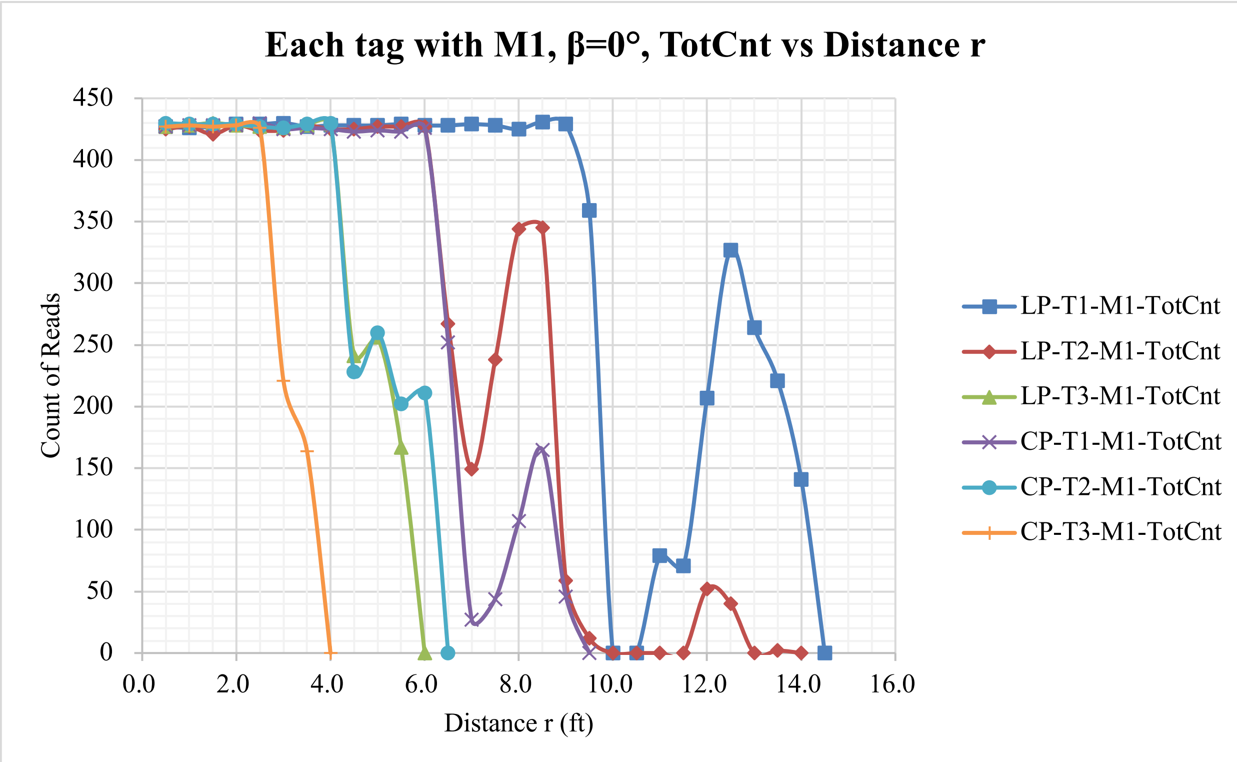


Figure 36 Each Tag with M1, TotCnt versus Distance when β=0°

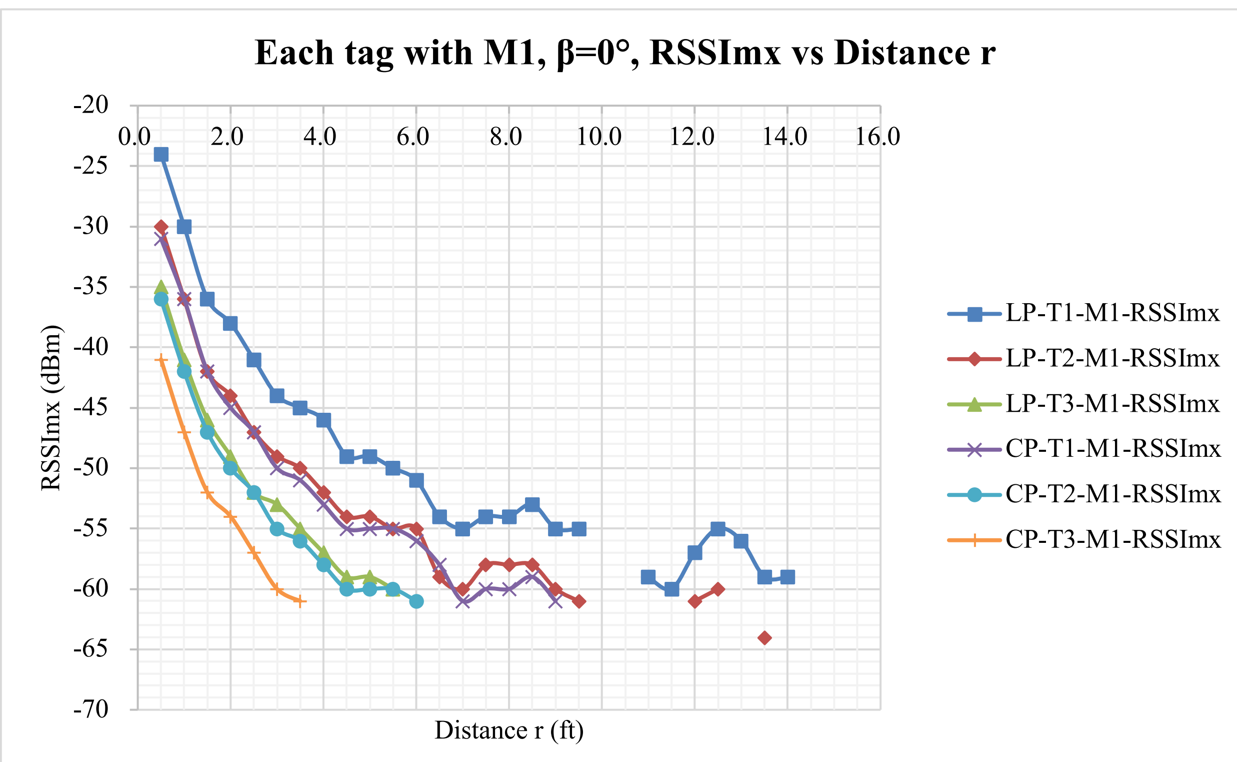


Figure 37 Each Tag with M1, RSSImx versus Distance when β=0°

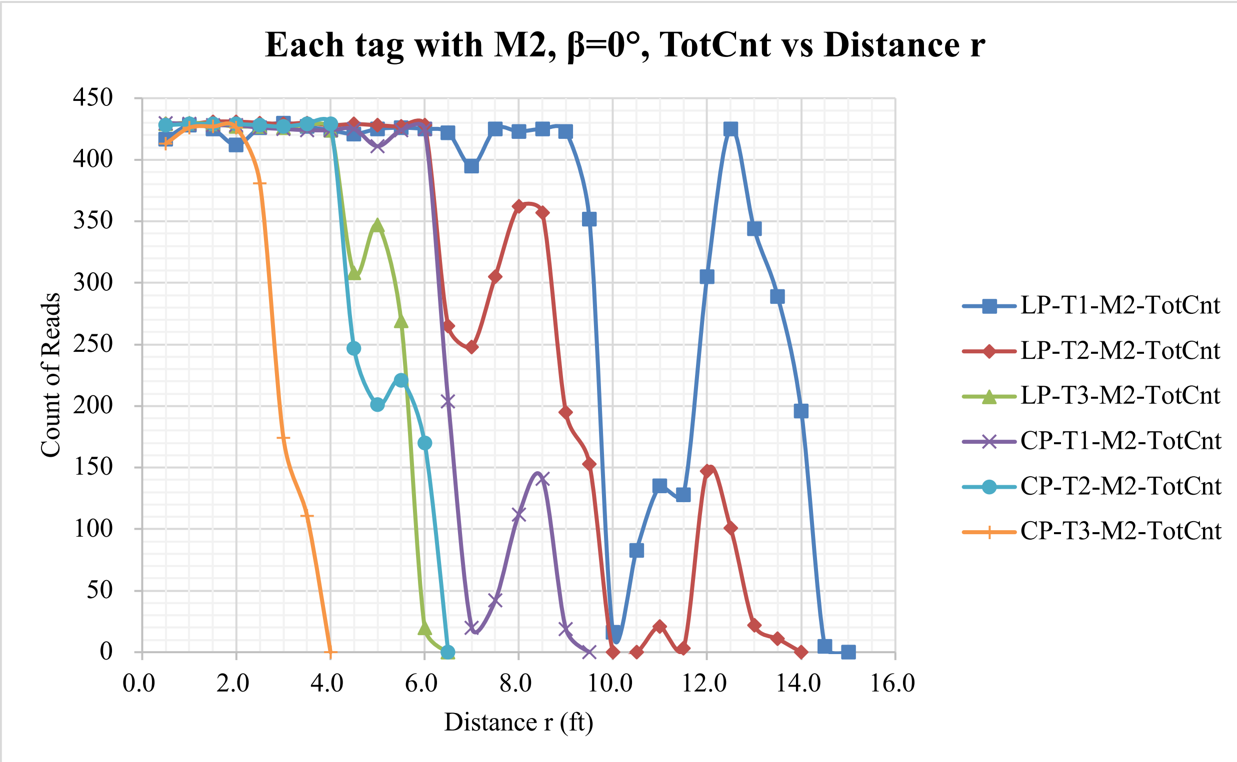


Figure 38 Each Tag with M2, TotCnt versus Distance when β=0°

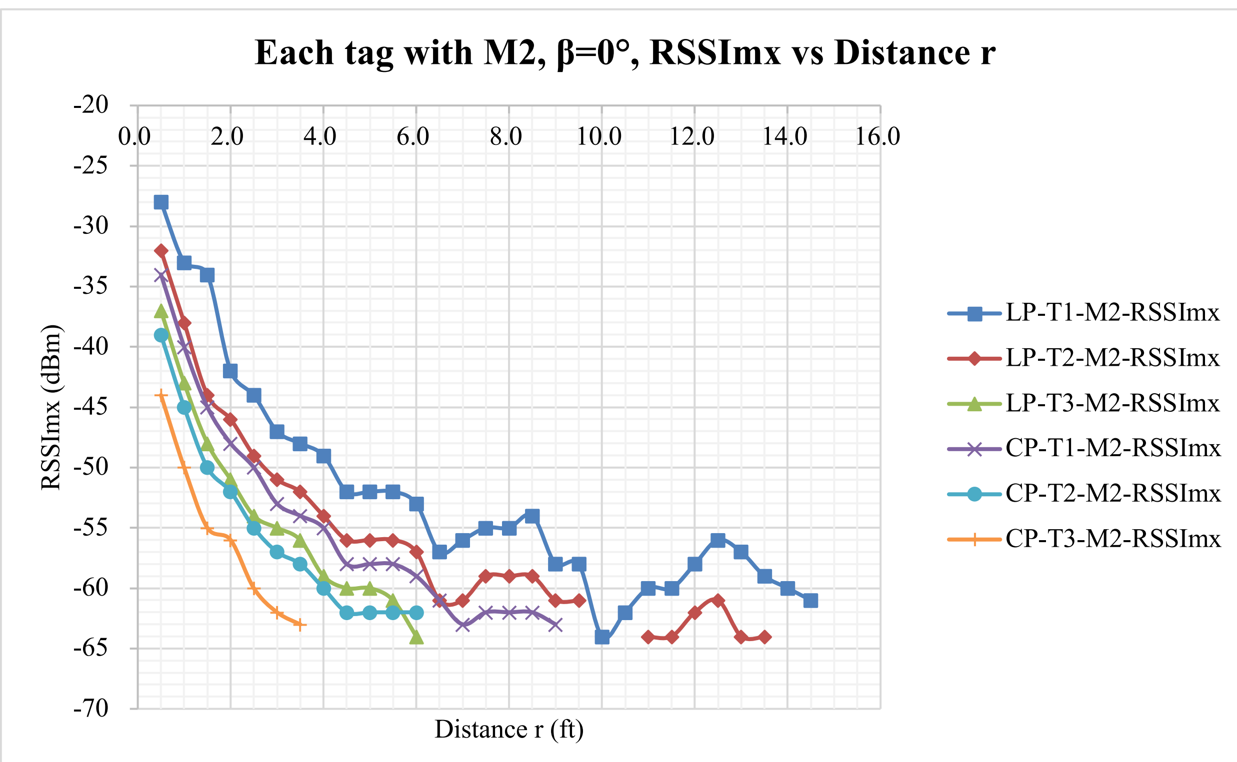


Figure 39 Each Tag with M2, RSSImx versus Distance when β=0°

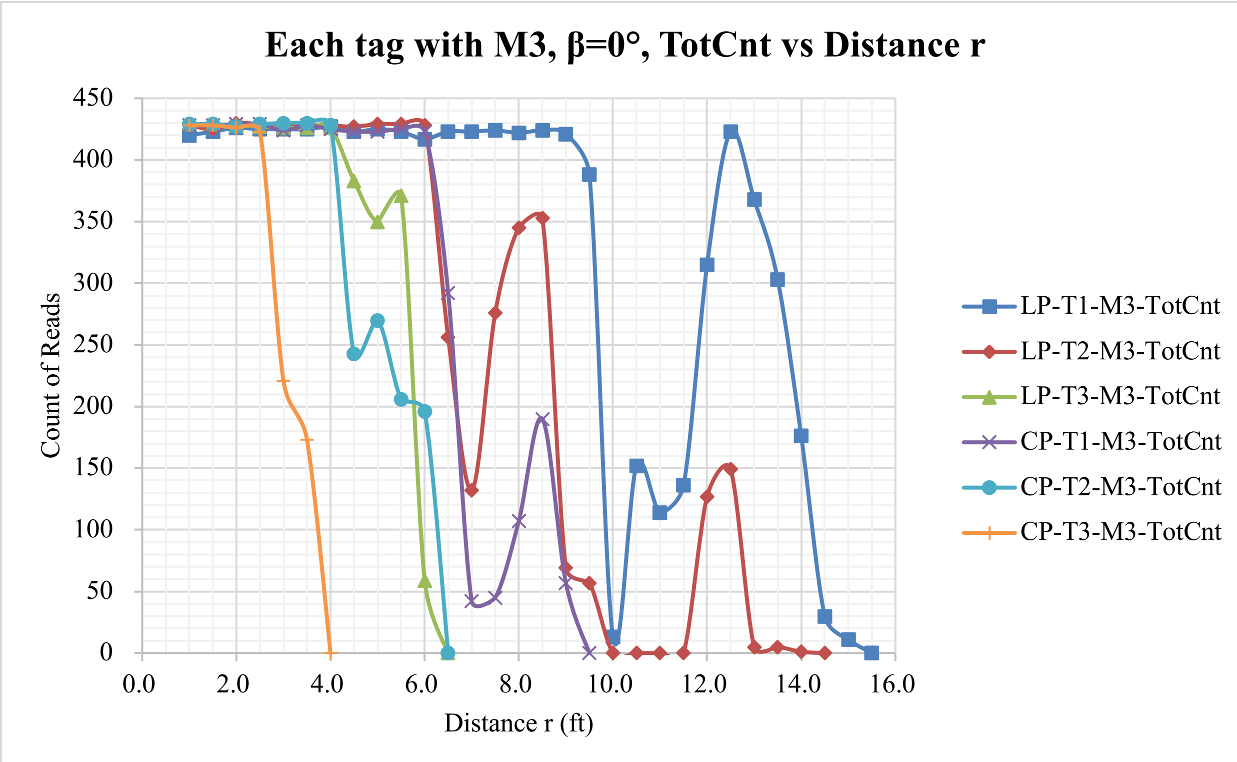


Figure 40 Each Tag with M3, TotCnt versus Distance when β=0°

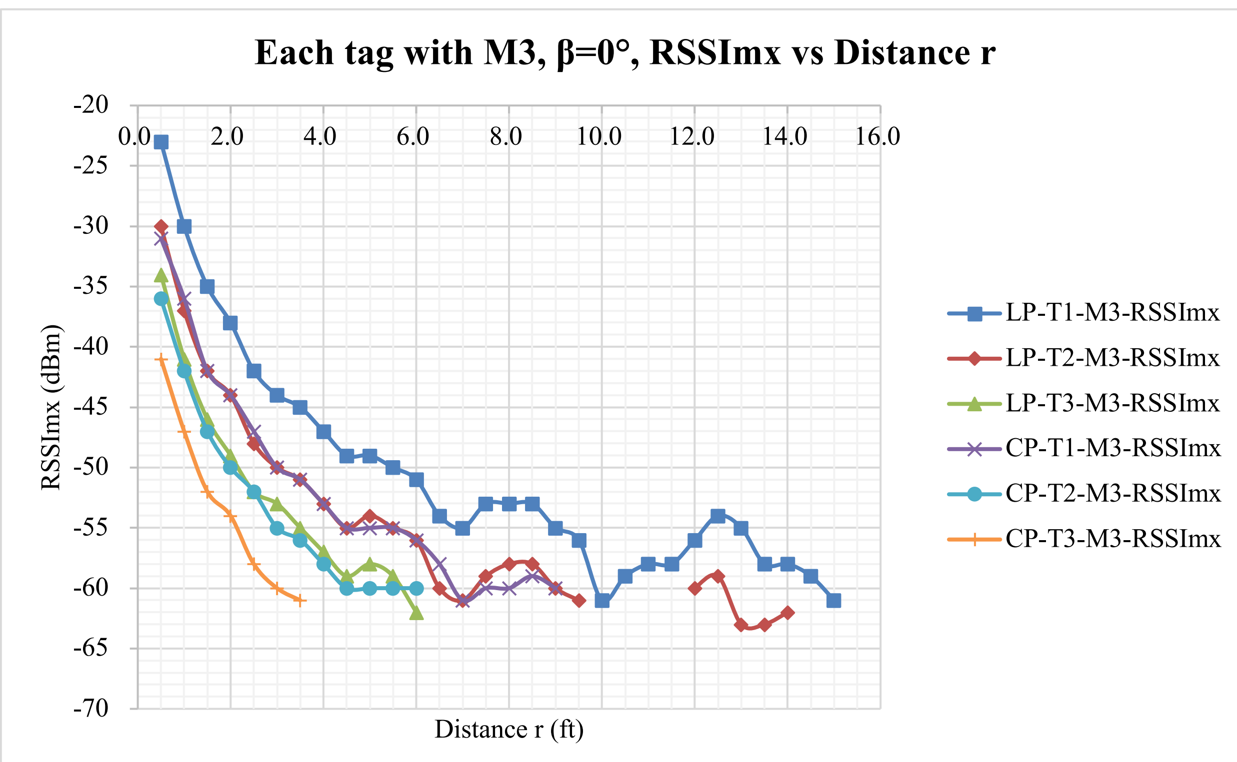


Figure 41 Each Tag with M3, RSSImx versus Distance when β=0°

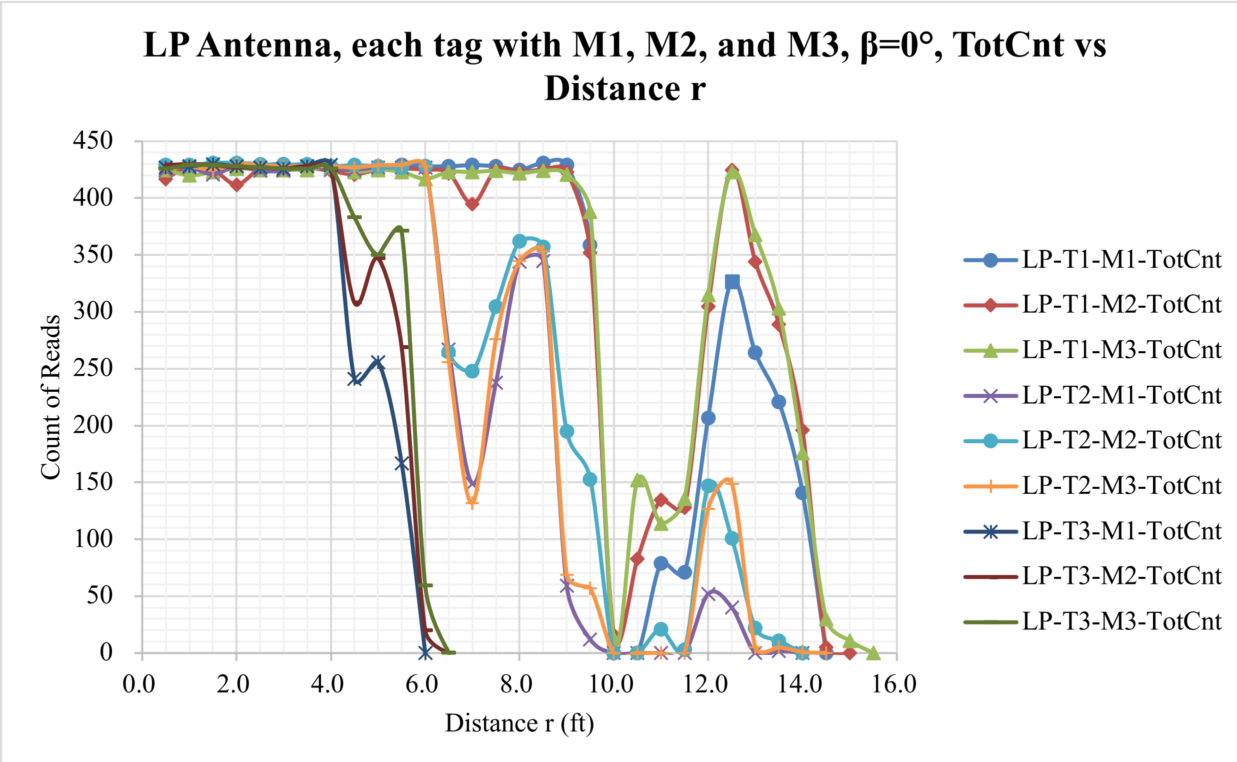


Figure 42 LP Antenna, Each Tag with M1, M2, and M3, TotCnt versus Distance when β=0°

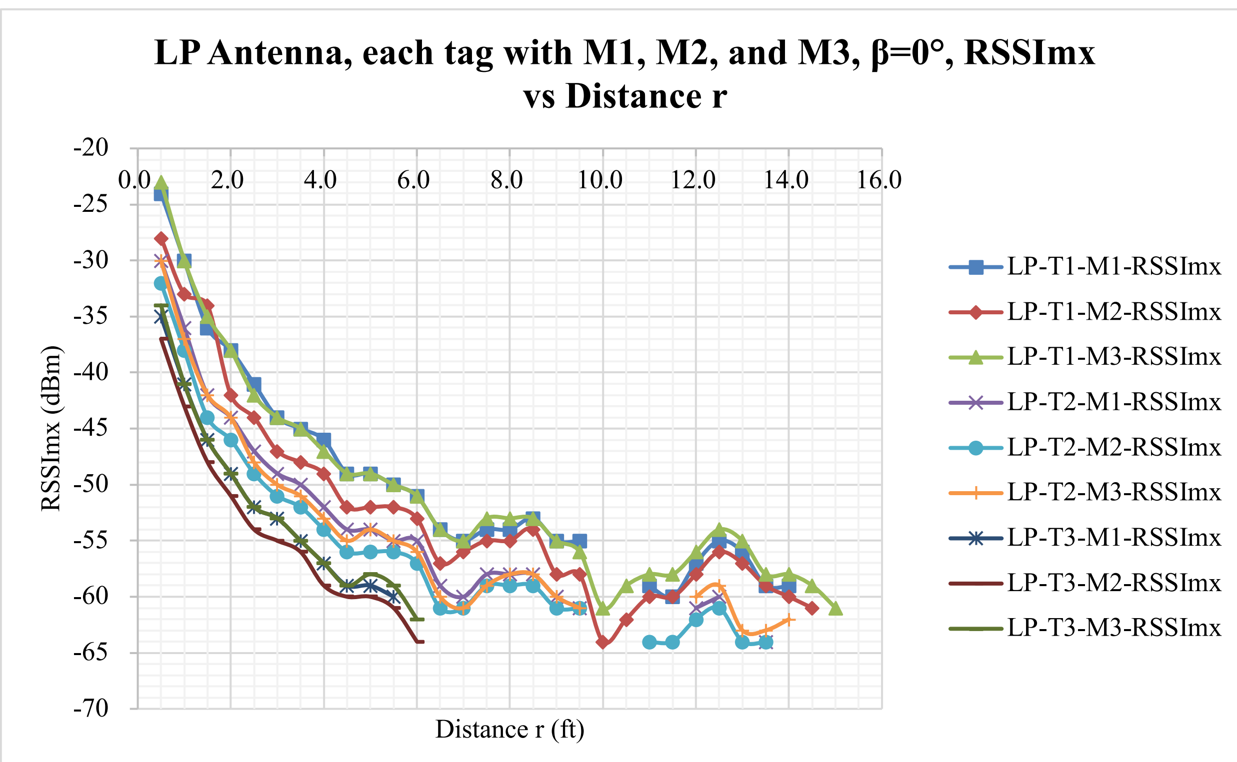


Figure 43 LP Antenna, Each Tag with M1, M2, and M3, RSSImx versus Distance when β=0°

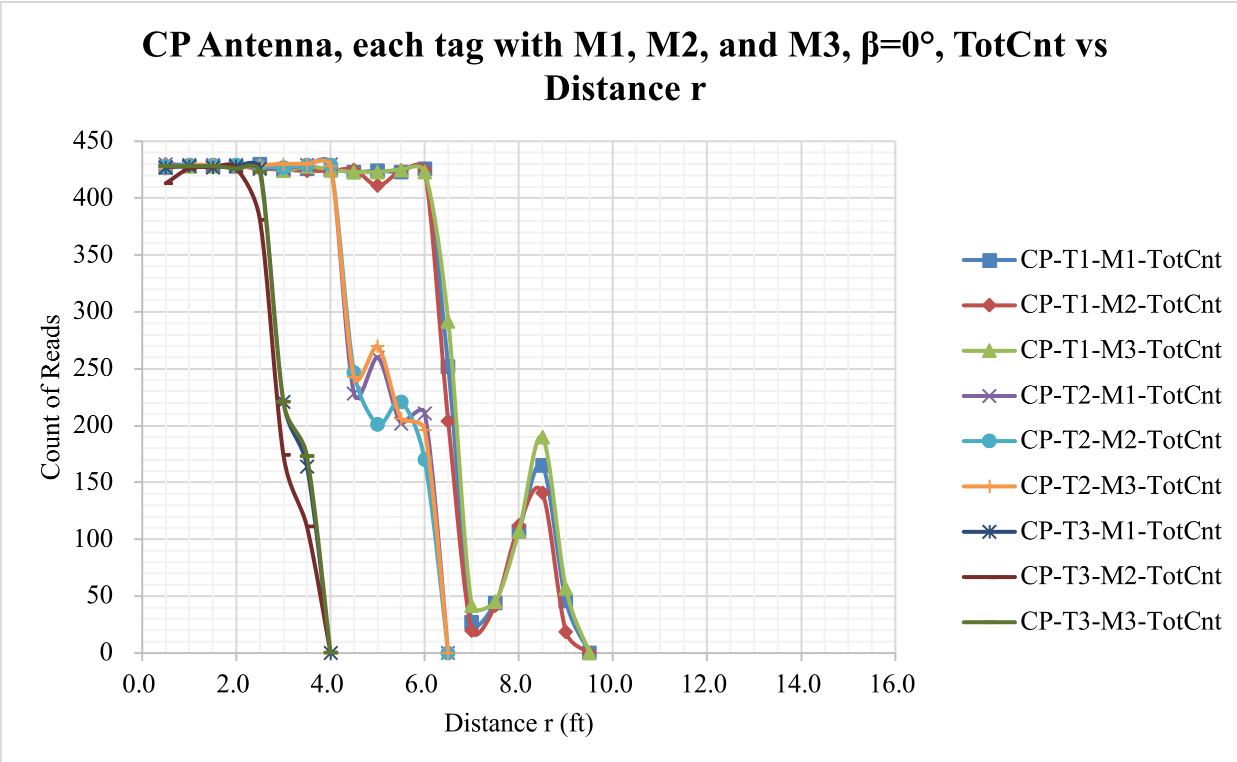


Figure 44 CP Antenna, Each Tag with M1, M2, and M3, TotCnt versus Distance when β=0°

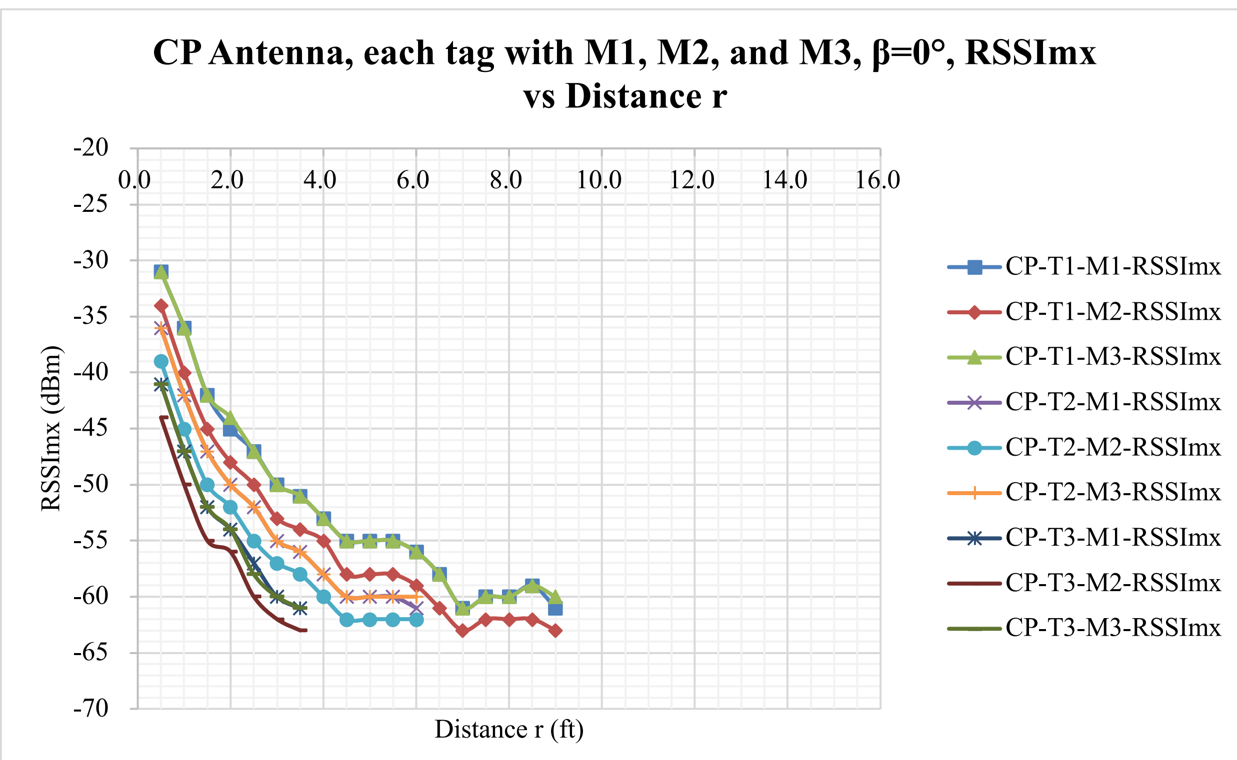


Figure 45 CP Antenna, Each Tag with M1, M2, and M3, TotCnt versus Distance when β=0°

4.2 Results of the Orientation Read Rate Test

In the orientation read rate test, the reader read the tag while the tag was located at the distance r=2 feet, and rotated to 60 orientations characterized by α-β-γ. The 60 sets of α-β-γ were randomly generated, where α, β, γ were integer multiples of 15°, and $0°\leq\alpha<180°$, $0°\leq\beta<360°$, $0°\leq\gamma\leq360°$. The measurement at each orientation of α-β-γ consisted of three trials, 5 seconds run for each trial. The reader recorded the TotCnt and RSSImx of each trial. Then, the integer of the average TotCnt of three trials, and the value of the maximum RSSImx of three trials were calculated and used to represent the TotCnt and RSSImx value of this measurement. The following terms were defined:

A *Read Orientation* was defined as a measurement of three trials at the orientation α-β-γ that had an average TotCnt value of at least 1. A *No-read Orientation* was defined as a measurement that had an average TotCnt less than 1. The No-read Orientations did not have any RSSImx value, since the reader could not detect any signal from the tag.

Table 11 to Table 16 are summaries of the orientation read rate test of the three tags with the four packaging materials using the LP and CP antenna. These tables first provide the count of Read Orientations for a tag with each material, then the maximum, minimum, mean, deviation values of the TotCnt and RSSImx was calculated from all the Read Orientations of the tag with a material. The TotCnt and RSSImx of the measurement at α=90°, β=0°, γ=0 and r=2 feet collected from the read range test are provided at the end of each table to serve as a reference. The orientation of 90°-0°-0° is the preferred orientation of each tag.

Table 11 Summary of the Orientation Read Rate Test of Tag 1 Using LP Antenna

LP Antenna, Tag 1					
Material		**M1**	**M2**	**M3**	**M4**
Count of Read Orientations		48	48	48	0
TotCnt of Read Orientations	**Max**	430	429	429	Not Applicable
	Min	138	22	333	
	Mean	407	401	422	
	Deviation	53.76	80.33	13.93	
RSSImx of Read Orientations	**Max**	-39	-42	-38	
	Min	-59	-63	-58	
	Mean	-45	-48	-44	
	Deviation	6	6	6	
Orientation of 90°-0°-0°	**TotCnt**	429	412	426	0
	RSSImx	-38	-42	-38	Not Applicable

Table 12 Summary of the Orientation Read Rate Test of Tag 1 Using CP Antenna

CP Antenna, Tag 1					
Material		**M1**	**M2**	**M3**	**M4**
Count of Read Orientations		50	47	48	0
TotCnt of Read Orientations	**Max**	430	430	429	Not Applicable
	Min	4	2	34	
	Mean	371	392	390	
	Deviation	126.96	88.55	93.79	
RSSImx of Read Orientations	**Max**	-44	-46	-44	
	Min	-63	-64	-61	
	Mean	-51	-54	-51	
	Deviation	5	5	5	
Orientation of 90°-0°-0°	**TotCnt**	428	428	429	0
	RSSImx	-45	-48	-44	Not Applicable

Table 13 Summary of the Orientation Read Rate Test of Tag 2 Using LP Antenna

LP Antenna Tag 2				
Material	**M1**	**M2**	**M3**	**M4**
Count of Read Orientations	45	45	45	0

Table 13 (cont'd)

LP Antenna Tag 2					
Material		**M1**	**M2**	**M3**	**M4**
TotCnt of Read Orientations	**Max**	430	429	430	Not Applicable
	Min	1	47	1	
	Mean	361	367	368	
	Deviation	134.88	120.84	121.36	
RSSImx of Read Orientations	**Max**	-45	-47	-44	
	Min	-63	-64	-62	
	Mean	-51	-54	-51	
	Deviation	5	5	5	
Orientation of 90°-0°-0°	**TotCnt**	428	431	430	0
	RSSImx	-44	-46	-44	Not Applicable

Table 14 Summary of the Orientation Read Rate Test of Tag 2 Using CP Antenna

CP Antenna, Tag 2					
Material		**M1**	**M2**	**M3**	**M4**
Count of Read Orientations		43	44	45	0
TotCnt of Read Orientations	**Max**	430	430	430	Not Applicable
	Min	7	2	14	
	Mean	348	335	336	
	Deviation	137.43	142.64	143.91	
RSSImx of Read Orientations	**Max**	-49	-51	-49	
	Min	-64	-67	-64	
	Mean	-56	-58	-56	
	Deviation	4	4	4	
Orientation of 90°-0°-0°	**TotCnt**	429	429	427	0
	RSSImx	-50	-52	-50	Not Applicable

Table 15 Summary of the Orientation Read Rate Test of Tag 3 Using LP Antenna

LP Antenna Tag 3					
Material		**M1**	**M2**	**M3**	**M4**
Count of Read Orientations		35	36	36	0
TotCnt of Read Orientations	**Max**	428	428	428	Not Applicable
	Min	45	47	4	

Table 15 (cont'd)

LP Antenna Tag 3					
Material		**M1**	**M2**	**M3**	**M4**
TotCnt of Read Orientations	**Mean**	405	400	393	
	Deviation	81.20	80.83	107.43	
RSSImx of Read Orientations	**Max**	-48	-50	-49	
	Min	-61	-63	-62	
	Mean	-53	-55	-52	
	Deviation	3	3	3	
Orientation of 90°-0°-0°	**TotCnt**	428	427	428	0
	RSSImx	-49	-51	-49	Not Applicable

Table 16 Summary of the Orientation Read Rate Test of Tag 3 Using CP Antenna

CP Antenna, Tag 3					
Material		**M1**	**M2**	**M3**	**M4**
Count of Read Orientations		31	32	32	0
TotCnt of Read Orientations	**Max**	428	429	428	Not Applicable
	Min	7	3	10	
	Mean	345	339	341	
	Deviation	137.94	148.61	147.88	
RSSImx of Read Orientations	**Max**	-53	-55	-53	
	Min	-63	-65	-63	
	Mean	-59	-60	-59	
	Deviation	3	3	3	
Orientation of 90°-0°-0°	**TotCnt**	428	426	426	0
	RSSImx	-54	-56	-54	Not Applicable

Comparing within each table to evaluate the effect of materials on the tag's performance in the orientation read rate test, the observations include:

1) There was no Read Orientation for M4 (PET/Al/polyethylene film) for any tags using either antenna;

2) Material M1, M2 and M3 resulted in similar counts of Read Orientations. The counts were either identical, or no more than 3 counts in difference;
3) Material M1, M2 and M3 had little difference on the maximum and mean values of TotCnt. The minimum TotCnt with M1, M2 and M3 showed difference in Table 11, Table 12, Table 13, and Table 15, but the difference was not consistent;
4) Material M2 showed smaller maximum, minimum and mean values of RSSImx than those of M1 and M3 in each table. The differences were within -5dBm;

Comparing between Table 11, Table 13, and Table 15, or comparing between Table 12, Table 14, and Table 16, tags with different antenna designs showed the following in the orientation read rate test:

1) Tag 1 had more Read Orientations than Tag 2, and Tag 3 had the least counts of Read Orientations;
2) All three tags had very similar values of the maximum TotCnt. Tag 1 had the greater mean values of TotCnt than the other two;
5) The maximum and mean values of RSSImx of Tag 1 were greater than those of Tag 2, and Tag 3 had the lowest values of the maximum and mean RSSImx. The minimum values of RSSImx of each tag were very similar.

Comparing Table 11 to Table 12, Table 13 to Table 14, and Table 15 to Table 16, the effect of the LP and CP antenna on the tag's performance in the orientation read rate test are shown below:

1) Tag 1 and Tag 2 showed very similar values of the count of Read Orientations between

measurements using the LP antenna and CP antenna. Tag 3 had the more Read Orientations while using the LP antenna;

2) Polarizations of the antennas did not have effect on the maximum TotCnt value in the tables. However, in general, the measurements with the LP antenna had greater values of mean TotCnt. The effect of antennas on the minimum TotCnt was not consistent across different tags;

3) Measurements with the LP antenna resulted in larger values in the RSSImx categories than those with the CP antenna;

The following figures are created to visually present the data. Figure 46 to Figure 51 show the O-RDRate of each tag with each material tested by the LP antenna and CP antenna. Figures of TotCnt versus RSSImx of each tag are provided in Appendix 4 to show how the results were clustered. M4 are excluded in the figures of TotCnt versus RSSImx in the appendix, as there was no Read-Orientation for M4 for any tags using either antenna.

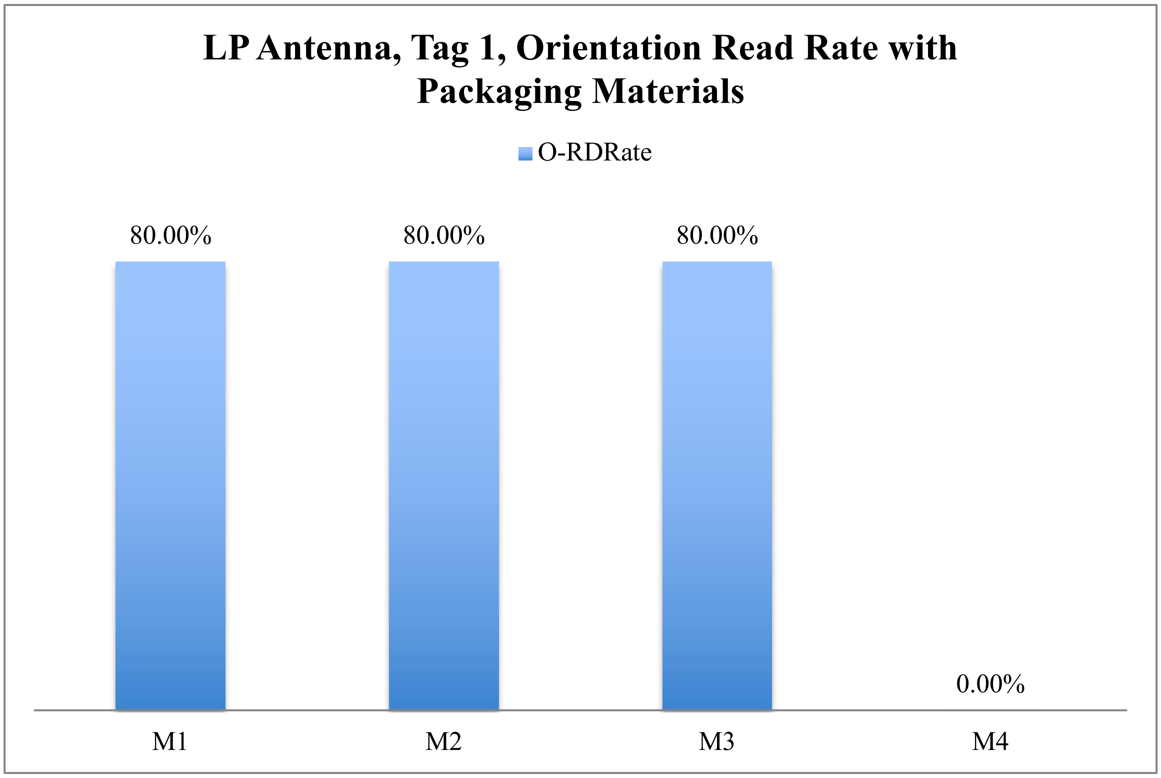


Figure 46 Orientation Read Rate of Tag 1 with Four Materials Tested Using LP Antenna

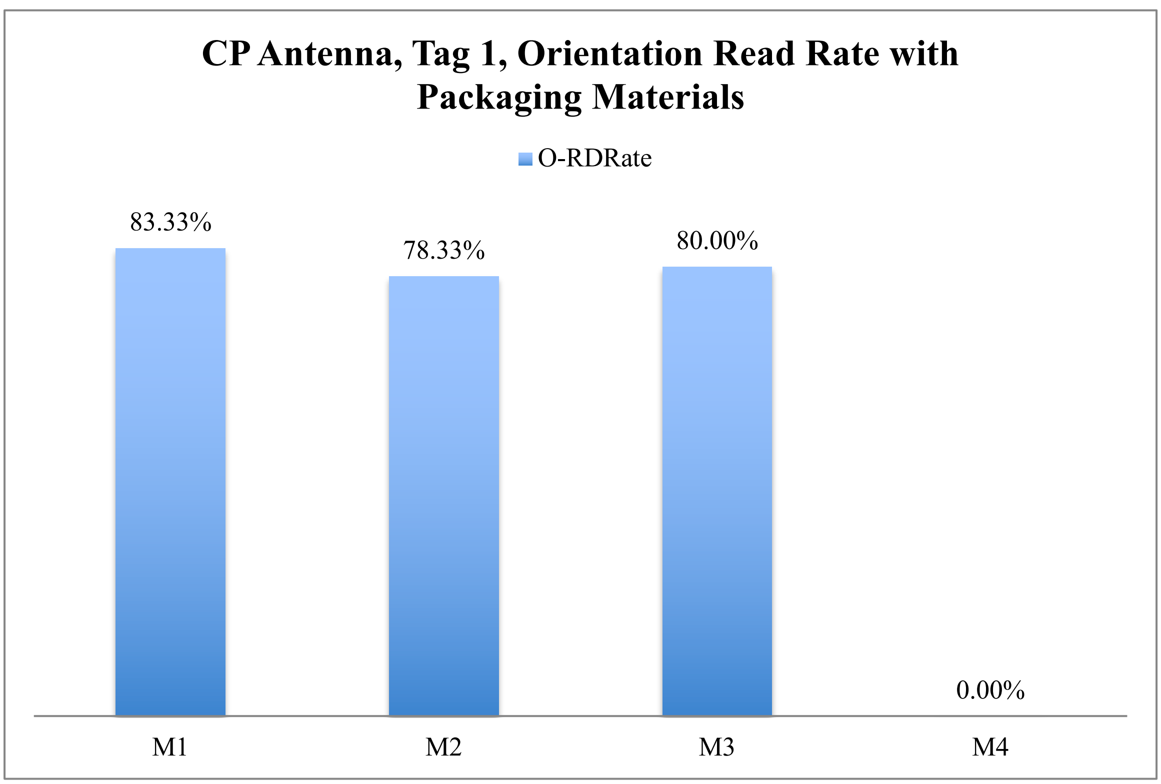


Figure 47 Orientation Read Rate of Tag 1 with Four Materials Tested Using CP Antenna

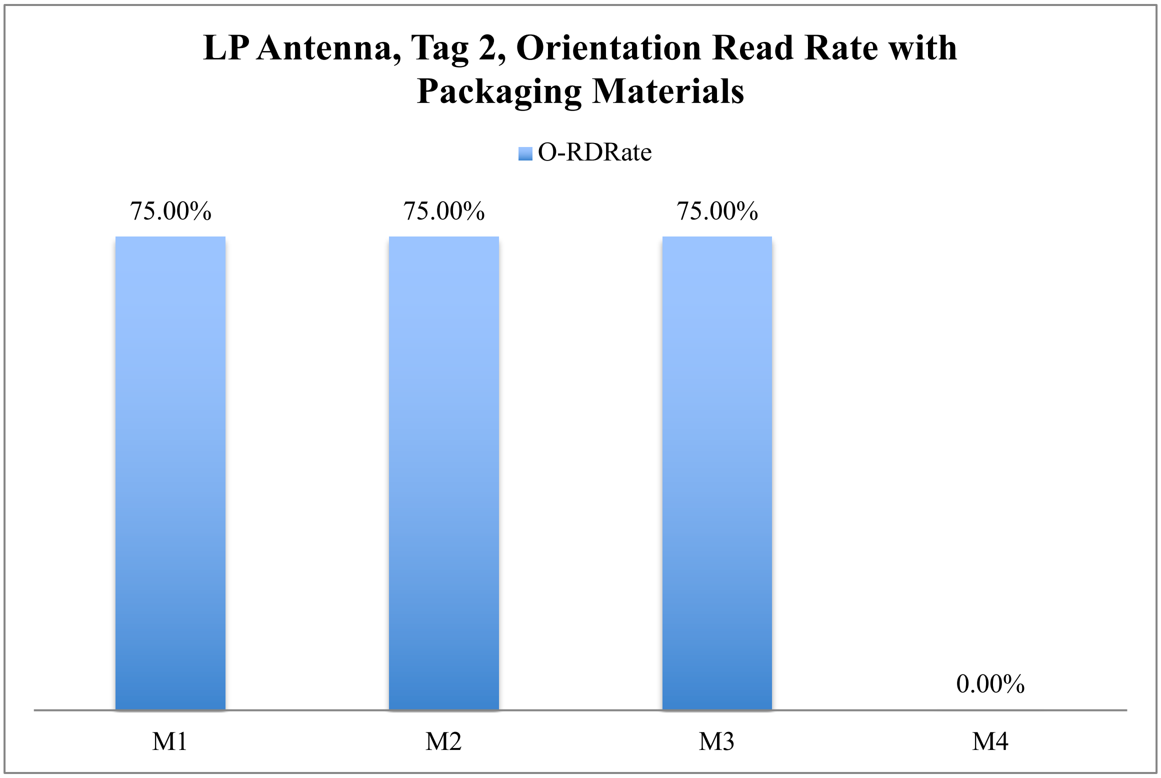


Figure 48 Orientation Read Rate of Tag 2 with Four Materials Tested Using LP Antenna

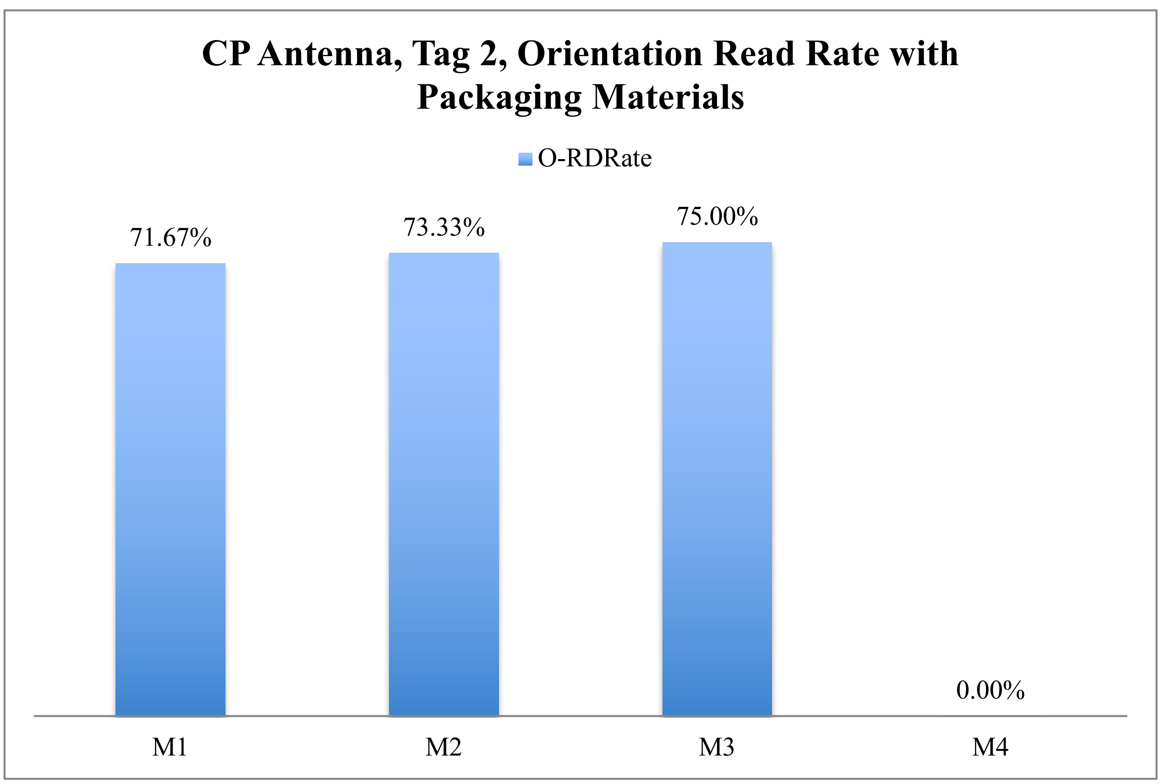


Figure 49 Orientation Read Rate of Tag 2 with Four Materials Tested Using CP Antenna

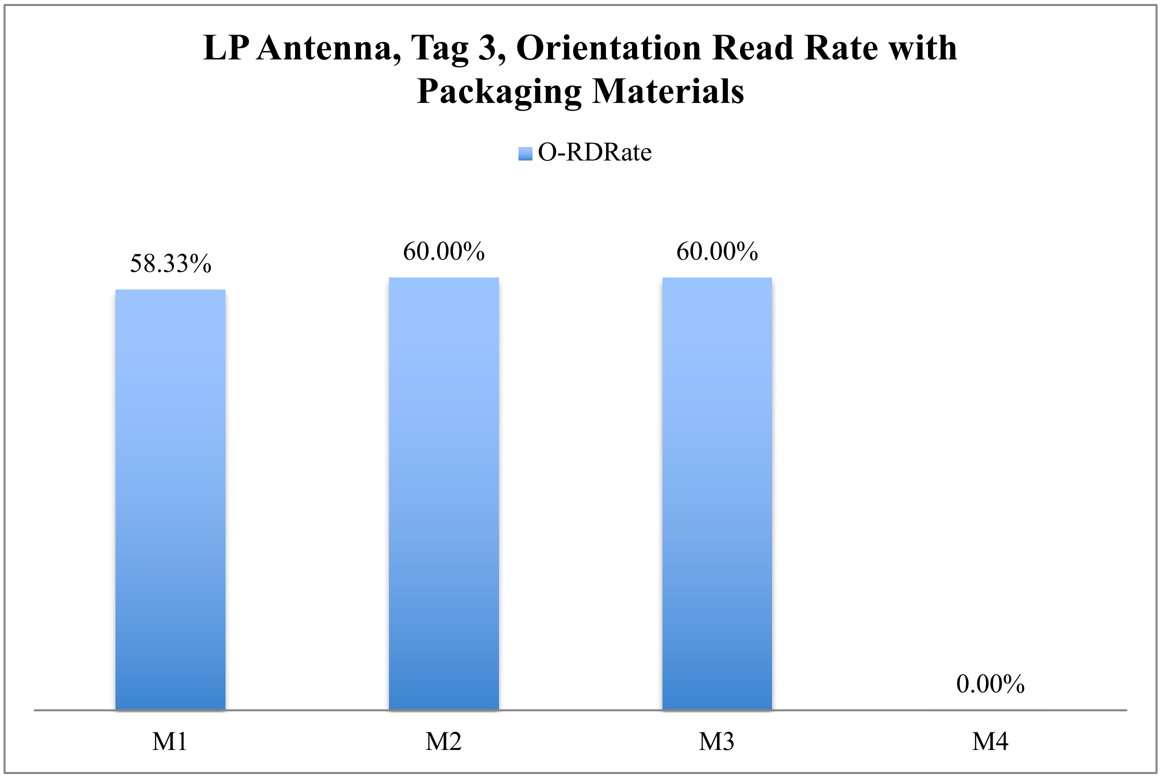


Figure 50 Orientation Read Rate of Tag 3 with Four Materials Tested Using LP Antenna

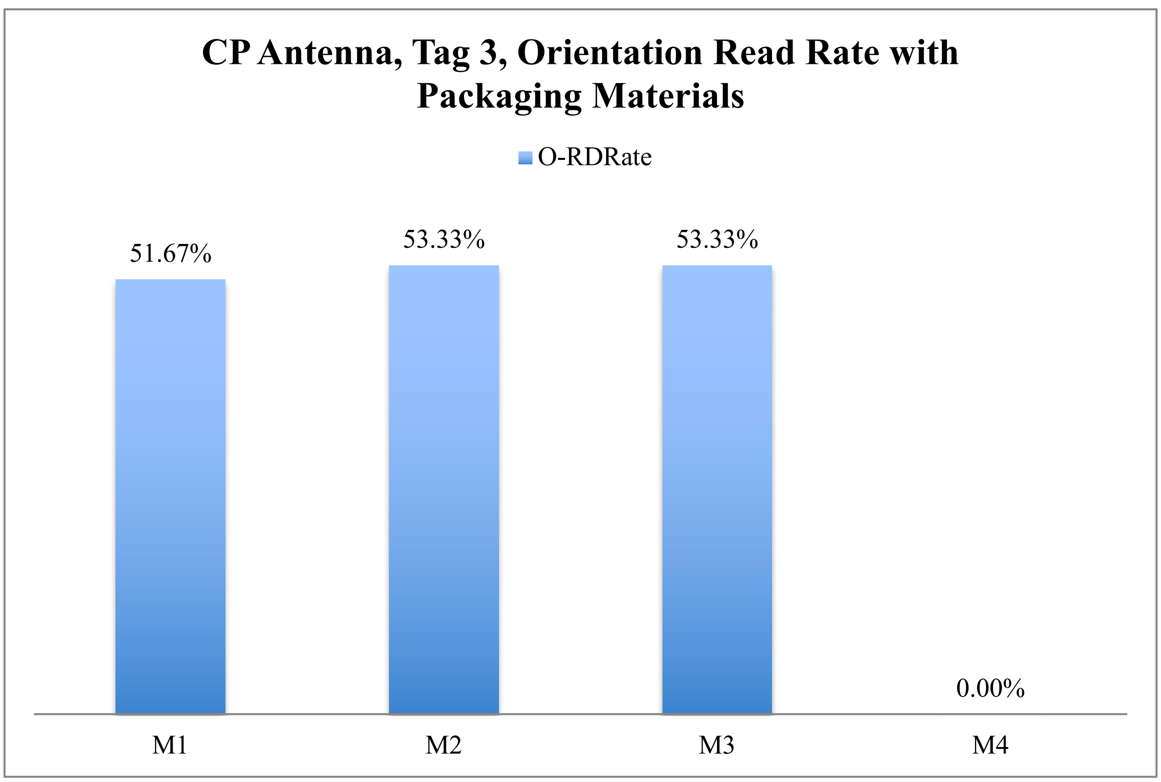


Figure 51 Orientation Read Rate of Tag 3 with Four Materials Tested Using CP Antenna

Chapter 5

Analysis and Discussion

5.1 Overview

The results of the experiments showed that M1, M2, and M3 had very little effect on the read range and O-RDRate of the tag, while with M4 the tag was not read by the reader in either the read range test or the orientation read rate test. The hypothesis of this research that were established in Chapter 1 were:

- Hypothesis 1: Packaging materials will NOT have a consistent effect on read range across different antenna designs of general-purpose dipole antenna transponders.
- Hypothesis 2: Packaging materials will NOT have a consistent effect on orientation read rate across different antenna designs of general-purpose dipole antenna transponders.

Observation of the experiment results indicated that both the two hypotheses were false, in other words, packaging materials have a consistent effect on the read range and O-RDRate of general-purpose dipole antenna transponders. To support the observation, a statistical model for each sub-test was created using SAS with the assistance of the MSU College of Agriculture and Natural Resources (CANR) Statistical Consulting Center (SCC). For the read range test, a survival analysis model was employed as a novel method to analyze the effects on the tag's read range. Survival analysis models are usually used to evaluate factors that influence the time to an event, for example, to examine influence of factors such as age, gender, and body mass index on survival time after heart attack [69]. In the read range test, the survival analysis model was used to examine factors including material, antenna, and tag affects on the read range, i.e. the Rβ. For the orientation read rate test, a completely randomized design model was used to analyze the effects of material, antenna, and tag on the TotCnt in order to support the conclusion of Hypothesis 2.

5.2 Analysis of the Read Range Test

In the survival analysis model for the read range test, materials M1, M2, and M3 were used. M4 was excluded, since it did not have any "survival time". First, assessment of whether different categories of variables have different survival functions was conducted. The survival function was originally interpreted as the probability of surviving past time t [69]. In this research, the survival function was described as the probability of reading a tag past distance r.Table 17, Table 18, and Table 19 shows the test of equality over factors of material (M1, M2 and M3), antenna (LP and CP antenna), and tag (Tag 1, Tag 2 and Tag 3), respectively. In the survival analysis model, P values smaller than 0.01 are considered as significant.

Table 17 shows that P values of the Log-Rank, Wilcoxon and -2Log Chi-Squire tests were all greater than 0.01, which means that survival functions of M1, M2 and M3 showed no evidence of difference. In other words, material M1, M2 and M3 did not have significant effect on the tag's read range. Table 18 has P values all smaller than 0.01, suggesting that the effect of reader antenna polarization on the tag's read range was significant. Similar to Table 18, P values in Table 19 are all smaller than 0.01, thus indicate that different tags have significantly different read ranges.

Table 17 Test of Equality over Material (M1, M2 and M3)

Test of Equality over Material			
Test	**Chi-Square**	**DF**	**Pr > Chi-Square**
Log-Rank	0.4634	2	0.7932
Wilcoxon	0.2088	2	0.9009
-2Log(LR)	0.0766	2	0.9624

Table 18 Test of Equality over Antenna

Test of Equality over Antenna			
Test	**Chi-Square**	**DF**	**Pr > Chi-Square**
Log-Rank	25.4413	1	<.0001
Wilcoxon	16.6251	1	<.0001
-2Log(LR)	13.9277	1	0.0002

Table 19 Test of Equality over Tag

Test of Equality over Tag			
Test	**Chi-Square**	**DF**	**Pr > Chi-Square**
Log-Rank	71.9002	2	<.0001
Wilcoxon	49.5087	2	<.0001
-2Log(LR)	26.3705	2	<.0001

Second, a Cox proportional hazards regression was used to confirm the above results.

Table 20 shows the analysis of maximum likelihood estimates of the Cox proportional hazards regression model. The hazard ratio in the table indicates the risk that the tag cannot be read at distance r.

Table 20 shows that Tag 1 performed better than the reference tag (Tag 3) with a hazard ratio of 0.177. So, Tag 1 had a $|(0.117-1)| * 100\% = 82.3\%$ decrease in the risk of not being read by the reader compared to Tag 3. And the difference between Tag 1 and Tag 3 was significant with P<0.0001. Tag 2 also performed better than Tag 3. The hazard ratio of Tag 2 was 0.334, and this indicated that Tag 2 had a $|(0.334 - 1)| * 100\% = 66.6\%$ decrease in the risk of not being read by the reader compared to Tag 3: the difference between Tag 2 and Tag 3 was significant as well, with a P value less than 0.0001. The CP antenna performed a lot worse than the LP antenna with the hazard ratio of 2.420. The CP antenna had $|(2.420 - 1)| * 100\% = 142.0\%$ more risk of failing to detect a tag at distance r. The difference between the CP antenna and the LP antenna was significant with P<0.0001. Finally, M2 showed a hazard ratio of 0.902 and M3 showed a hazard ratio of 0.863 compared to the reference material (M1). However, the difference between M2 and M1, as well as that between M3 and M1 was not significant with the p=0.5385 and p=0.3818, respectively.

Table 20 Result of the Cox Proportional Hazard Regression of the Survival Analysis

Analysis of Maximum Likelihood Estimates								
Parameter		**DF**	**Parameter Estimate**	**Standard Error**	**Chi-Square**	**Pr > ChiSq**	**Hazard Ratio**	**Label**
Tag	**1**	1	-1.73423	0.21262	66.5269	<.0001	0.177	Tag 1
Tag	**2**	1	-1.09569	0.18885	33.6621	<.0001	0.334	Tag 2
Antenna	**CP**	1	0.88357	0.15442	32.7392	<.0001	2.420	Antenna CP
Material	**M2**	1	-0.10274	0.16704	0.3783	0.5385	0.902	Material M2
Material	**M3**	1	-0.14734	0.16846	0.7650	0.3818	0.863	Material M3

Hence, the *Hypothesis 1: Packaging materials will NOT have a consistent effect on read range across different antenna designs of general-purpose dipole antenna transponders* was determined to be false. For all three general-purpose dipole antenna tags tested in this research, the read range of one tag was significantly different from that of the others, except the read ranges tested with M4. The tag's read range with M1, M2 and M3 tested using the LP antenna was significantly larger than that of using the CP antenna. However, M1, M2 and M3 did not have significant effect on the tag's read range, while M4 always resulted in null read range for all three tags. The effect of packaging materials was consistent on read range across different antenna designs of general-purpose dipole antenna transponders.

5.3 Analysis of the Orientation Read Rate Test

The O-RDRate was calculated as the count of Read Orientations over all 60 orientations (Table 4). Figure 46 to Figure 51 indicated that material M1, M2 and M3 had very little effect on the O-RDRate of a tag, while M4 resulted in 0% O-RDRate of all three tags. The data set of the orientation read rate test had two responses: TotCnt and RSSImx, while RSSImx did not have any value for the No-read Orientations. In order to further examine the effects of packaging materials on the tag's performance in the orientation read rate test, a completely randomized design analysis model was conducted and the response TotCnt was used to investigate how packaging materials influence the tag's O-RDRate.

First, all the TotCnt data collected using the two antennas, three tags with four packaging materials was imported in the SAS program. The assumptions of normality and equal variance of the response TotCnt were checked. Figure *52* shows the results of SAS program and indicates that the TotCnt data was not quite normal.

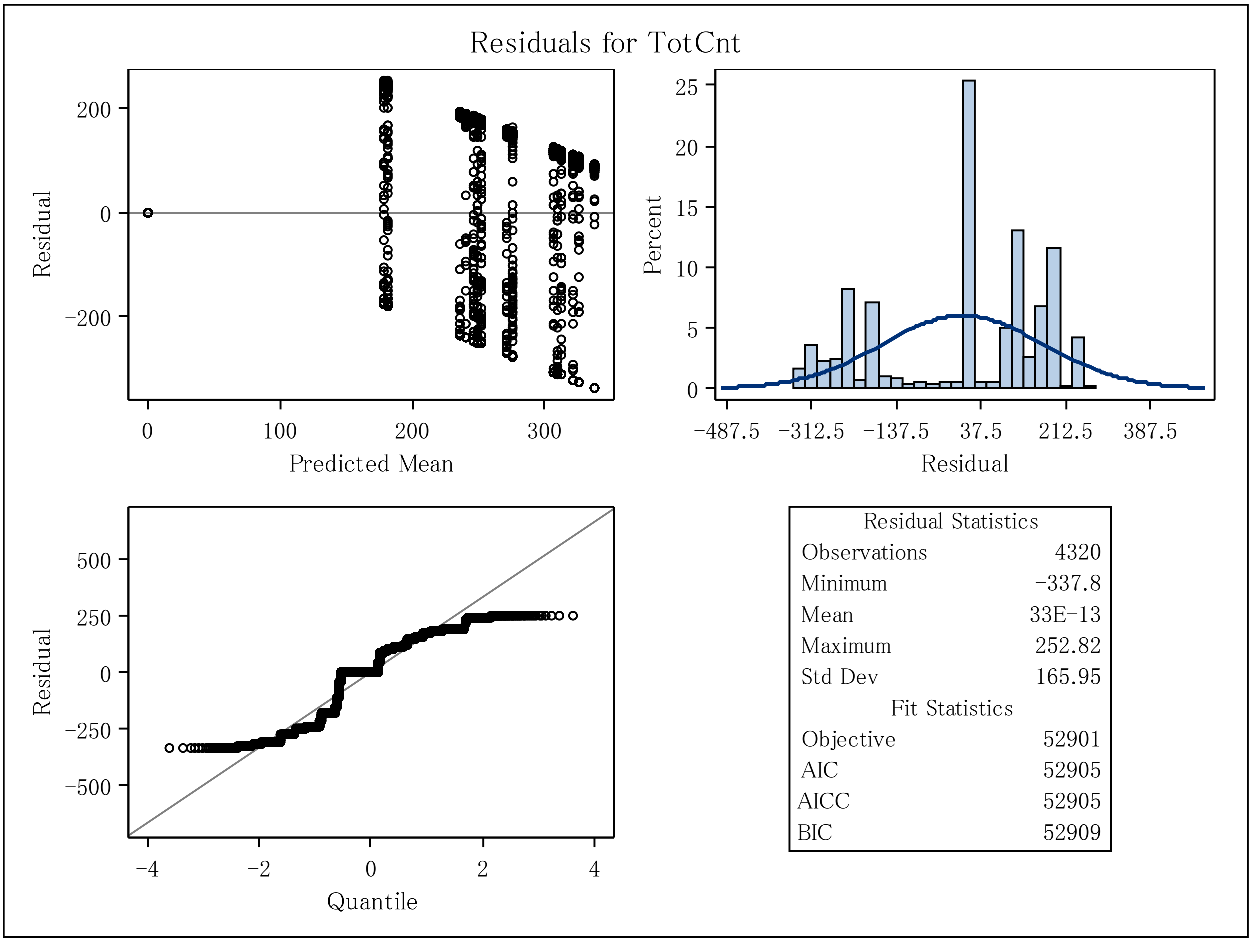


Figure 52 Residuals for TotCnt in the Orientation Read Rate Test

Then two models: one model with equal variance and the other one with unequal variance were run. The Akaike Information Criterion (AIC) values of the two models were compared to decide the better model for analyzing the TotCnt data. Table 21 and Table 22 show the AIC value of the equal variance model and unequal variance model, respectively. The model with unequal variance had slightly smaller AIC, hence this model was used for further analysis.

Table 21 Fit Statistics of the Model with Equal Variance

Fit Statistics	
-2 Res Log Likelihood	52901.2
AIC (Smaller is Better)	52905.2
AICC (Smaller is Better)	52905.2
BIC (Smaller is Better)	52909.4

Table 22 Fit Statistics of the Model with Unequal Variance

Fit Statistics	
-2 Res Log Likelihood	52730.1
AIC (Smaller is Better)	52740.1
AICC (Smaller is Better)	52740.1
BIC (Smaller is Better)	52750.6

With the unequal variance model, results of the analysis are presented below. P values smaller than 0.01 are considered as indicating the variable had significant effect on the response of TotCnt. Table 23 shows the effect of different variables on the value of TotCnt in the orientation read rate test. The P values in Table 23 indicate that antenna, material and tag all had significant effects on the TotCnt value. Antenna by material, antenna by tag, and tag by material had significant interaction effects on the TotCnt. But antenna, material and tag together did not have a significant effect on the TotCnt in the orientation read rate test.

Table 23 Effect of Antenna, Tag and Material on the TotCnt in the Orientation Read Rate Test

Type 3 Tests of Fixed Effects				
Effect	**Num DF**	**Den DF**	**F Value**	**Pr > F**
Antenna	1	3330	55.55	<.0001
Material	3	2123	1009.66	<.0001
Antenna*Material	3	2123	4.13	0.0062
Tag	2	3330	199.00	<.0001
Antenna*Tag	2	3330	7.06	0.0009
Material*Tag	6	2603	14.87	<.0001
Antenna*Material*Tag	6	2603	0.73	0.6260

Table 24 compares the least square means of the TotCnt values collected using the LP and CP antenna. This table again indicates that antenna had a statistically significant effect on the tag's TotCnt in the orientation read rate test. More specifically, the measurements with the LP antenna had an average of 25.14 more TotCnt per trial than those with the CP antenna, and this difference was significant.

Table 24 Least Squares Means of TotCnt Tested with the LP and CP Antennas

Effect of Antenna on TotCnt						
	Antenna	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Least Squares Means	CP	184.83	19.2436	59.6	9.60	<.0001
	LP	209.97	19.2436	59.6	10.91	<.0001
Differences of Least Squares Means		-25.1444	3.3737	3330	-7.45	<.0001

Table 25 shows the least square means of the TotCnt values with different packaging materials. The first four cells of the Estimate column show the average TotCnt of a trial tested with the correspondent packaging material. In the Differences of Least Squares Means category, M1, M2 and M3 had small values of Estimate when compared with each other, and these differences were not statistically significant as the correspondent P values were all larger than 0.01. M4 had a significant difference from the other three materials with P values in row 7, row 9 and row 10 are all smaller.

Table 25 Least Squares Means of TotCnt with Different Packaging Materials

Effect of Material on TotCnt						
	Material	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Least Squares Means	M1	261.72	19.3163	60.6	13.55	<.0001
	M2	261.81	19.3070	60.4	13.56	<.0001
	M3	266.08	19.3262	60.7	13.77	<.0001
	M4	1.324E-9	19.6125	64.2	0.00	1.0000
Differences of Least Squares Means	M2-M1	0.09352	4.0775	1917	0.02	0.9817
	M2-M3	-4.2667	4.1243	1950	-1.03	0.3010
	M2-M4	261.81	5.3064	1482	49.34	<.0001
	M3-M1	4.3602	4.1677	1960	1.05	0.2956
	M4-M1	-261.72	5.3402	1503	-49.01	<.0001
	M4-M3	-266.08	5.3760	1511	-49.49	<.0001

Table 26 shows the least square means of TotCnt with three tags. Tag 1 averaged 42.73 and 82.41 more TotCnt per trial than Tag 2 and Tag 3, respectively. Tag 2 averaged 39.68 more TotCnt per trial than Tag 3. Differences between tags were statistically significant.

Table 26 Least Squares Means of TotCnt with Different Tags

Effect of Tag on TotCnt						
	Tag	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Least Squares Means	Tag 1	239.12	19.3174	60.5	12.38	<.0001
	Tag 2	196.38	19.3174	60.5	10.17	<.0001
	Tag 3	156.70	19.3174	60.5	8.11	<.0001
Differences of Least Squares Means	Tag 1 –Tag 2	42.7313	4.1319	3330	10.34	<.0001
	Tag 1 – Tag 3	82.4139	4.1319	3330	19.95	<.0001
	Tag 2 – Tag3	39.6826	4.1319	3330	9.60	<.0001

Table 27 presents the analysis output of the effect of the interaction between the antenna and tag on the TotCnt. The Difference of Least Squares Means category in Table 27 shows that even though using the LP antenna to test Tag 1 resulted in a greater average TotCnt than using the CP antenna, the effect of antenna on Tag 1's TotCnt was not significant as the P value was 0.0173. However, since 0.0173 is close to 0.1, it needs future reseach to further evaluate the effect of antenna on Tag 1's TotCnt. For Tag 2 and Tag 3, the effect of antenna was significant.

Table 27 Least Squares Means of TotCnt with Antenna by Tag

Effect of Antenna*Tag on TotCnt						
	Antenna*Tag	**Estimate**	**Standard Error**	**DF**	**t Value**	**Pr > |t|**
Least Squares Means	CP*Tag 1	232.16	19.5371	63.3	11.88	<.0001
	LP*Tag 1	246.07	19.5371	63.3	12.60	<.0001
	CP*Tag 2	187.06	19.5371	63.3	9.57	<.0001
	LP*Tag 2	205.71	19.5371	63.3	10.53	<.0001
	CP*Tag 3	135.27	19.5371	63.3	6.92	<.0001
	LP*Tag 3	178.13	19.5371	63.3	9.12	<.0001
Differences of Least Squares Means	CP*Tag 1 – LP*Tag 1	-13.9153	5.8434	3330	-2.38	0.0173
	CP*Tag 2 – LP*Tag 2	-18.6583	5.8434	3330	-3.19	0.0014
	CP*Tag 3 – LP*Tag 3	-42.8597	5.8434	3330	-7.33	<.0001

To summarize, the analysis of the orientation read rate test showed that *Hypothesis 2: Packaging materials will NOT have a consistent effect on orientation read rate across different antenna designs of general-purpose dipole antenna transponders* was false. For all three tags tested in this research, material M1, M2 and M3 did not have significant effect on the tag's O-RDRate, and M4 always led to a zero percent O-RDrate. Packaging materials had a consistent effect on O-RDRate across different antenna designs of general-purpose dipole antenna transponders. Three tags had significantly different O-RDRates. For the O-RDRate of Tag 2 or Tag 3, the effect of antenna polarization was significant, and the tag read by the LP antenna had the higher O-RDRate and the more TotCnt per trial. However, antenna polarization might not have a significant effect on the O-RDRate of Tag 1 (P=0.0173). The effect of antenna polarization on O-

RDRate might not consistent across different antenna designs of general-purpose dipole antenna transponders, and needs further study to investigate.

To apply the results to the real-world application of RFID systems, one can expect the consistent effect of different packaging material on general-purpose passive dipole-antenna transponder performance. In other words, generally speaking, a transponder that performs better than another while attached on a given material will still perform better on another material, and general-purpose passive diopole antenna transponder will not yield any read while using with materials that contains madel. As the tag's antenna designs had a significant effect on tranponder read range and orientation read rate, it is suggested to perform the read range test and orientation read rate test described in this research with all the tags on a packaging material to determine the tag's performance, then choose the desired tag or tags for the proposed application. According to the results of this research, one can expect that a tag with larger read range generally will have larger orientation read rate. Furthermore, reader antenna's polarization is a significant effect on the tag's read range and orientation read rate (except for Tag1's orientation read rate), and generally the linear antenna will result in larger read range and larger orientation read rate. However, linear antenna may have blind spots around 10 feet due to the Gen 2 protocol [53] (e.g. Figure 12), and circular antenna may have blind spots around 7 feet (e.g. Figure 15). Thus, it is suggested to perform tests with both antenna at planned location to avoid blind spots before complete installation of an RFID system.

Chapter 6

Conclusions and Future Research

In this thesis, three general-purpose dipole antenna passive RFID tags were evaluated when they were attached to four packaging material samples. Tag performance of read range, which is the maximum distance the tag can be detected by the reader, and orientation read rate, which is the percentage of orientations in which the transponder can be read, out of all the possible orientations evaluated within a three-dimensional space were quantified and analyzed. Four commonly used packaging materials were chosen, including uncoated corrugated paperboard, PE film, PE corrugated board, and PET/Al/PE laminated film to investigate the effects of packaging materials on tag performance. A transponder support that could rotate, tilt, and incline the tag with the packaging material sample was made for this research. Both the LP and CP antenna were used in the test.

A survival analysis model that was a novel means to analyze read range test data was conducted. Results showed that all tags tested with the PET/Al/PE film could not be read by the reader, while the other three packaging materials yield no evidence of significant effects on the tag's read range. Thus, it was concluded that packaging materials have a consistent effect on read range across different antenna designs of general-purpose dipole antenna transponders. Additionally, reader antenna polarization and tag antenna design both had significant effects on the tag's read range. Except for the measurements with the PET/Al/PE film, the tag had a larger read range when tested using the LP antenna, and the tag with the larger dimension (see tag dimensions in Table 3 and Figure 7) had the larger read range.

The orientation read rate test was analyzed using a completely randomized design analysis model. Results showed that all tags tested with the PET/Al/PE film had 0% O-RDRate, while the other three packaging material yield no evidence of a significant effect on the tag's O-RDRate, leading to the conclusion that most packaging materials have consistent effect on O-RDRate across different antenna designs of general-purpose dipole antenna tags. In addition, it was found that except for the measurements with the PET/Al/PE film, the tag's antenna design had a significant effect on the O-RDRate, with the larger antenna dimension resulting in the larger O-RDRate value. It was expected before the orientation read rate test that the tag measured by the CP antenna would have a higher O-RDRate than that of by the LP antenna. However, the results showed that the O-RDRate of a tag measured by the CP antenna was equal or smaller than the O-RDRate measured by the LP antenna. For Tag 1, antenna polarization did not have a significant effect on its O-RDRate. But for Tag 2 or Tag 3, the O-RDRate measured by the LP antenna was significantly higher than that measured by the CP antenna. So reader antenna polarizations did not have a consistent effect on O-RDRate across tags evaluated.

This study evaluated three dipole antenna passive tags with four packaging materials in a simulated manufacturing environment. Several ideas were spun off during this study, but were not conducted due to the limitations of time and resource. For future work beyond this study, it is suggested that more transponder designs and packaging materials be evaluated. This research was unable to clearly determine how a specific 3D orientation influences the tag's readability. Understanding the internal relationship between the tag's 3D orientation and tag performance would be the next step in continuing this research. In addition, the orientation read rate test in this research was conducted at a fixed distance of 2 feet from the reader antenna. For future research, the interaction effect of distance and 3D orientation on tag performance can be tested. Last but not least, this research was conducted in a room simulating the real-world environment and could not control the relative humidity. Thus, another testing idea for future study is to conduct the read range test and orientation read rate test for tags with packaging materials under different environmental relative humidities.

APPENDICES

Appendix 1

Pilot Test 1

The initial purpose of pilot test 1 was to develop a testing methodology to evaluate a UHF passive transponder's three-dimensional (3D) read range in a simulated manufacturing environment, and to find a method with the least possible measurements to accurately map a passive tag's 3D read range. The tag used in pilot test 1 was AD-381m5, which was Tag 3 in the thesis. In pilot test 1, the tag was attached to the center of 7×7 inch square high-density fiberboard (HDF) (Figure 53), and then was mounted on the transponder support described in Chapter 3. The RFID reader and antennas, the laboratory environment and setups were the same asin the tests in Chapter 3.

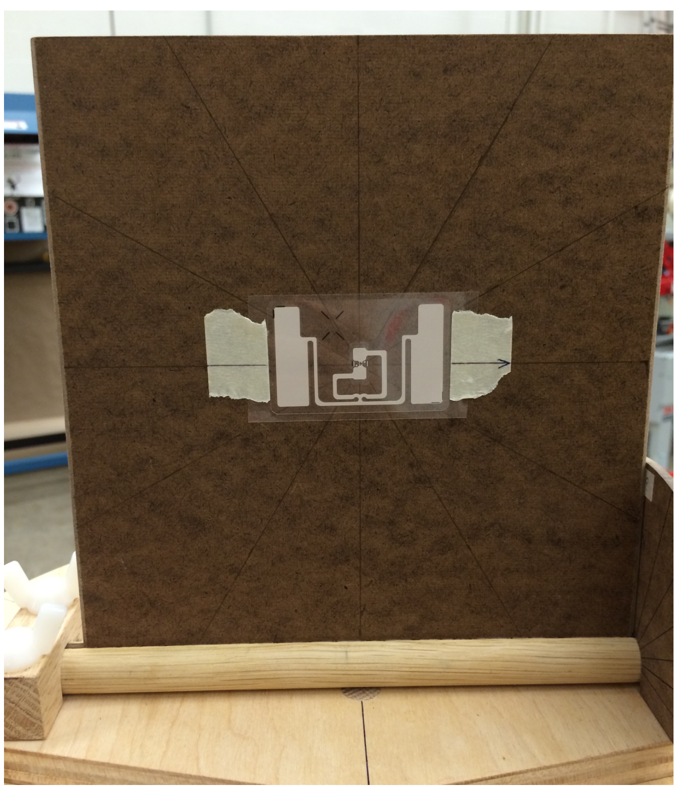


Figure 53 Tag AD-338m5 and the High-Density Fiberboard

In pilot test 1, the tag's critical distance and acquisition distance were both measured in 3D space. Thus the tag had two 3D read ranges. One was based on the critical distance and the other one was based on the acquisition distance. The procedures for mapping the tag's critical 3D read range are described as below:

1) Assemble the LP antenna to the reader, and configure the reader to a transmitting power of 20 dBm, and a receiving sensitivity of -70 dBm;
2) Attach the tag AD-381m5 to the center of the HDF with γ=0° using small pieces of masking tape, the angle γ is kept constant throughout the entire pilot test 1;
3) On the transponder support, rotate the HDF with the tag to α=0° and β=0°, then place the transponder support at the distance r=0.5 foot;
4) Turn on the reader to automatically read the tag 3 times, 5 seconds each time. Delay between two runs is 5 seconds;
5) Save the data file with the information of reader antenna polarization, angle α and β, and distance r;
6) Move the transponder support to r=1 foot and repeat steps 4 and 5;
7) Move the transponder support outwards from the antenna with an increment of 0.5 foot each time, until the tag cannot be detected by the reader for 5 concutive increases in distance;
8) Record the last distance r the tag can be read as $R_{0\text{-}0\text{-}cr}$. The $R_{0\text{-}0\text{-}cr}$ is the tag's critical distance at α=0° and β=0°;

9) Move the transponder support back to r=0.5 foot, turn the angle β to 15° and repeat steps 4 to step 7, record the $R_{0\text{-}15\text{-}cr}$;

10) Increase the angle β by 15° each time and repeat step 4 to step 7 until β=345°; Record corresponding $R_{\alpha\text{-}\beta\text{-}cr}$ at each β;

11) Rotate the angle α to 15° and β to 0°, repeat step 4 to 10;

12) Increase the angle α by 15° each time until α=165°. Repeat step 4 to 10 for each α.

The test was done when all the critical distance $R_{\alpha\text{-}\beta\text{-}cr}$, where α is every 15° from 0° to 165°, and β is every 15° from 0° to 345°, as well as the TotCnt and RSSImx of all the distance r of every 0.5 foot within each $R_{\alpha\text{-}\beta\text{-}cr}$ were recorded. Then the CP antenna was used to measure the $R_{\alpha\text{-}\beta\text{-}cr}$ of the tag by following the same procedures above. The tag's 3D critical read range could be outlined by all the $R_{\alpha\text{-}\beta\text{-}cr}$.

The procedures for mapping the tag's acquisition 3D read range were conducted reversely. For each α and β, where α is every 15° from 0° to 165°, and β is every 15° from 0° to 345°, the measurement of the tag was started at the distance r that was 2 feet greater than the corresponding $R_{\alpha\text{-}\beta\text{-}cr}$. The tag was moved towards to the antenna with an increment of 0.5 foot, and the first distance r at which the reader could read the tag was recorded as $R_{\alpha\text{-}\beta\text{-}ac}$. The test was done when all the acquisition distance $R_{\alpha\text{-}\beta\text{-}ac}$, as well as the TotCnt and RSSImx at distance r of every 0.5 foot within each $R_{\alpha\text{-}\beta\text{-}ac}$ were measured.

While both the 3D read ranges were determined, data managing processes for pilot test 1 were the same as the tests discussed in Chapter 3. There were 288 sets of α-β measured for mapping each of the 3D read range. Figure 54 and Figure 55 below shows the comparisons between the $R_{\alpha\text{-}\beta\text{-}cr}$ and $R_{\alpha\text{-}\beta\text{-}ac}$ of the tag measured using the LP antenna and CP antenna, respectively.

Figure 54 shows that 93.40% of the $R_{\alpha\text{-}\beta\text{-}cr}$ and $R_{\alpha\text{-}\beta\text{-}ac}$ were equal to each other while using the LP antenna, and Figure 55 indicates that 87.20% of the $R_{\alpha\text{-}\beta\text{-}cr}$ and $R_{\alpha\text{-}\beta\text{-}ac}$ were equal while using the CP antenna. Observation of Figure 54 and Figure 55 shows that moving the tag outwards or towards to the reader's interrogation zone had little effect on the tag's read range.

In order to examine whether the tag's 3D critical read range is statistically identical to the 3D acquisition read range, the same survival analysis model described in Chapter 5 for analyzing the read range test was used. Table 28 shows the test of equality over the different procedures for determining the tag's critical distance and acquisition distance using the survival analysis model.

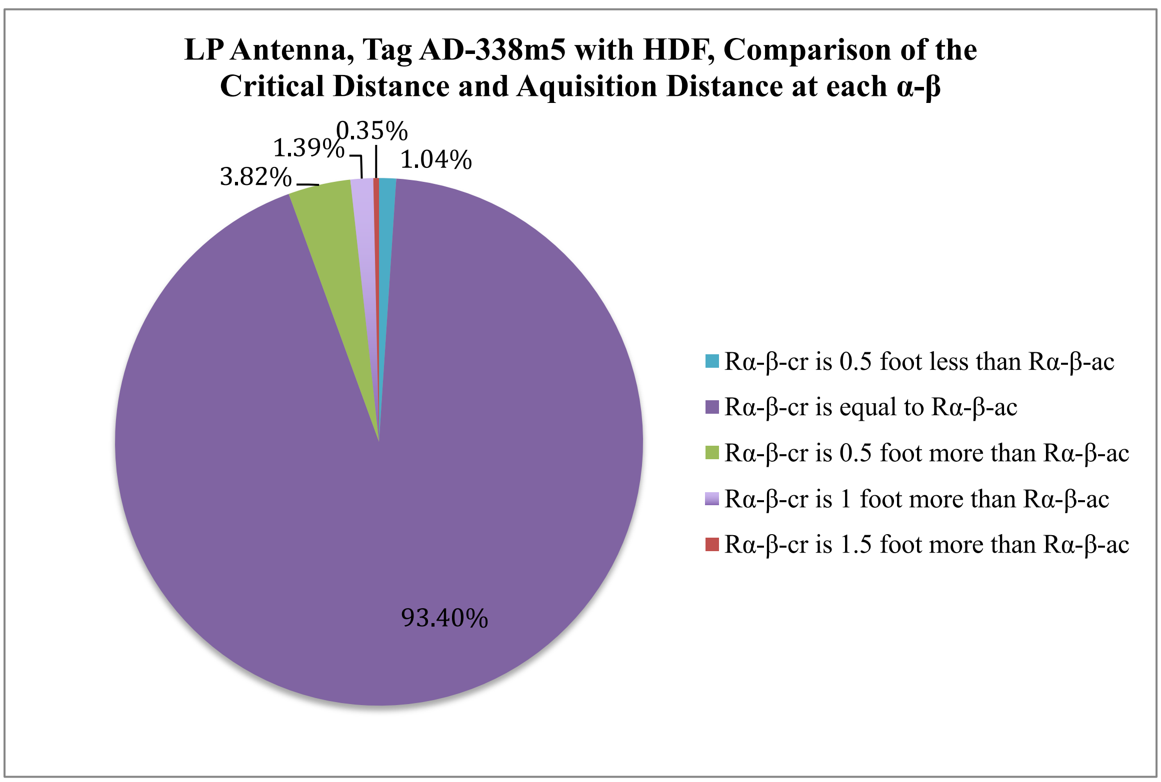


Figure 54 Comparison of the Rα-β-cr and Rα-β-ac Measured by the LP Antenna

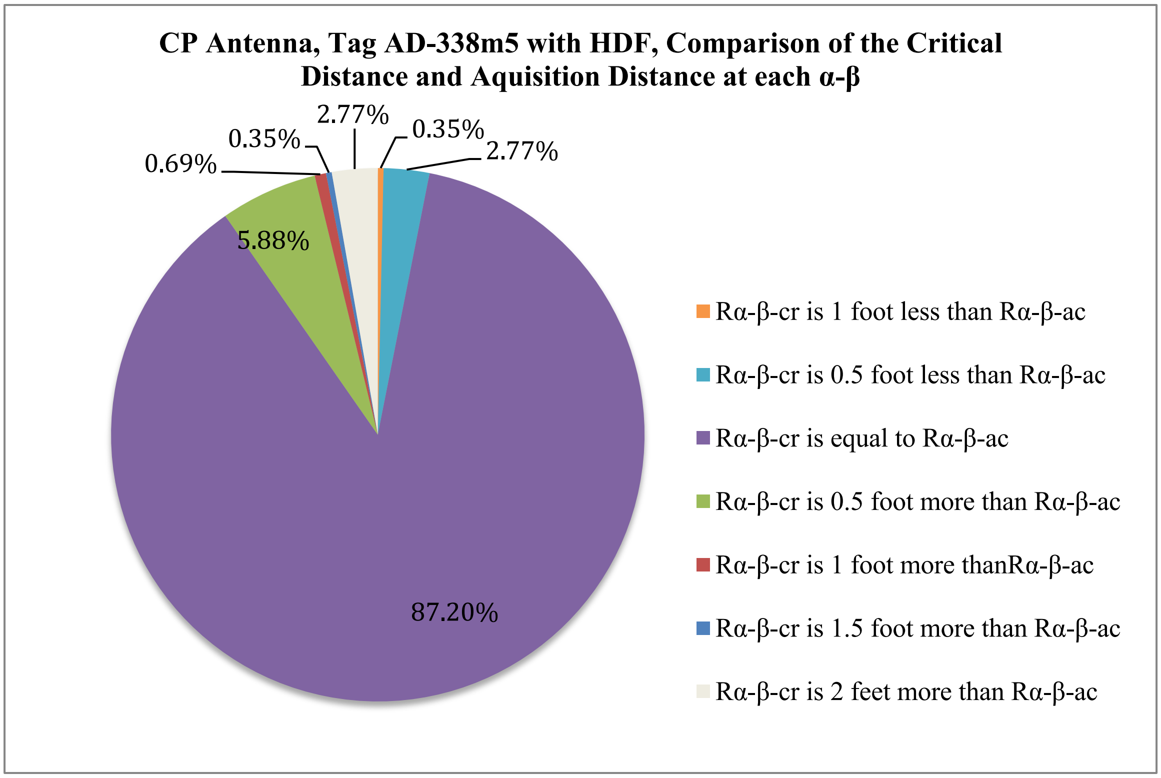


Figure 55 Comparison of the Rα-β-cr and Rα-β-ac Measured by the CP Antenna

Table 28 Test of Equality over Procedures for Critical Distance and Acquisition Distance

Test of Equality over Procedure			
Test	**Chi-Square**	**DF**	**Pr > Chi-Square**
Log-Rank	0.0000	1	1.0000
Wilcoxon	0.0000	1	1.0000
-2Log(LR)	0.0000	1	1.0000

All the three tests in the Table 28 give p=1.0000, which indicates the possibilities of reading a tag past distance r by moving the tag outward or towards to the reader's interrogation zone were equal. In other words, the tag's critical distance and acquisition distance were statistically identical. To simplify the procedures for mapping a tag's 3D read range, measurements of only one type of the maximum read distance is enough.

Further, it was observed in the results of pilot test 1 that the angle α did not have much effect on the read range of the tag. Although the complete set of the pilot test 1 results is not provided in consideration of the reasonable length of this document, the analysis of the effect of α on the tag's read range is given below in Table 29. There were 12 different angles α in pilot test 1. Table 29 shows that α did not a have significant effect on the probability that the reader can read the tag past distance r, as all three p values in the table are greater than 0.05. Thus, in the read range test descrived in Chapter 3, angle α was fixed to 90°.

Table 29 Test of Equality over Angle α

Test of Equality over Angle α			
Test	**Chi-Square**	**DF**	**Pr > Chi-Square**
Log-Rank	12.7816	11	0.3078
Wilcoxon	5.5241	11	0.9032
-2Log(LR)	2.6626	11	0.9945

The initial purpose of this pilot test was to determine the least possible amount of data that was necessary to map the same 3D read range with the complete data set in a simulated manufacturing environment. Specifically to say, in pilot test 1, the tag was measured at every 15° of angle α, every 15° of angle β and every 0.5 foot of distance r. The 3D read range of the tag was outlined using this set of data. However, the test of the critical read range using the LP antenna consisted of more than 2500 Read Points, and that of using the CP antenna had more than 2000 Read Points. Taking these many measurements is time consuming and not efficient for practical use. So, it is necessary to investigate if measurements with greater increments of α, β and r can draw a statistically same 3D read range compared to that determined by the measurements with smaller increments.

In order to achieve this goal, a surface regression analysis model was developed using the SAS software. The procedures for analyzing the data of pilot test 1 was planned as

1) Find the best-fit function of α, β and r to predict the TotCnt or RSSImx value with the complete data set. The value of root mean square error (RMSE) of the regression function will be given;

2) Find the regression function with a smaller set of data. For example, using data of α at every 30°, β at every 15° and r at every 1 foot to determine the regression function. Then the RMSE of the new regression function will be calculated;

3) Compare the values of the two RMSE to determine if the two regression functions are similar. If so, then the data set with the larger increment is sufficient to map a 3D read range that is similar to the 3D read range using the data set with the smaller increment.

The surface regression analysis results with the complete data set of the critical 3D read range test are given in Table 30 to Table 37. Table 31 shows that the R-square of the regression function defined in Table 30 was 0.4526, that means the regression function could only represent 45.26% of all the TotCnt values collected in the critical 3D read range test using the CP antenna. The RMSE in Table 31 was larger than 130 and also indicates that the regression function could not predict the TotCnt value well. Similarly, the values of R-square and RMSE in Table 33, Table 35 and Table 37 all indicate that the complete data set in pilot test 1 using either the LP antenna or the CP antenna could not predict the TotCnt and RSSImx well. In other words, even with measurements at every 15° of angle α, every 15° of angle β and every 0.5 foot of distance r, the 3D read range was not accurate enough to predict the TotCnt and RSSImx value at a given distance and orientation of the tag. Hence, the method was considered as failed.

Pilot test 1 did not successfully determine a measuring procedure with greater increments of α, β and r that can draw a statistically same 3D read range compared to that determined by measurements at every 15° of angle α, every 15° of angle β and every 0.5 foot of distance r. Thus, in consideration of pratical time consumption of testing, as well as by reading relevant research, it was determined that in the read range test described in Chapter 3, the increment for β is 30° and for r is 0.5 foot.

Table 30 CP Antenna, TotCnt as a Function of α, β and r

Parameter	DF	Estimate	Standard Error	t Value	Pr > |t|	Parameter Estimate from Coded Data
Intercept	1	429.395522	17.146470	25.04	<.0001	237.618156
α	1	-0.377823	0.225056	-1.68	0.0933	-11.975450
β	1	-0.140543	0.106373	-1.32	0.1866	-12.854500
r	1	4.642091	6.360012	0.73	0.4655	-285.035018
α*α	1	0.001921	0.001124	1.71	0.0877	13.073532
β*α	1	0.000263	0.000473	0.56	0.5780	3.748578
β*β	1	0.000262	0.000242	1.08	0.2803	7.790216
r*α	1	-0.030519	0.026365	-1.16	0.2472	-9.441808
r*β	1	-0.010830	0.013937	-0.78	0.4372	-7.005798
r*r	1	-8.972400	0.727842	-12.33	<.0001	-126.174377

Table 31 CP Antenna, Response Surface for TotCnt

Response Surface for Variable TotCnt: TotCnt	
Response Mean	302.966443
Root MSE	130.966667
R-Square	0.4526
Coefficient of Variation	43.2281

Table 32 RSSImx as a Function of α, β and r

Parameter	DF	Estimate	Standard Error	t Value	Pr > |t|	Parameter Estimate from Coded Data
Intercept	1	-34.832497	0.630599	-55.24	<.0001	-54.901310
α	1	0.050054	0.008280	6.05	<.0001	0.217177
β	1	-0.018359	0.003877	-4.74	<.0001	-0.306015
r	1	-7.779622	0.257372	-30.23	<.0001	-8.656255
α*α	1	-0.000334	0.000041360	-8.07	<.0001	-2.272750
β*α	1	0.000008611	0.000017424	0.49	0.6212	0.122542
β*beta	1	0.000028897	0.000008837	3.27	0.0011	0.859874
r*α	1	0.001548	0.001113	1.39	0.1644	0.446850
r*β	1	0.001476	0.000580	2.55	0.0110	0.891259
r*r	1	0.615511	0.031838	19.33	<.0001	7.540012

Table 33 CP Antenna, Response Surface for RSSImx

Response Surface for Variable RSSImx: RSSImx	
Response Mean	-48.943860
Root MSE	4.409493
R-Square	0.6678
Coefficient of Variation	-9.0093

Table 34 LP Antenna TotCnt as a Function of α, β and r

Parameter	DF	Estimate	Standard Error	t Value	Pr > |t|	Parameter Estimate from Coded Data
Intercept	1	451.198221	11.836325	38.12	<.0001	248.466267
α	1	-0.404511	0.158548	-2.55	0.0108	-26.676099
β	1	-0.122817	0.073313	-1.68	0.0939	-12.547912
r	1	-9.579790	2.404469	-3.98	<.0001	-227.150132
α*α	1	0.003151	0.000795	3.96	<.0001	21.447806
β*α	1	0.000004625	0.000335	0.01	0.9890	0.065824
β*beta	1	0.000327	0.000170	1.93	0.0542	9.740338
r*α	1	-0.062797	0.010077	-6.23	<.0001	-33.674998
r*β	1	-0.009034	0.004897	-1.84	0.0651	-10.129247
r*r	1	-1.330519	0.158135	-8.41	<.0001	-56.214437

Table 35 LP Antenna, Response Surface for TotCnt

Response Surface for Variable TotCnt: TotCnt	
Response Mean	291.598593
Root MSE	131.517969
R-Square	0.4518
Coefficient of Variation	45.1024

Table 36 LP Antenna, RSSImx as a Function of α, β and r

Paramete r	DF	Estimate	Standard Error	t Value	Pr > |t|	Parameter Estimate from Coded Data
Intercept	1	-31.544414	0.437705	-72.07	<.0001	-56.125717
α	1	0.029538	0.005944	4.97	<.0001	-0.316744
β	1	-0.019646	0.002747	-7.15	<.0001	-0.277280
r	1	-5.620905	0.092702	-60.63	<.0001	-8.958679
α*α	1	-0.000266	0.000029868	-8.91	<.0001	-1.811815
β*α	1	0.000012724	0.000012619	1.01	0.3134	0.181081
β*beta	1	0.000039680	0.000006369	6.23	<.0001	1.180722
r*α	1	0.001237	0.000398	3.11	0.0019	0.637891
r*β	1	0.000489	0.000195	2.51	0.0122	0.527019
r*r	1	0.296380	0.006236	47.53	<.0001	11.577345

Table 37 LP Antenna, Response Surface for RSSImx

Response Surface for Variable RSSImx: RSSImx	
Response Mean	-49.588350
Root MSE	4.542763
R-Square	0.7184
Coefficient of Variation	-9.1609

Appendix 2

Pilot Test 2

Pilot test 2 consisted of two sub-tests. The first test was to determine if angle γ had an effect on a tag's performance. The tag AD-381m5 which was Tag 3, and the HDF that was the same as in pilot test 1 were used in the first test of pilot test 2. The RFID reader and antennas, the laboratory environment and setups were the same as for the tests in Chapter 3. The procedures of this test were

10) Assemble the LP antenna to the reader, and configure the reader to a transmitting power of 20 dBm, and a receiving sensitivity of -70 dBm;
11) Locate the transponder support at the distance r=2 feet for the entire test;
12) Assemble the HDF to the transponder support and turn the angle α to 90° and angle β to 0°;
13) Attach the tag to the HDF at γ=0° using small pieces of masking tape, the center of the tag is aligned with the center of the HDF;
14) Read the tag 3 times, 5 seconds each time, and 5 seconds delay between each run;
15) Save the data file with information of reader antenna polarization, angle α, β, and γ in the filename;
16) Keep the same α and β, and rotate γ to 30°. Repeat step 5 and step 6;
17) Rotate γ every 30° from 0° to 330° and repeat step 5 and 6;
18) Turn the HDF to α=120° and β=315°, and repeat step 4 to step 8;
19) Turn the HDF to α=150° and β=345°, and repeat steps from 4 to 8;

20) Assemble the CP antenna to the reader and configure the reader the same, repeat steps from 2 to step 10.

The TotCnt results of the first test are shown below in Figure 56 to Figure 61. Each value of the TotCnt used in the figures was the average TotCnt of the measurement of three trials at angle γ. Figure 56 to Figure 61 show that at three sets of α-β, angle γ had different effects on the TotCnt of the tag. The tag at certain angles of γ could not be read by the reader, no matter which reader antenna was used. In addition, the angle γ resulted in 0 TotCnt was not consistent across different α-β combinations and different polarization of antennas. For example, at α=90° and β=0°, γ=90° and 270° resulted in 0 TotCnt while testing with the LP antenna (Figure 56). At the same α-β but testing with CP antenna, γ=90°, 270° and 300° resulted in 0 TotCnt (Figure 59). At α=120° and β=315° and using LP antenna, γ=60°, 240° and 270°resulted in 0 TotCnt (Figure 57).

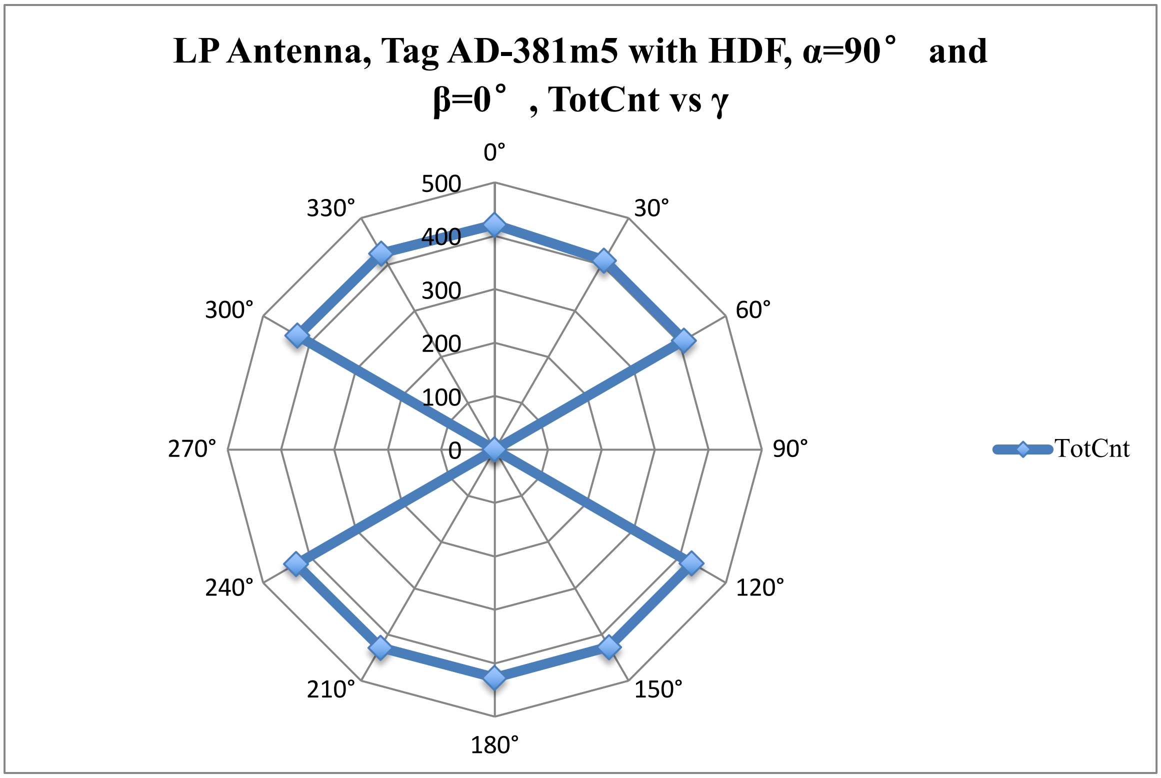


Figure 56 LP Antenna, Tag AD-381m5 with HDF, α=90° and β=0°, TotCnt versus γ

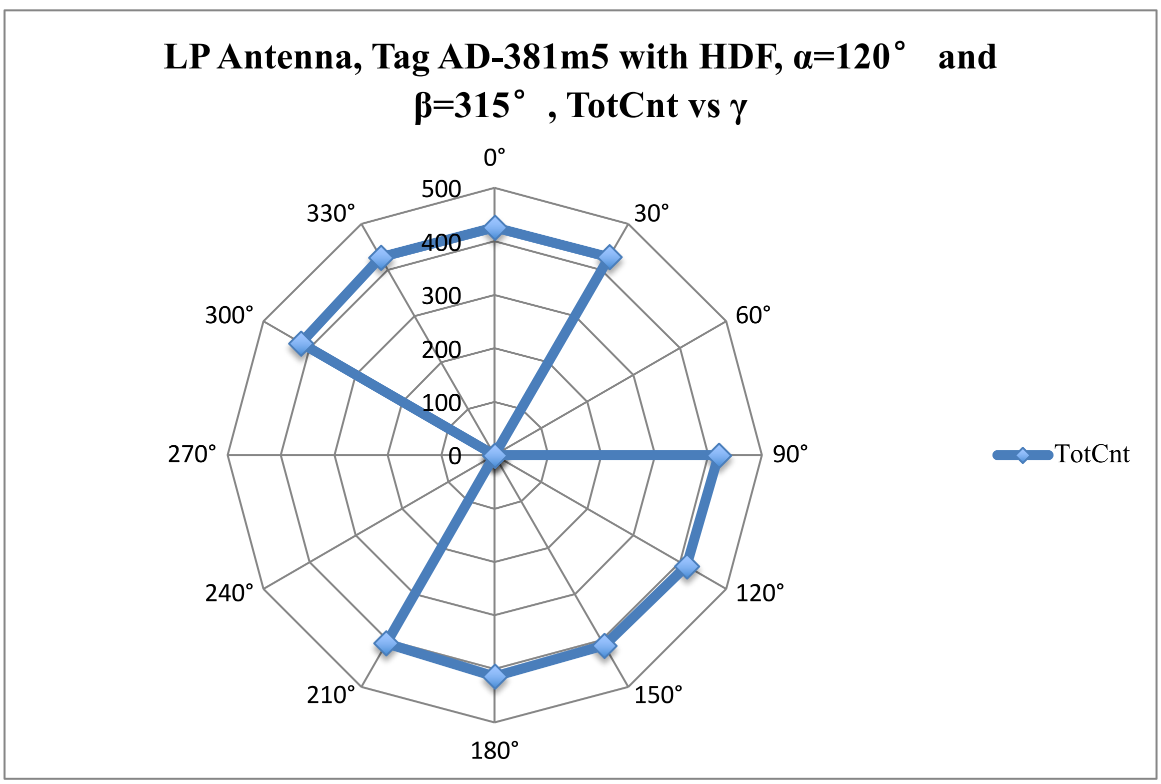


Figure 57 LP Antenna, Tag AD-381m5 with HDF, α=120° and β=315°, TotCnt versus γ

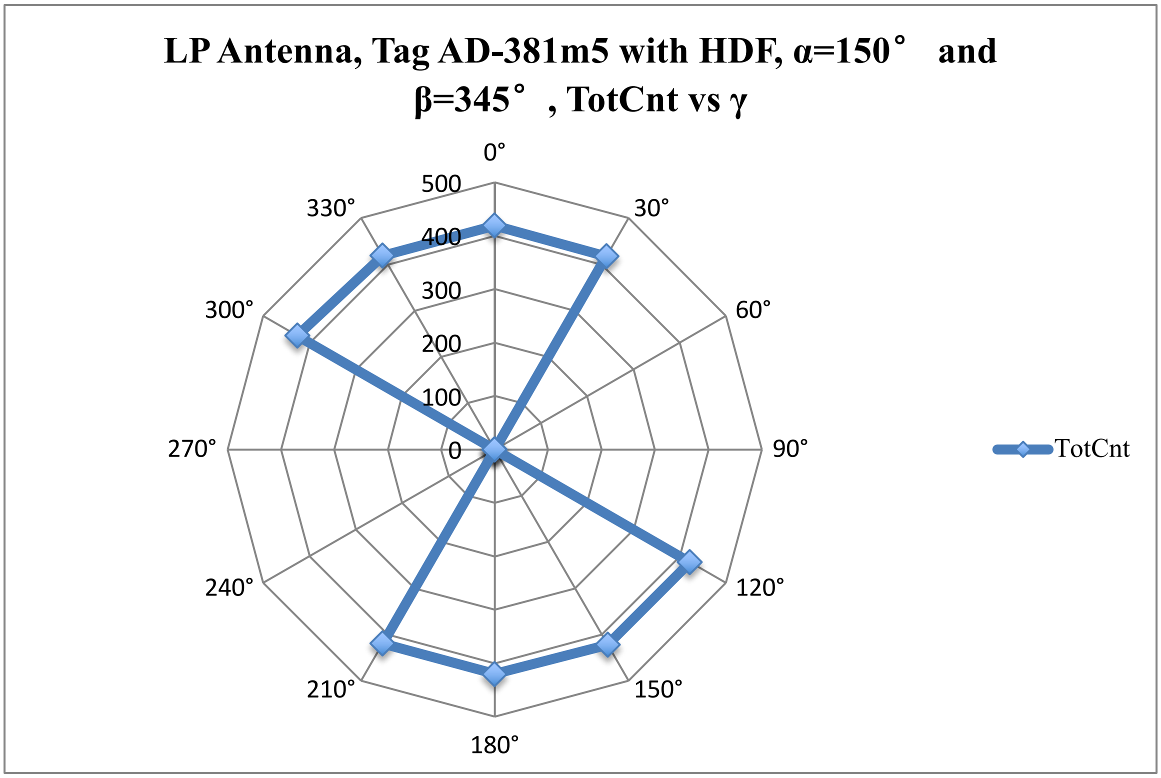


Figure 58 LP Antenna, Tag AD-381m5 with HDF, α=150° and β=345°, TotCnt versus γ

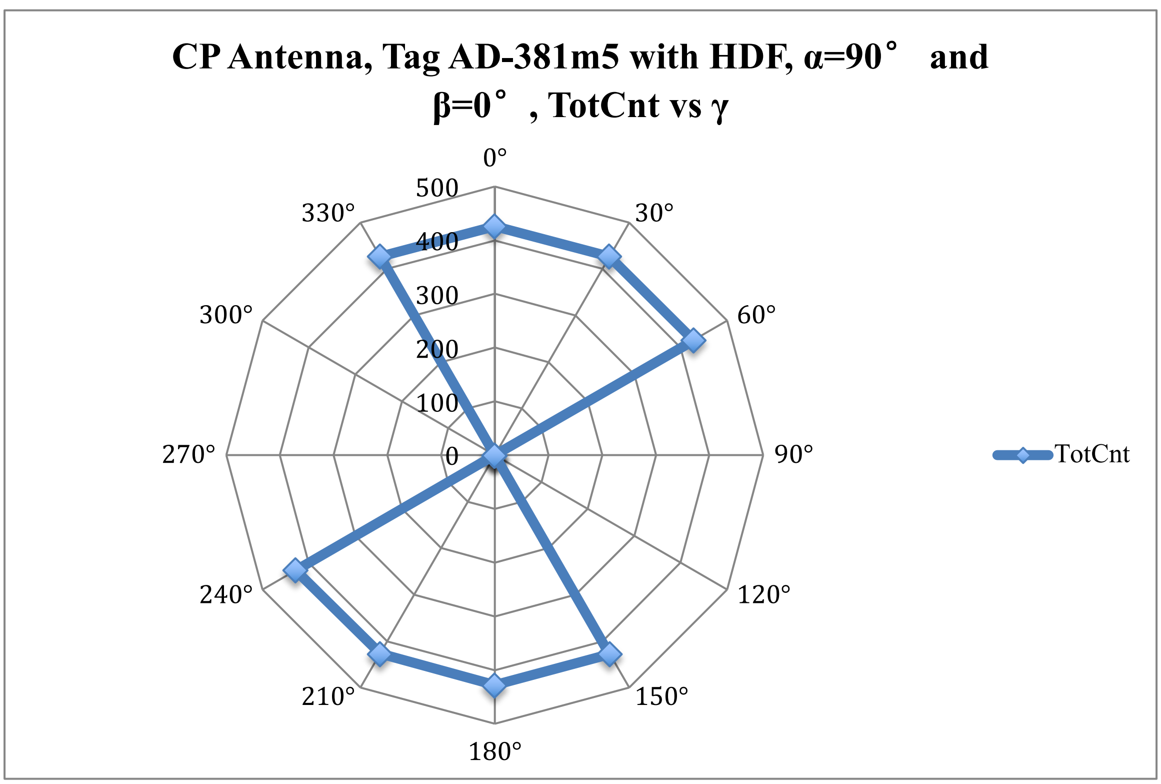


Figure 59 CP Antenna, Tag AD-381m5 with HDF, α=90° and β=0°, TotCnt versus γ

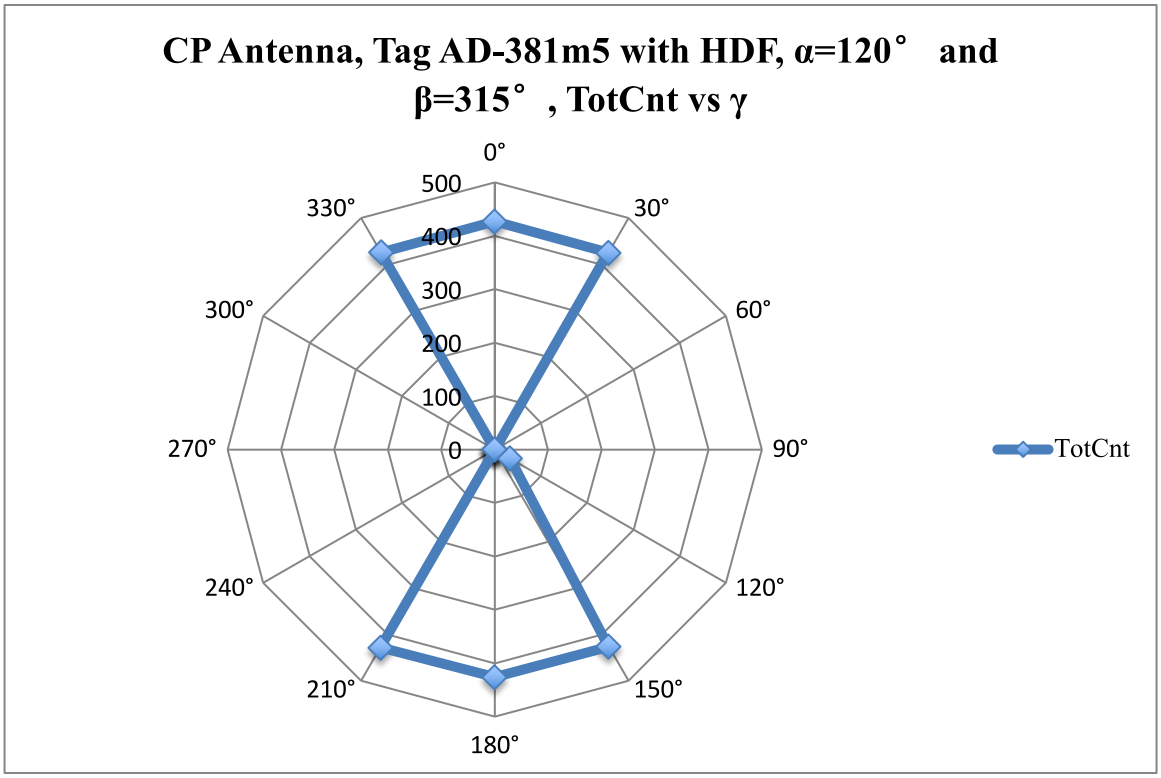


Figure 60 CP Antenna, Tag AD-381m5 with HDF, α=120° and β=315°, TotCnt versus γ

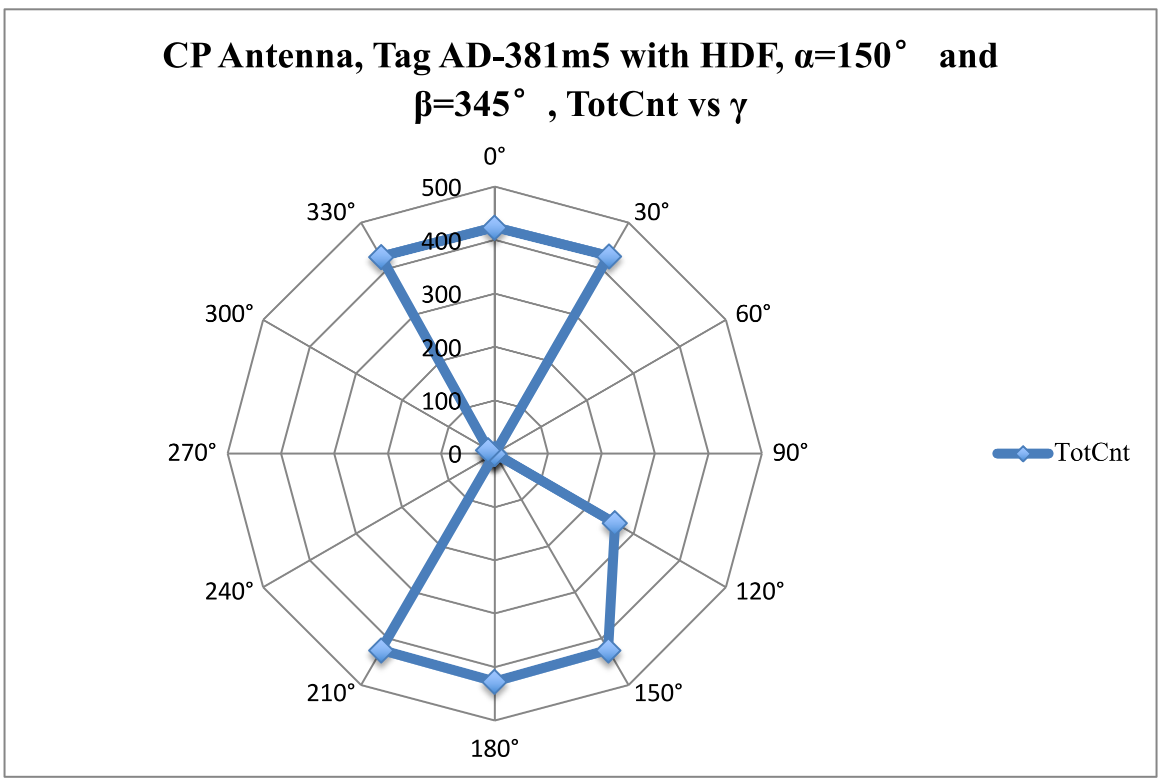


Figure 61 CP Antenna, Tag AD-381m5 with HDF, α=150° and β=345°, TotCnt versus γ

The purpose of the second test of pilot test 2 was to determine if different materials have a consistent effect on tags' read range across different tags. The tag AD-227m5, AD-233m5 and AD-381m5 were used, and they were the same types of tag tested in the read range test and the orientation read rate test described in Chapter 3. The materials used in this test were an uncoated corrugated paperboard (material M1 in the Chapter 3 tests), a medium-density fiberboard (MDF, see Figure 62), a low-density fiberboard (LDF, see Figure 63), and the HDF that was the same as in pilot test 1 and the first test of pilot test 2. Except for the uncoated corrugated paperboard, the other three materials in this test are not typically used for packaging. The RFID reader and antennas, the laboratory environment and setups were the same as for the tests in Chapter 3.

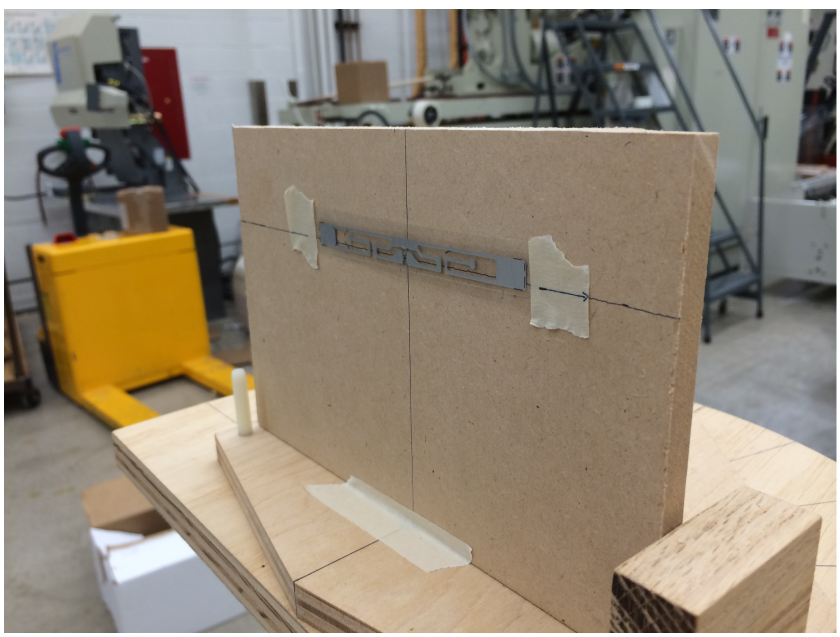


Figure 62 the Medium Density Fiberboard

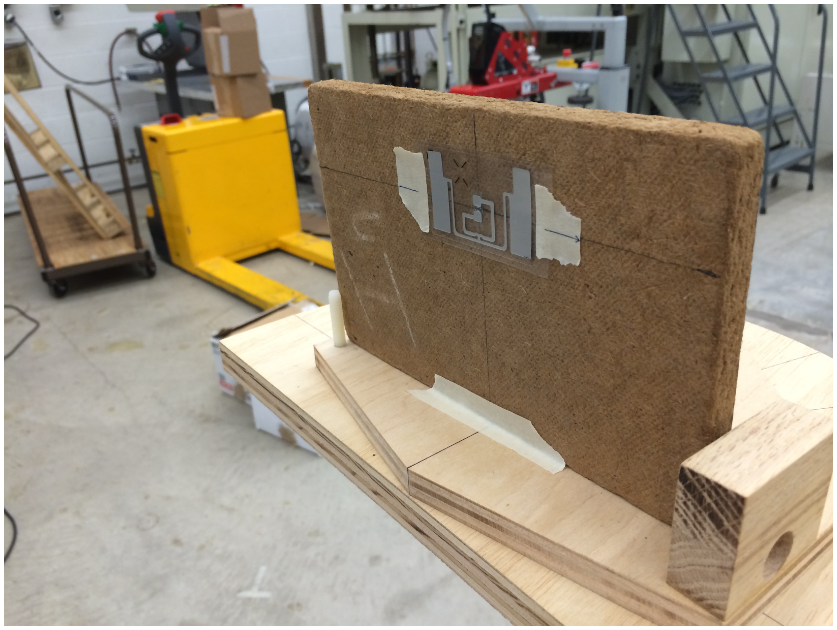


Figure 63 the Low Density Fiberboard

The procedures of this test were:

14) Assemble the LP antenna to the reader, and configure the reader to a transmitting power of 20 dBm, and a receiving sensitivity of -70 dBm;

15) Assemble the material sample to the transponder support and set the angle α to 90° and β to 0°. α and β are constant for all the following procedures;

16) Attach the tag to the material sample at γ=0° using small pieces of masking tape. For the uncoated corrugated paperboard and the HDF, the center of the tag was aligned with the center of the material samples. The MDF and LDF samples are not 7×7 square inches for the reason of limited resource. So the tag was attached to the MDF and LDF at the same height above the ground as it was attached to the HDF and the uncoated corrugated paperboard. Angle γ keeps to 0° for all the procedures;

17) Move the transponder support to the distance r=0.5 foot;

18) Turn on the reader to automatically read the tag 3 times, 5 seconds each time. Delay between two runs is 5 seconds;

19) Move the transponder support to 1 foot and repeat step 5;

20) Move the transponder support outwards from the antenna with a increment of 0.5 foot each time, until the tag can not be detected by the reader for 5 consecutive increases in distance;

21) Record the last distance r the tag can be read as R_{max}. Thus the maximum read distance of the tag with the material at α=90°, β=0° and γ=0°is measured;

22) Repeat above steps for all the three tags, four materials and two antennas.

The results of the second test are shown in Figure 64 and Figure 65. Figure 64 indicates that the tag AD-381m5 had the smallest R_{max} with the uncoated corrugated paperboard, while it had the greatest R_{max} with the MDF, and the R_{max} tested with the MDF was much larger than that with LDF and HDF. The four materials did not have same effect on the tag AD-233m5 and AD-227m5. For the tag AD-233m5 in Figure 64, the R_{max} tested with MDF, LDF and HDF were the same, while the R_{max} with the uncoated corrugated paperboard was 5.5 feet less than those with the other three materials. The R_{max} of the tag AD-227m5 with the four materials tested by the LP antenna were identical or very similar shown in Figure 64. Figure 65 indicates that the tag AD-381m5 had the smallest R_{max} with the uncoated corrugated paperboard, while the R_{max} of AD-381m5 with the MDF and the HDF were the same. For AD-233m5 and AD-227m5 tested by the CP antenna, the R_{max} of either tag with different materials were identical. So, a conclusion was drawn from the second test of the pilot test 2 that materials may not have a consistent effect on tag performance across different tags.

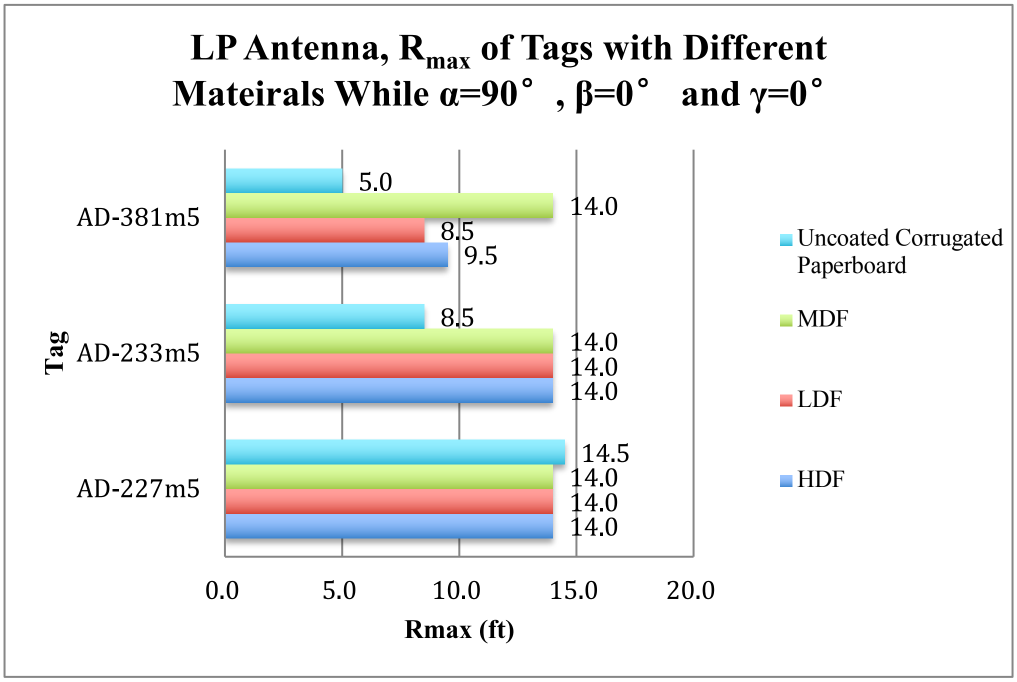


Figure 64 LP Antenna, Rmax of Tags with Different Materials while α=90°, β=0° and γ=0°

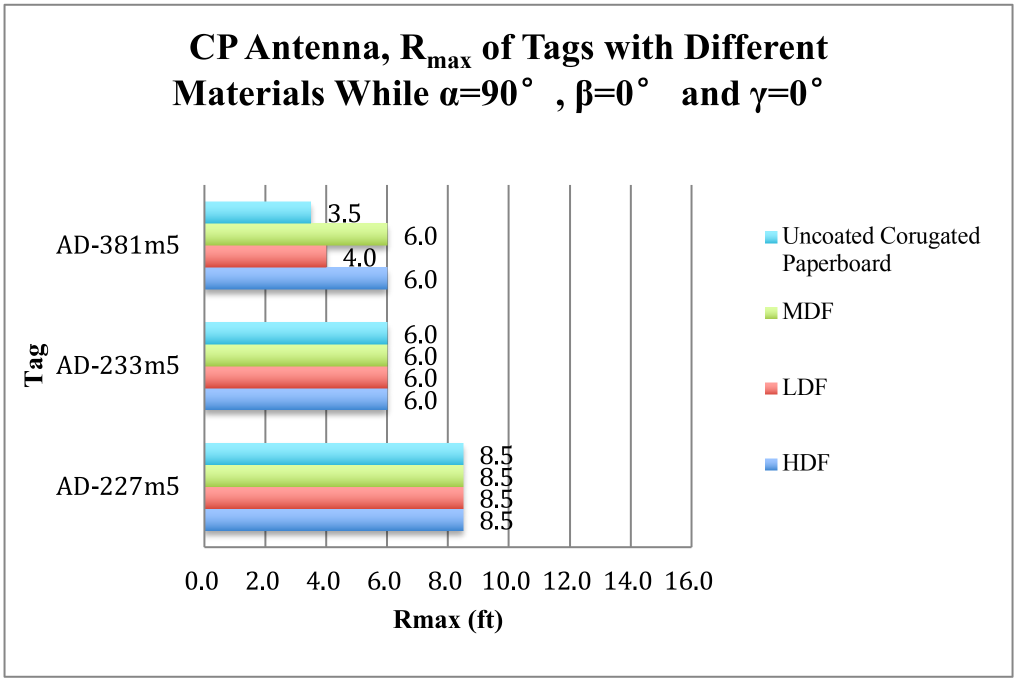


Figure 65 CP Antenna, Rmax of Tags with Different Materials while α=90°, β=0° and γ=0°

Appendix 3

Figures of TotCnt and RSSImx of Each Read Point in the Read Range Test

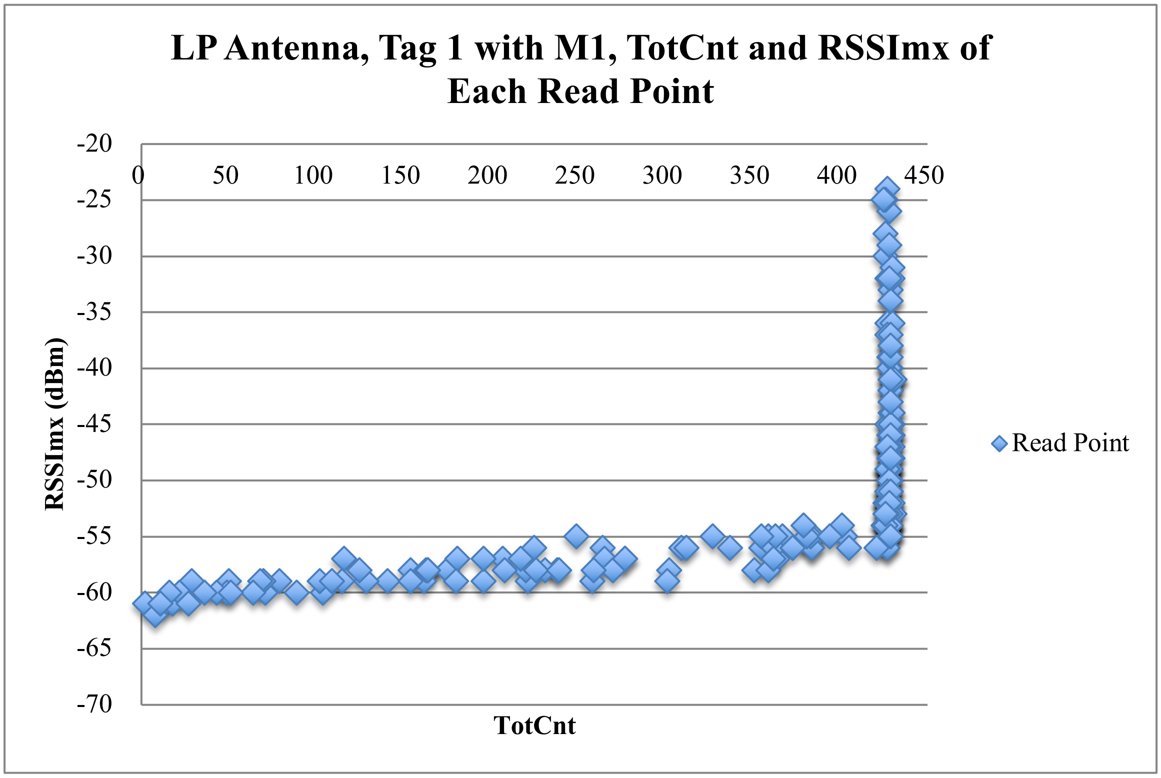


Figure 66 LP Antenna, Tag 1 with M1, TotCnt and RSSImx of Each Read Point

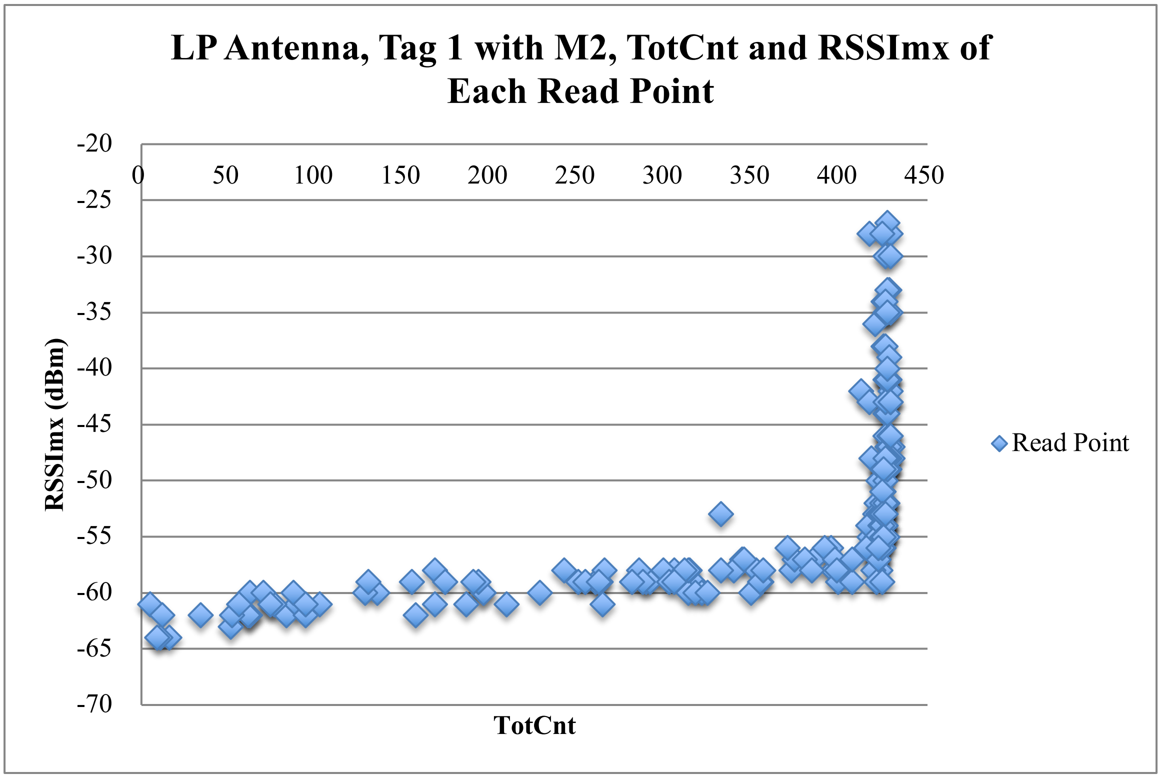


Figure 67 LP Antenna, Tag 1 with M2, TotCnt and RSSImx of Each Read Point

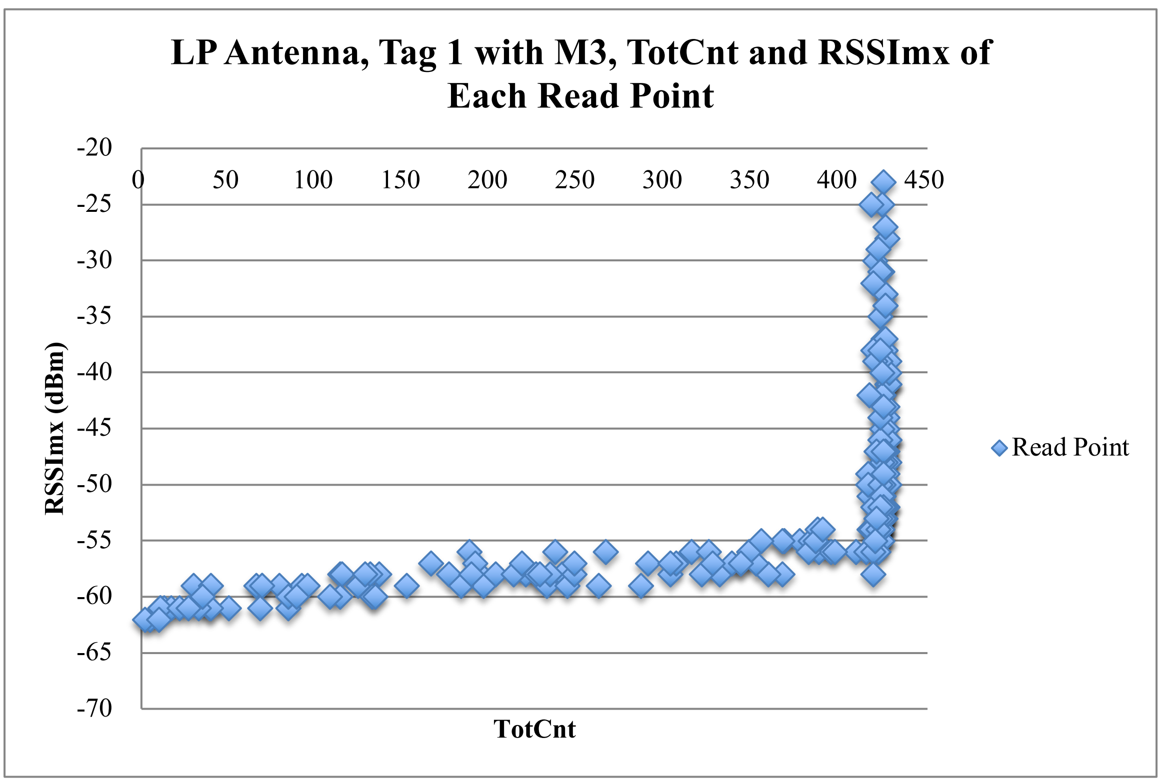


Figure 68 LP Antenna, Tag 1 with M3, TotCnt and RSSImx of Each Read Point

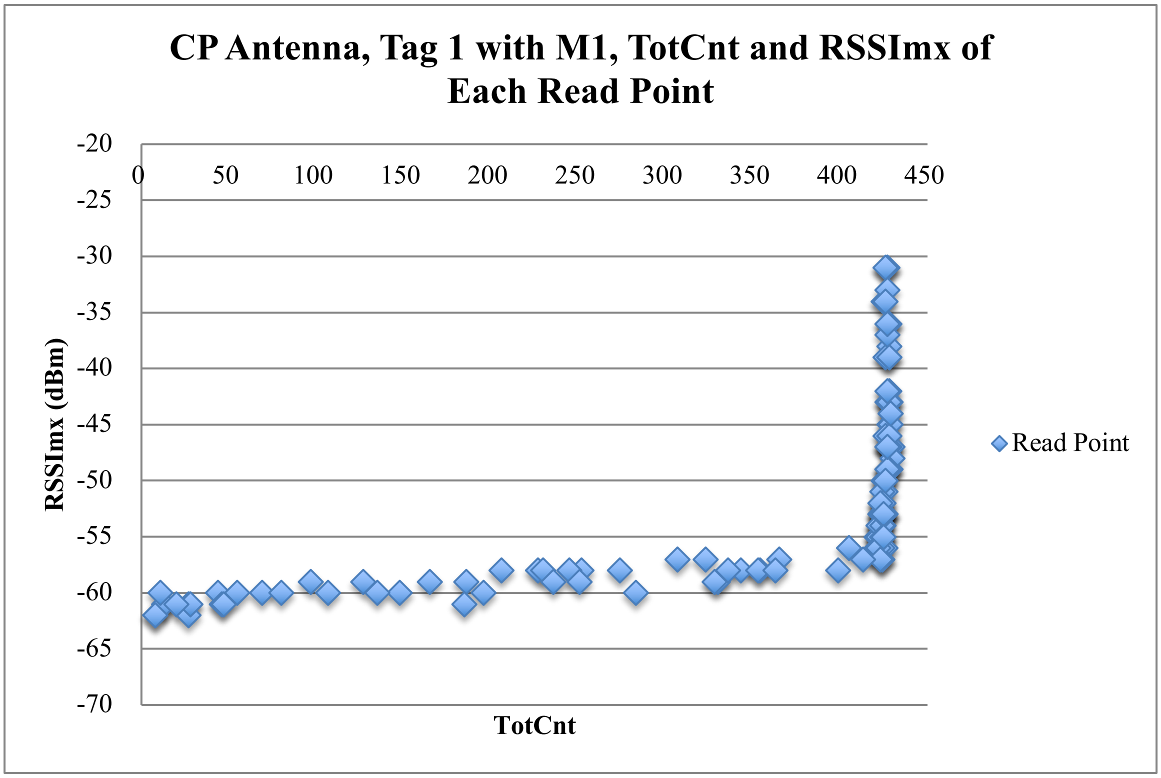


Figure 69 CP Antenna, Tag 1 with M1, TotCnt and RSSImx of Each Read Point

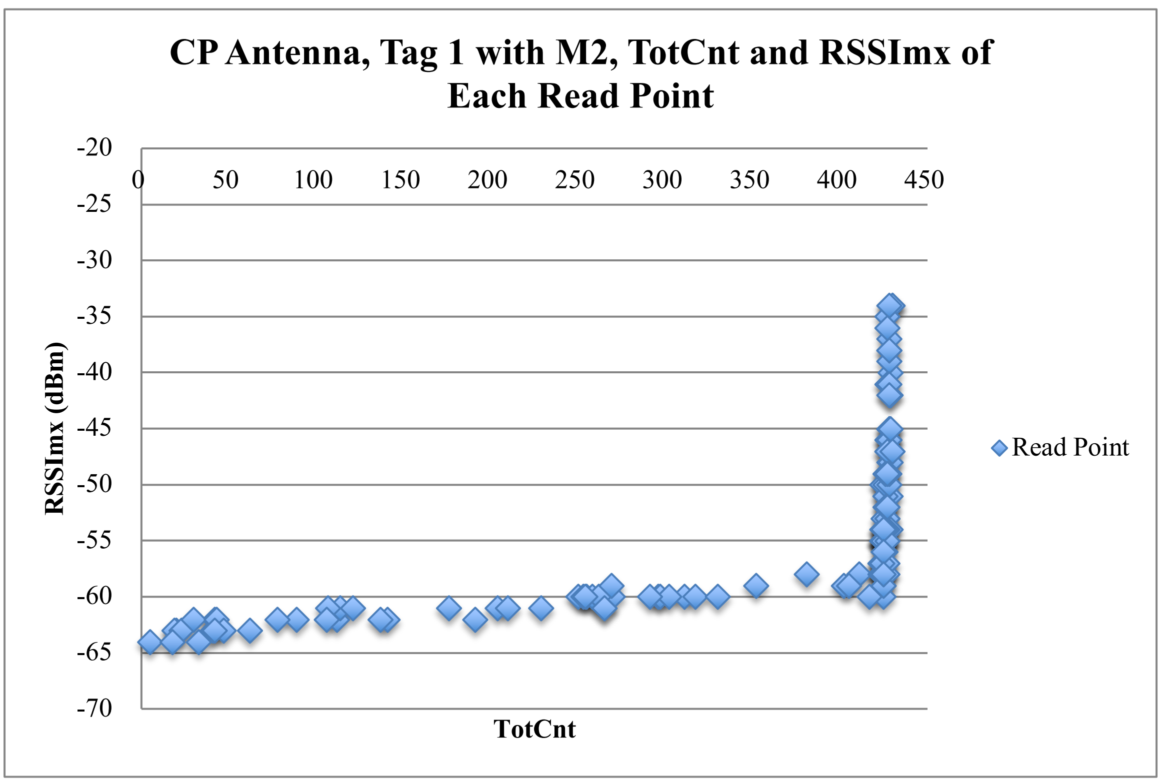


Figure 70 CP Antenna, Tag 1 with M2, TotCnt and RSSImx of Each Read Point

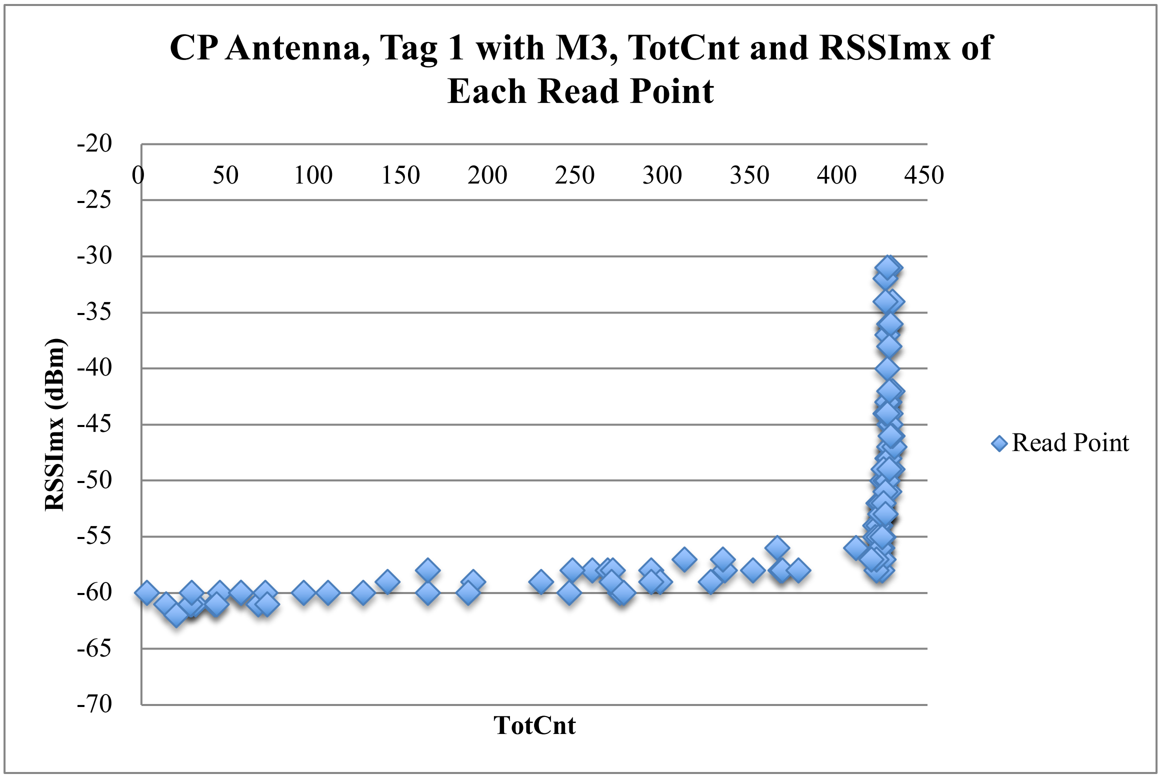


Figure 71 CP Antenna, Tag 1 with M3, TotCnt and RSSImx of Each Read Point

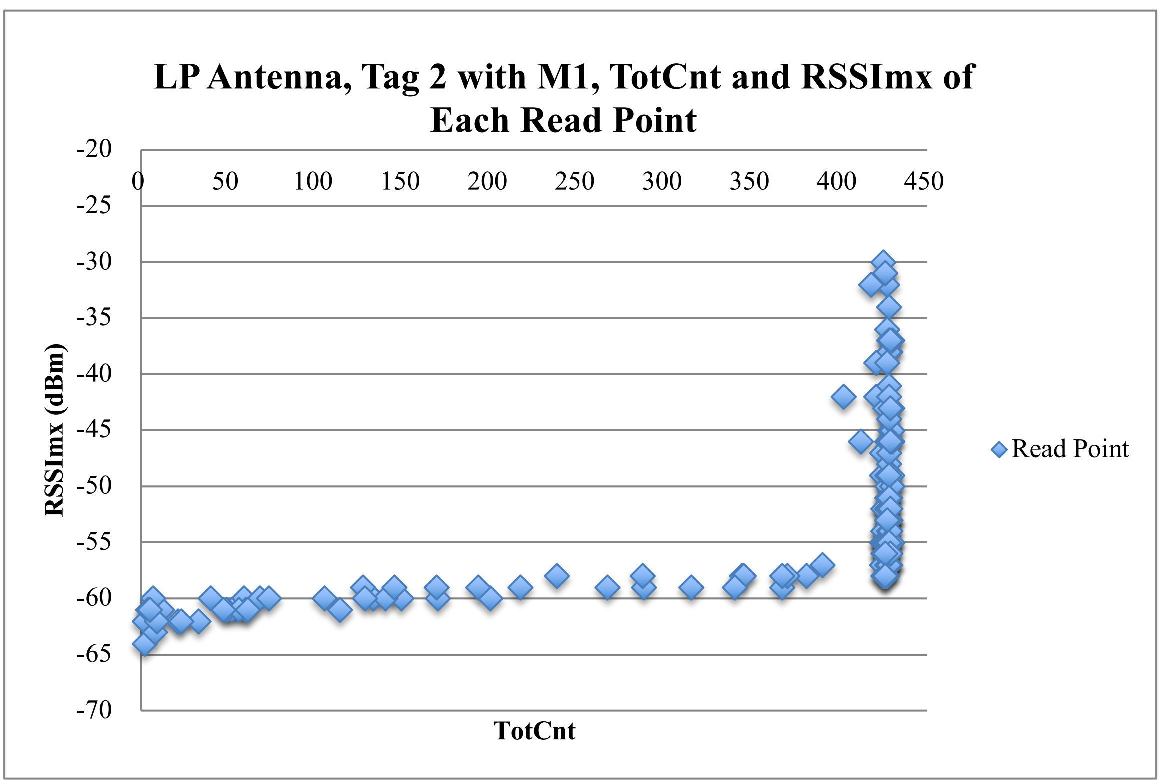


Figure 72 LP Antenna, Tag 2 with M1, TotCnt and RSSImx of Each Read Point

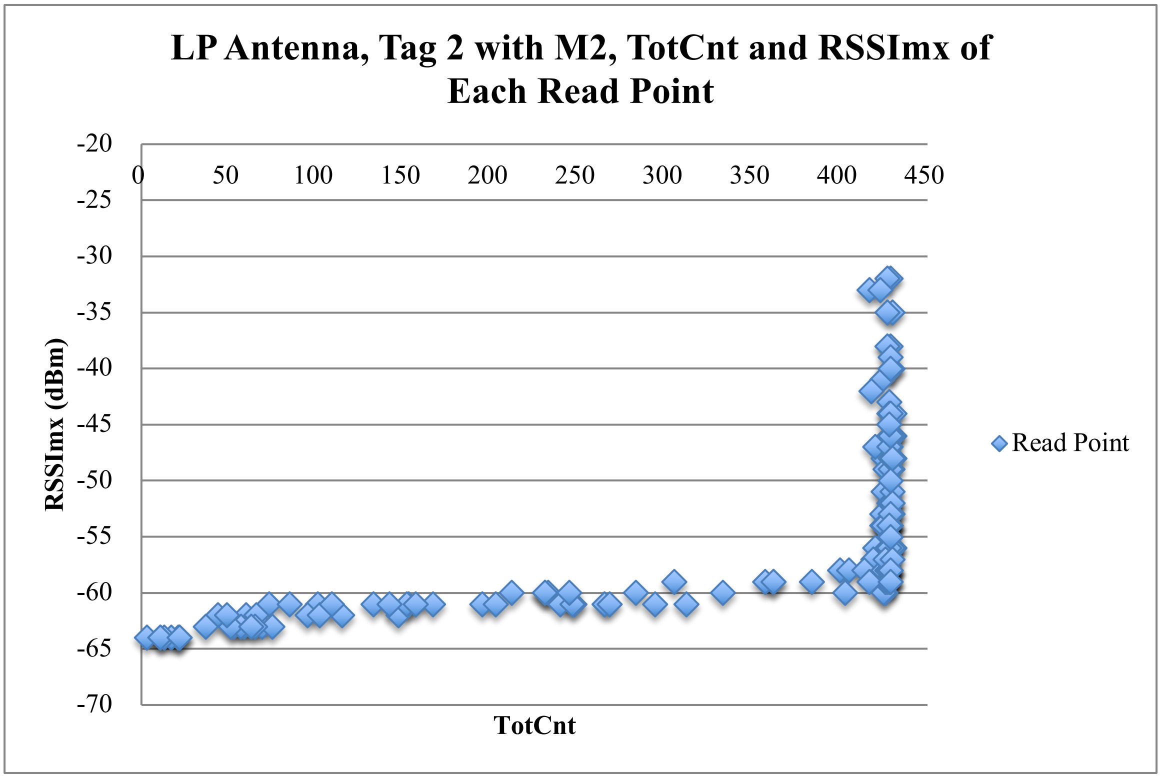


Figure 73 LP Antenna, Tag 2 with M2, TotCnt and RSSImx of Each Read Point

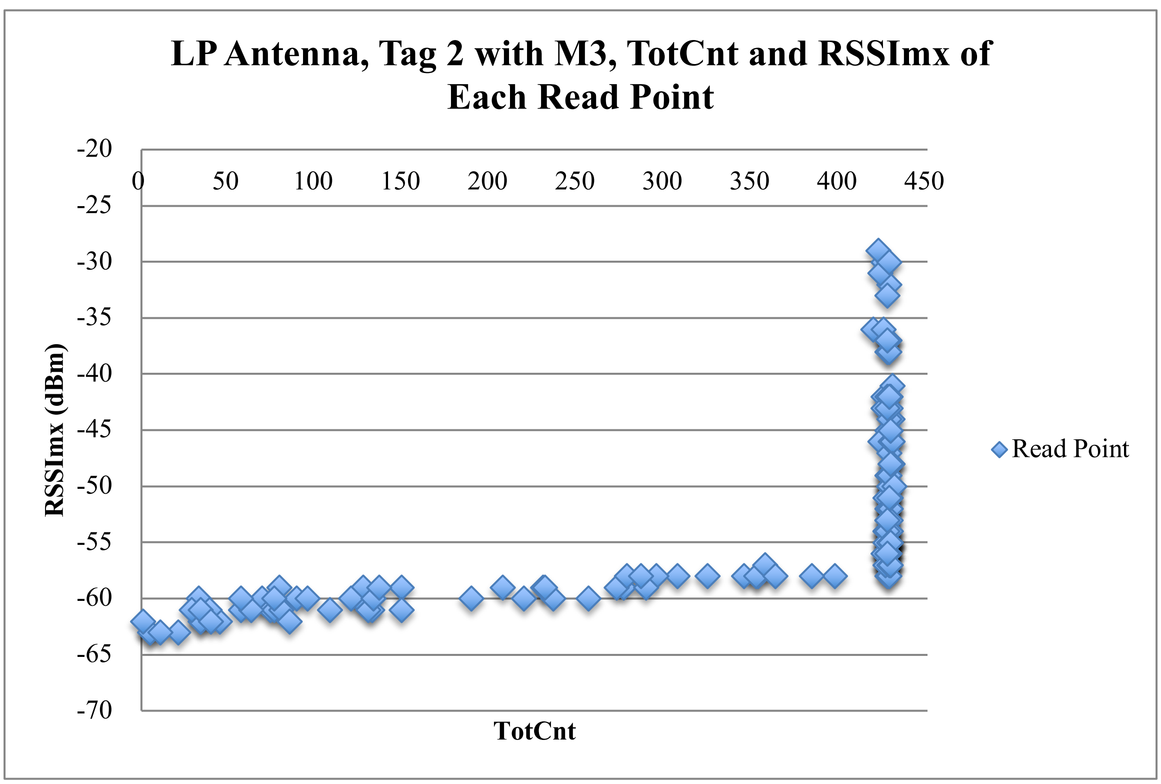


Figure 74 LP Antenna, Tag 2 with M3, TotCnt and RSSImx of Each Read Point

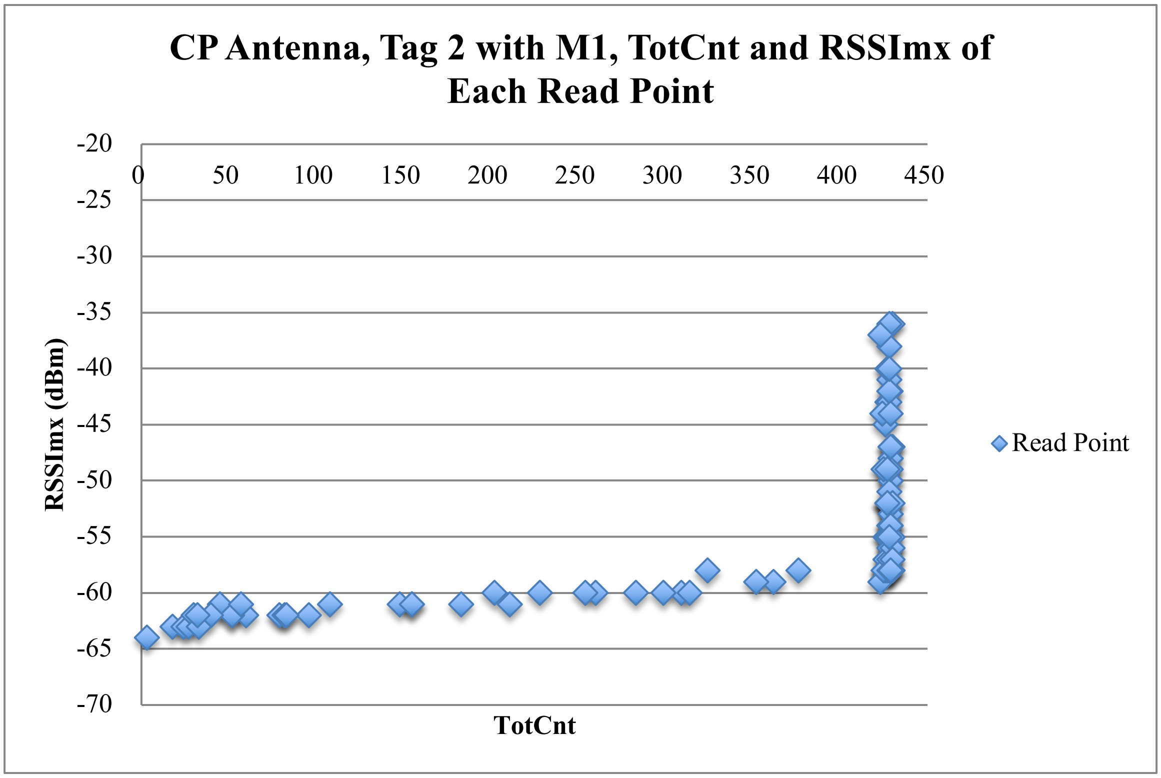


Figure 75 CP Antenna, Tag 2 with M1, TotCnt and RSSImx of Each Read Point

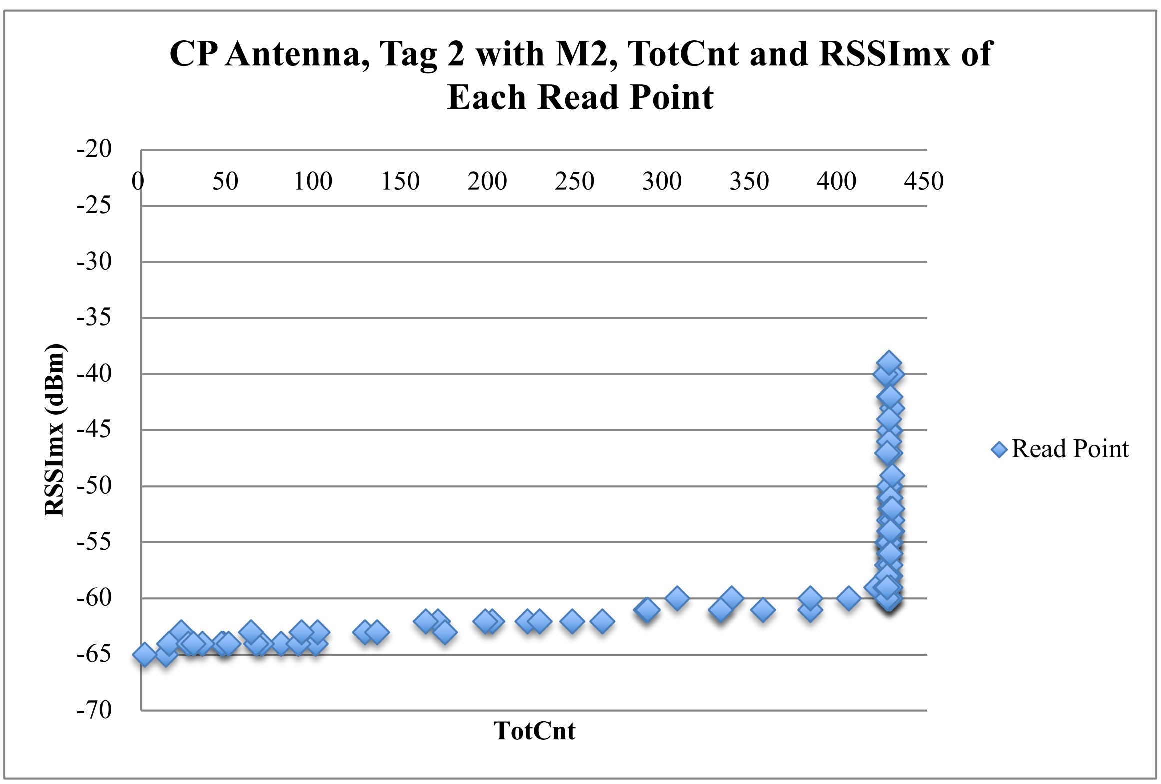


Figure 76 CP Antenna, Tag 2 with M2, TotCnt and RSSImx of Each Read Point

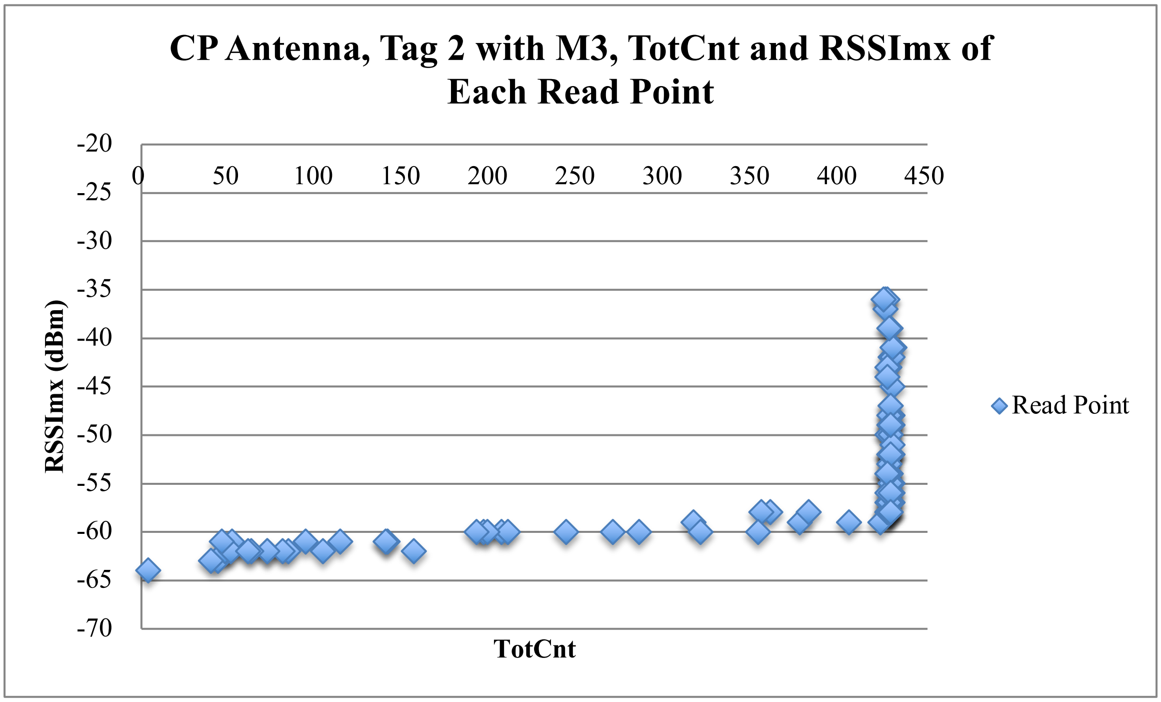


Figure 77 CP Antenna, Tag 2 with M3, TotCnt and RSSImx of Each Read Point

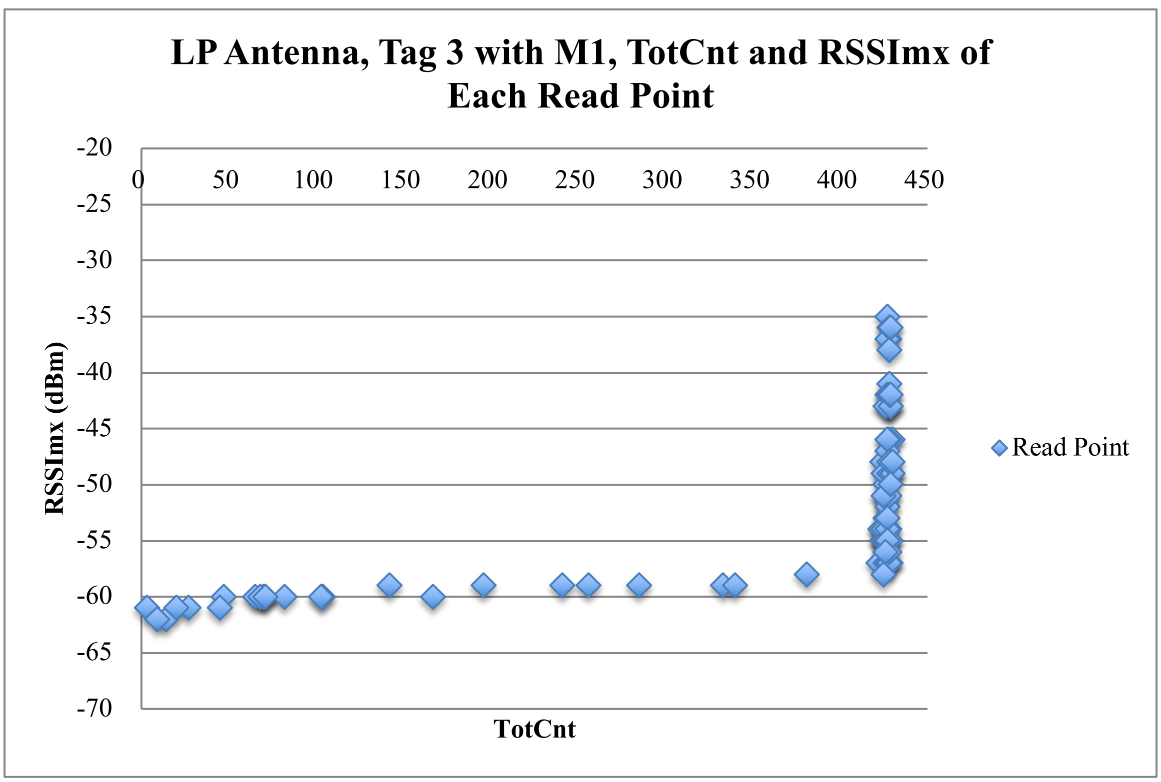


Figure 78 LP Antenna, Tag 3 with M1, TotCnt and RSSImx of Each Read Point

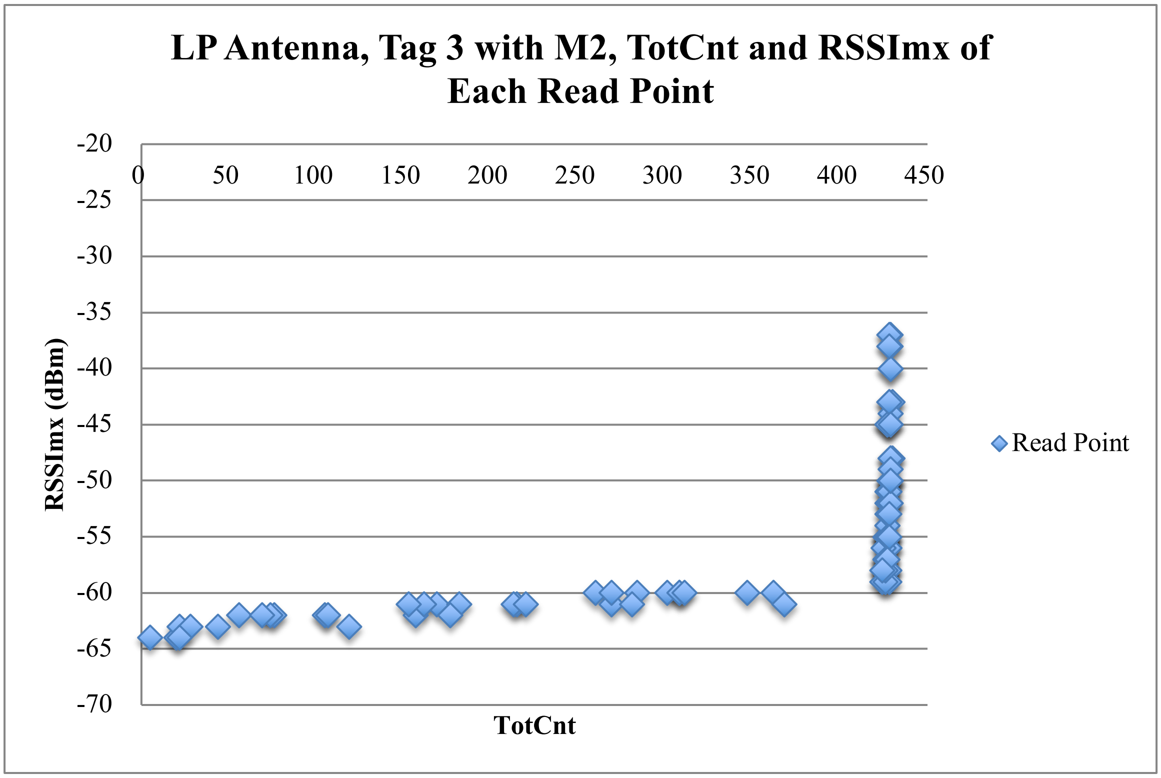


Figure 79 LP Antenna, Tag 3 with M2, TotCnt and RSSImx of Each Read Point

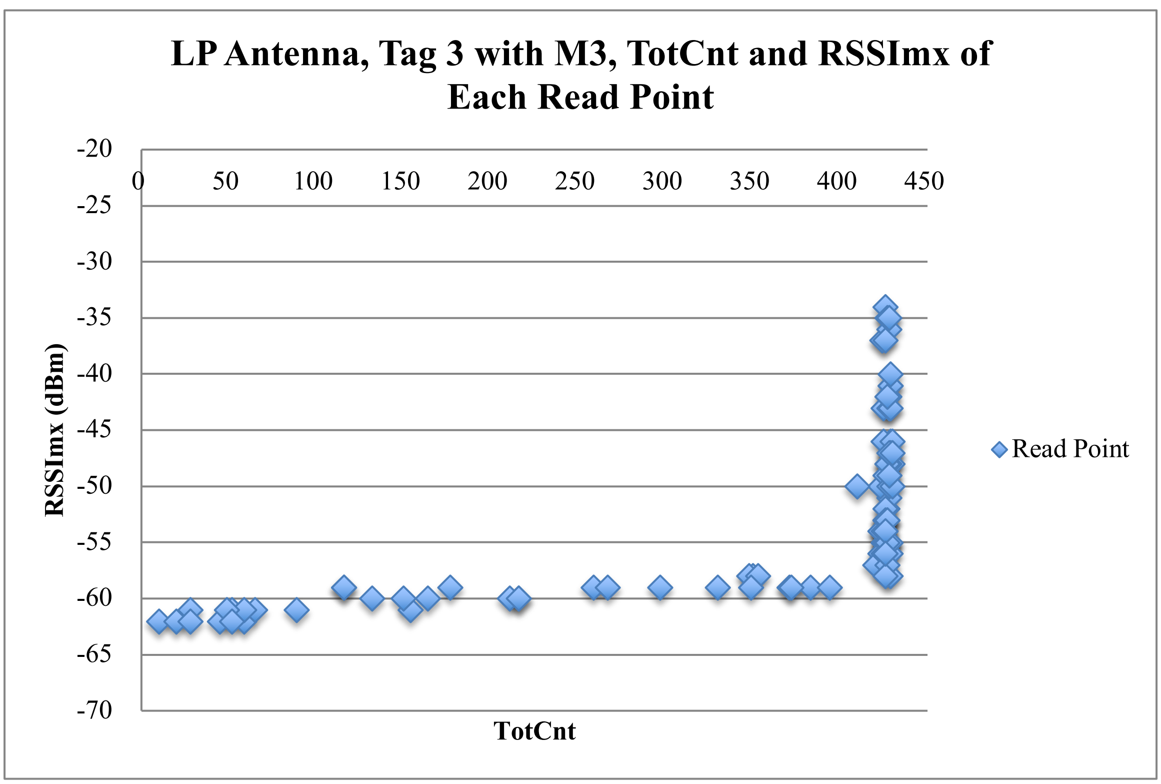


Figure 80 LP Antenna, Tag 3 with M3, TotCnt and RSSImx of Each Read Point

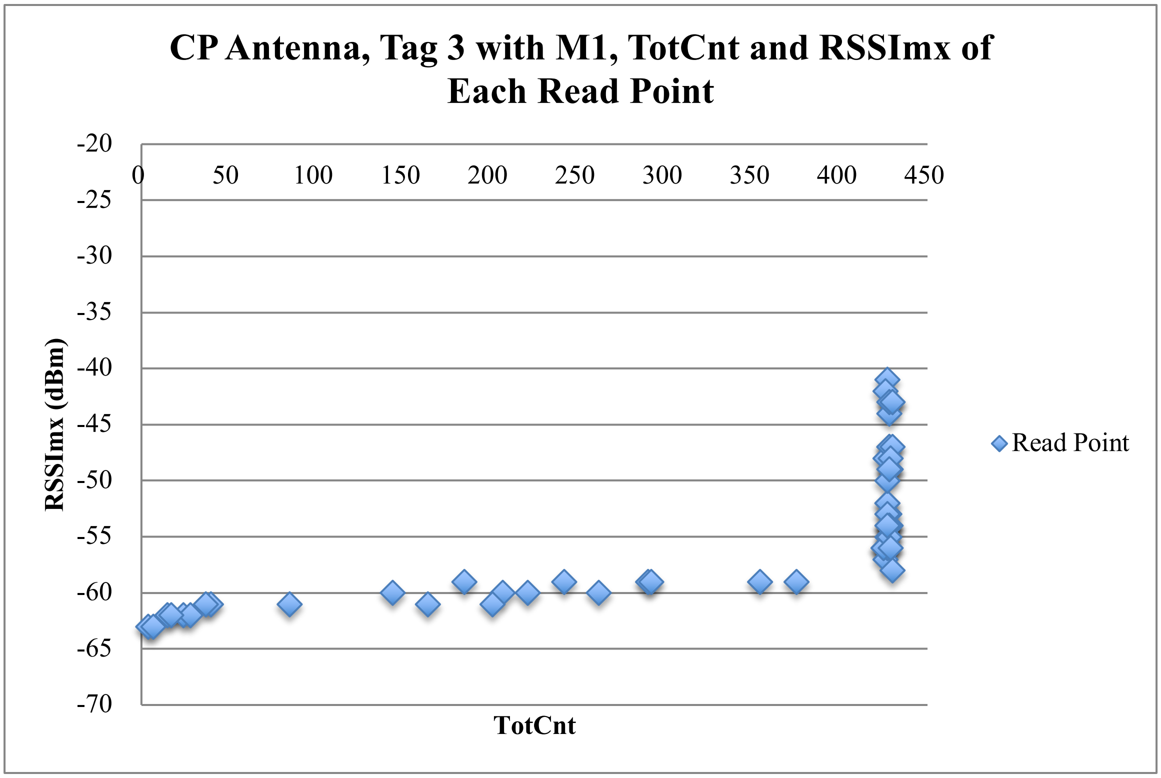


Figure 81 CP Antenna, Tag 3 with M1, TotCnt and RSSImx of Each Read Point

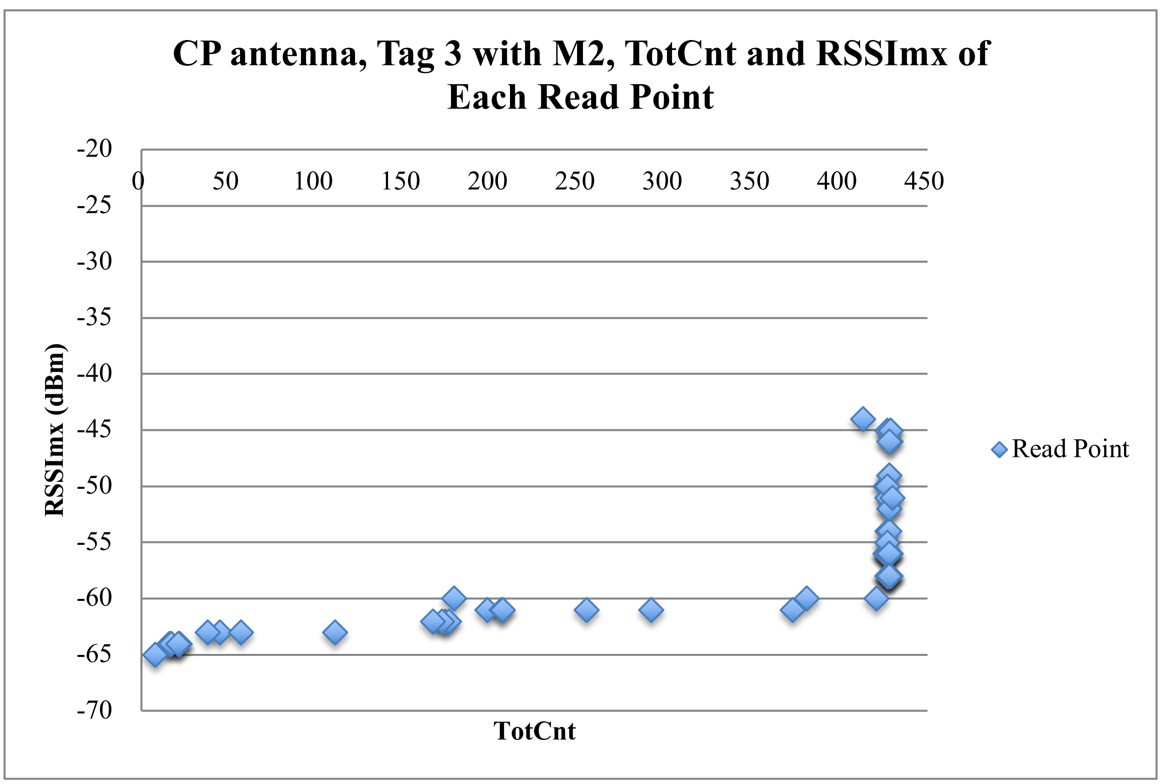


Figure 82 CP Antenna, Tag 3 with M2, TotCnt and RSSImx of Each Read Point

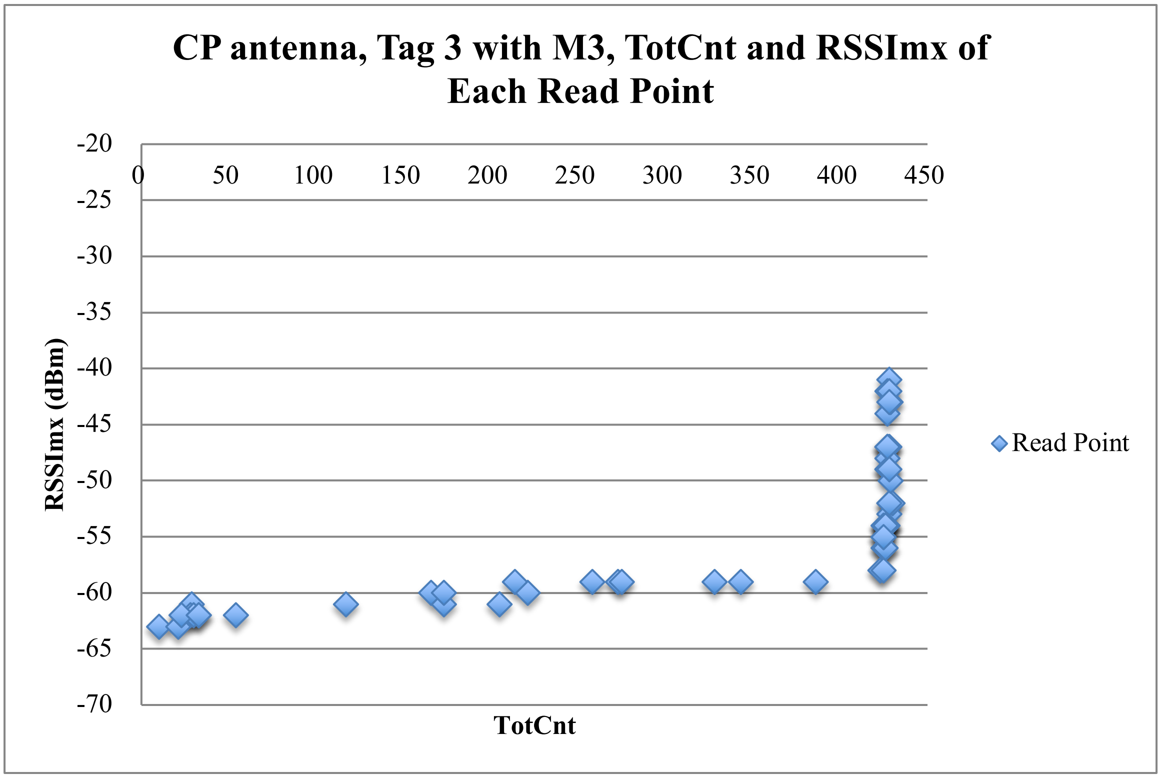


Figure 83 CP Antenna, Tag 3 with M3, TotCnt and RSSImx of Each Read Point

Appendix 4

Figures of TotCnt and RSSImx or Each Read Orientation in the O-RDRate Test

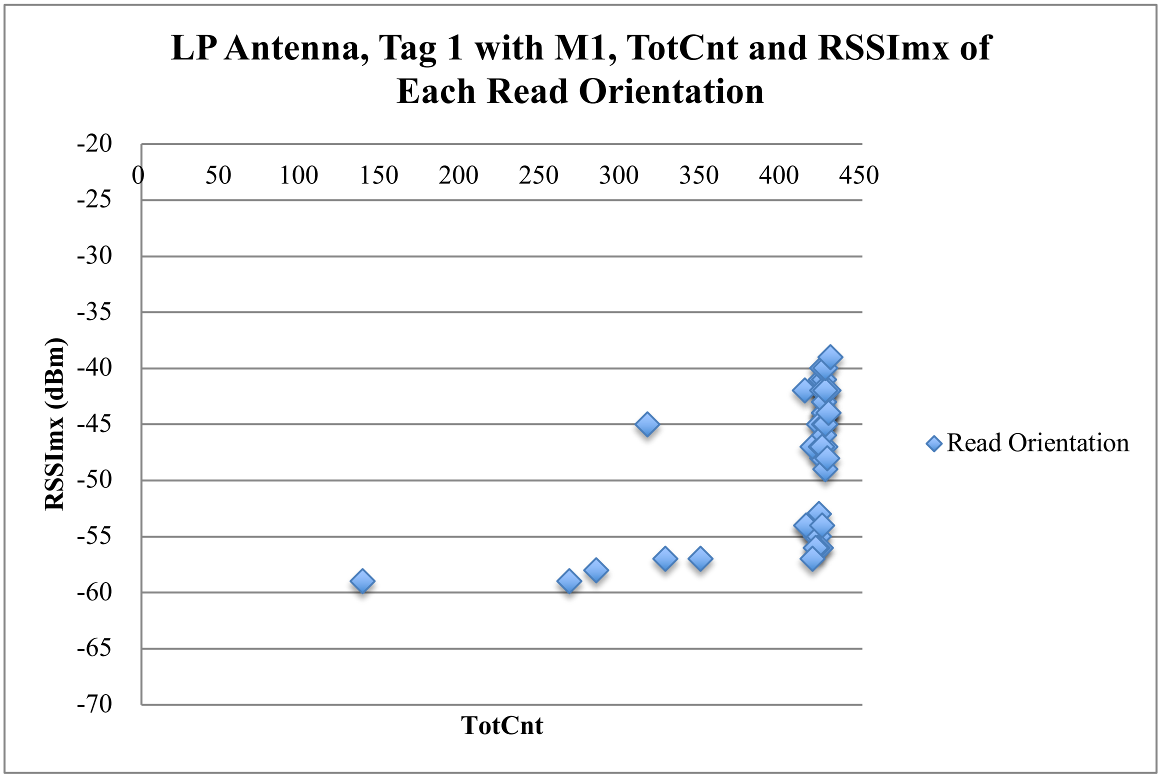


Figure 84 LP Antenna, Tag 1 with M1, TotCnt and RSSImx of Each Read Orientation

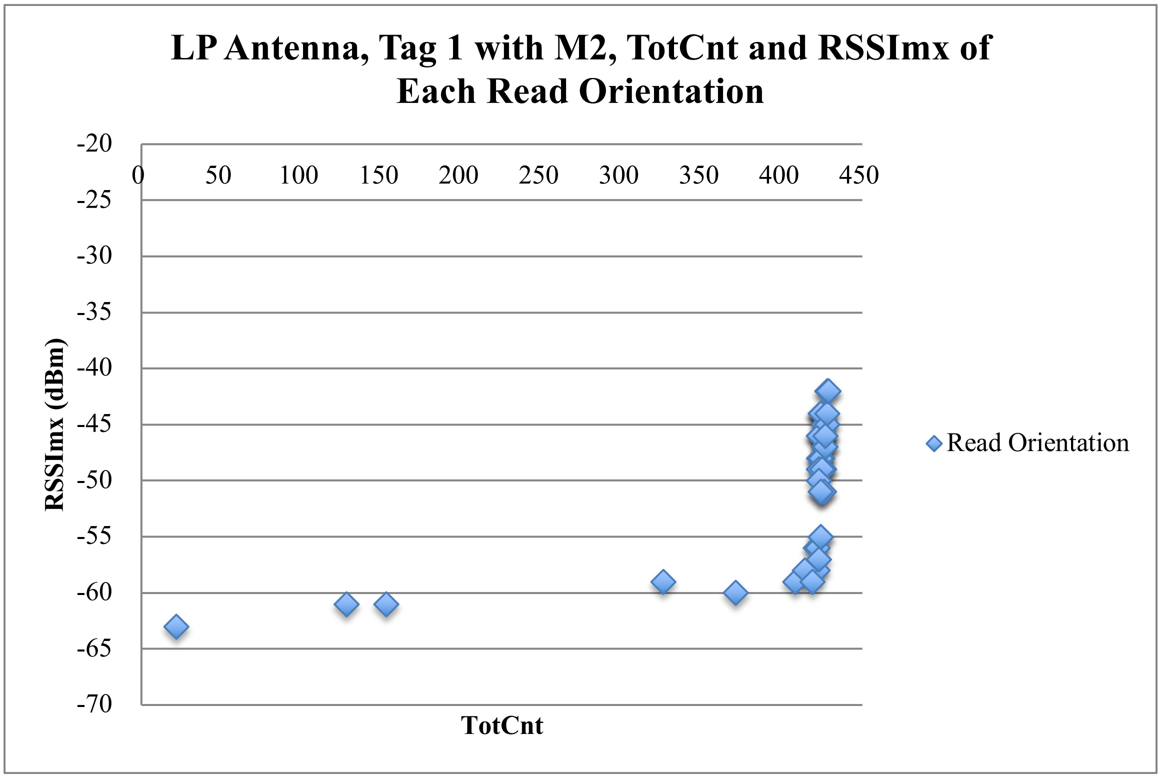


Figure 85 LP Antenna, Tag 1 with M2, TotCnt and RSSImx of Each Read Orientation

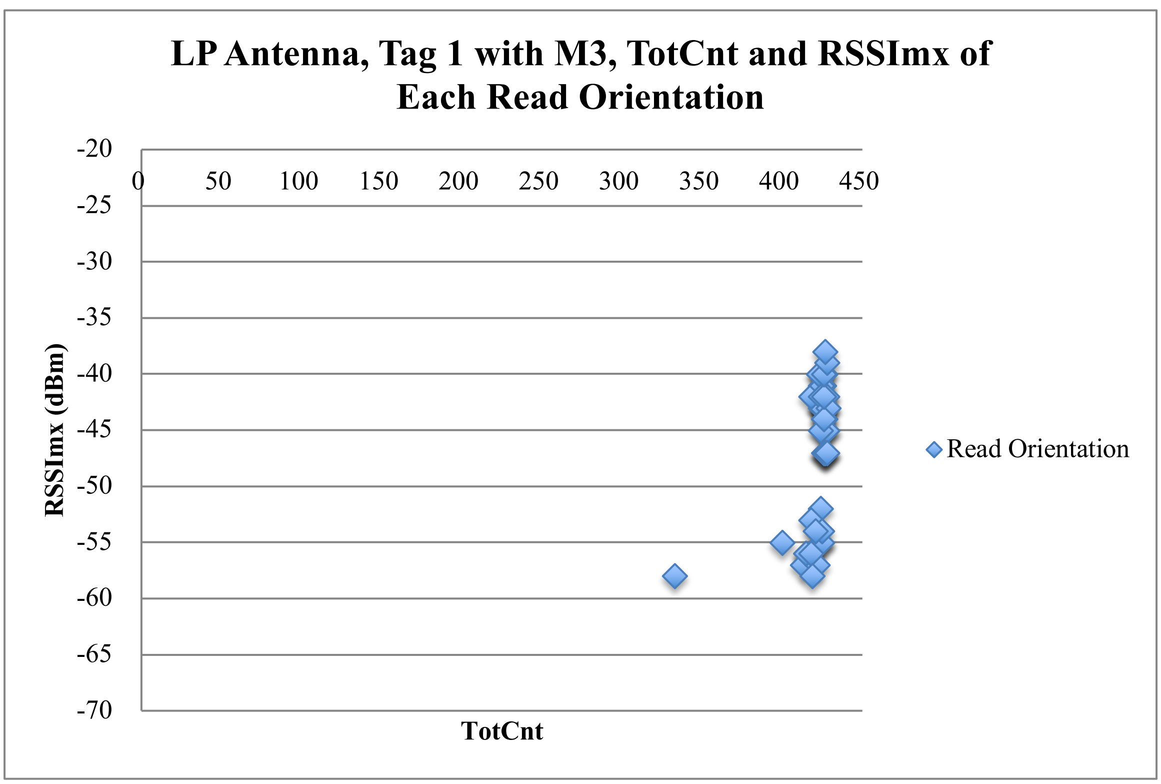


Figure 86 LP Antenna, Tag 1 with M3, TotCnt and RSSImx of Each Read Orientation

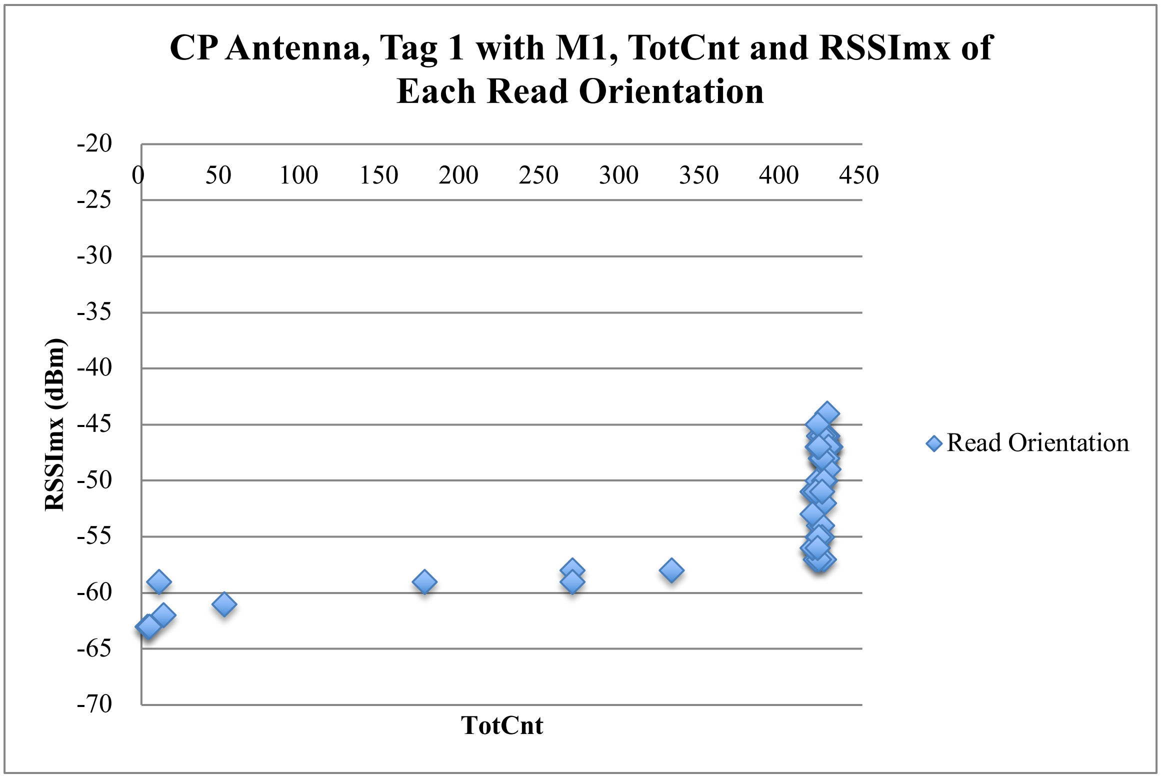


Figure 87 CP Antenna, Tag 1 with M1, TotCnt and RSSImx of Each Read Orientation

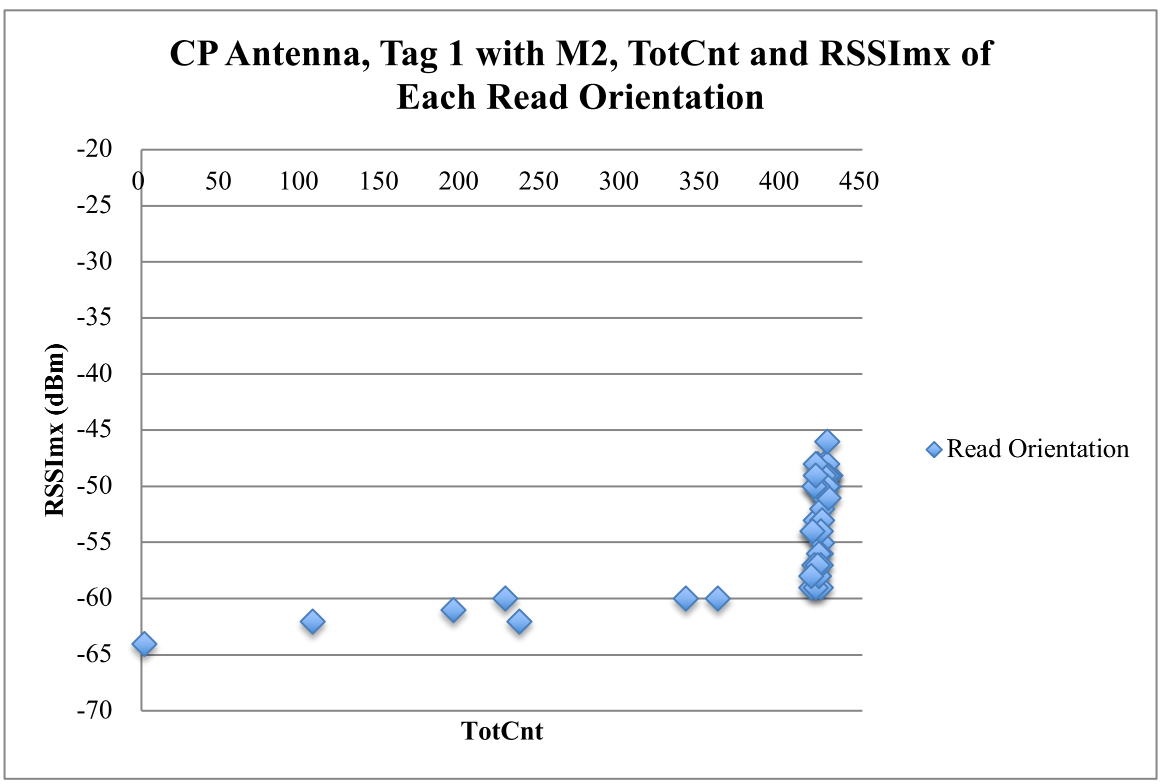


Figure 88 CP Antenna, Tag 1 with M2, TotCnt and RSSImx of Each Read Orientation

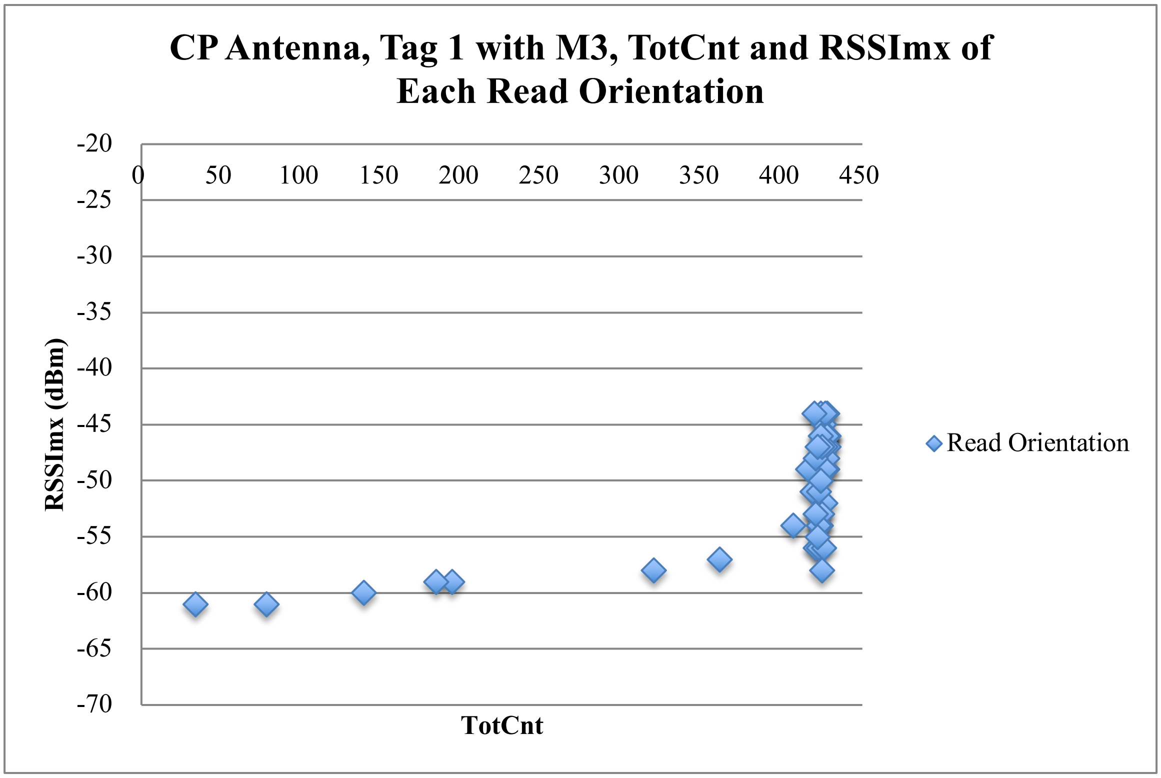


Figure 89 CP Antenna, Tag 1 with M3, TotCnt and RSSImx of Each Read Orientation

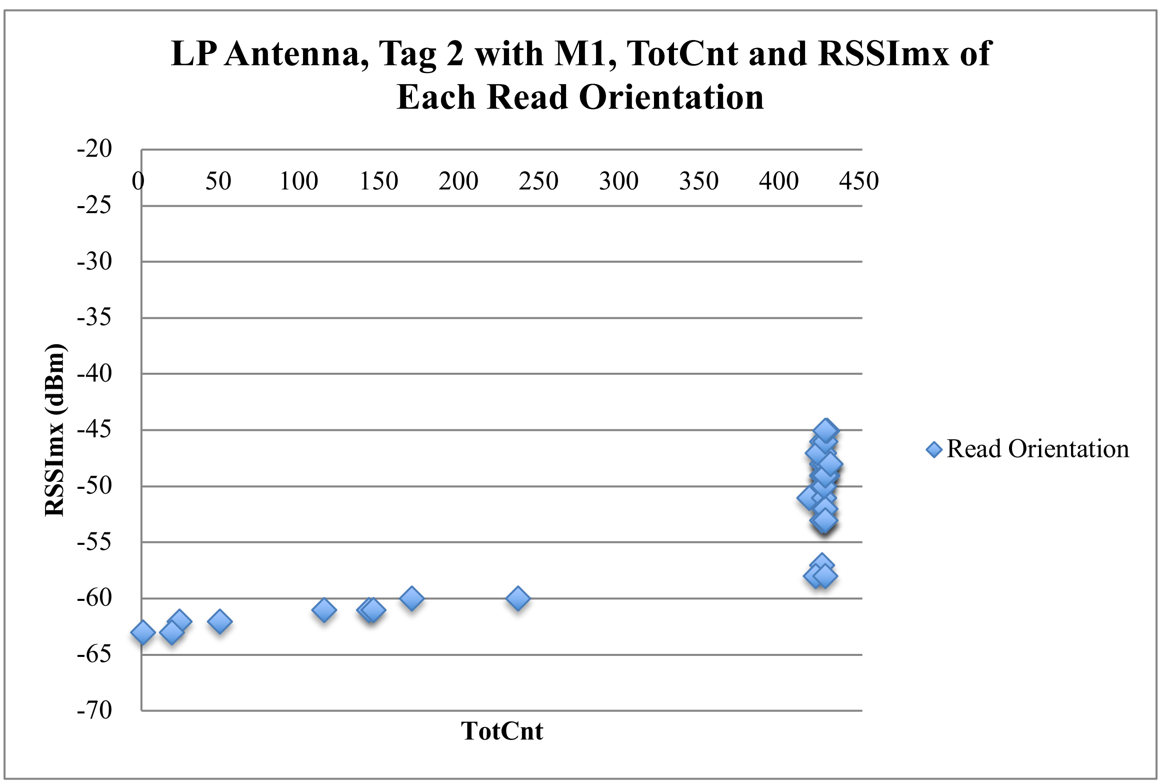


Figure 90 LP Antenna, Tag 2 with M1, TotCnt and RSSImx of Each Read Orientation

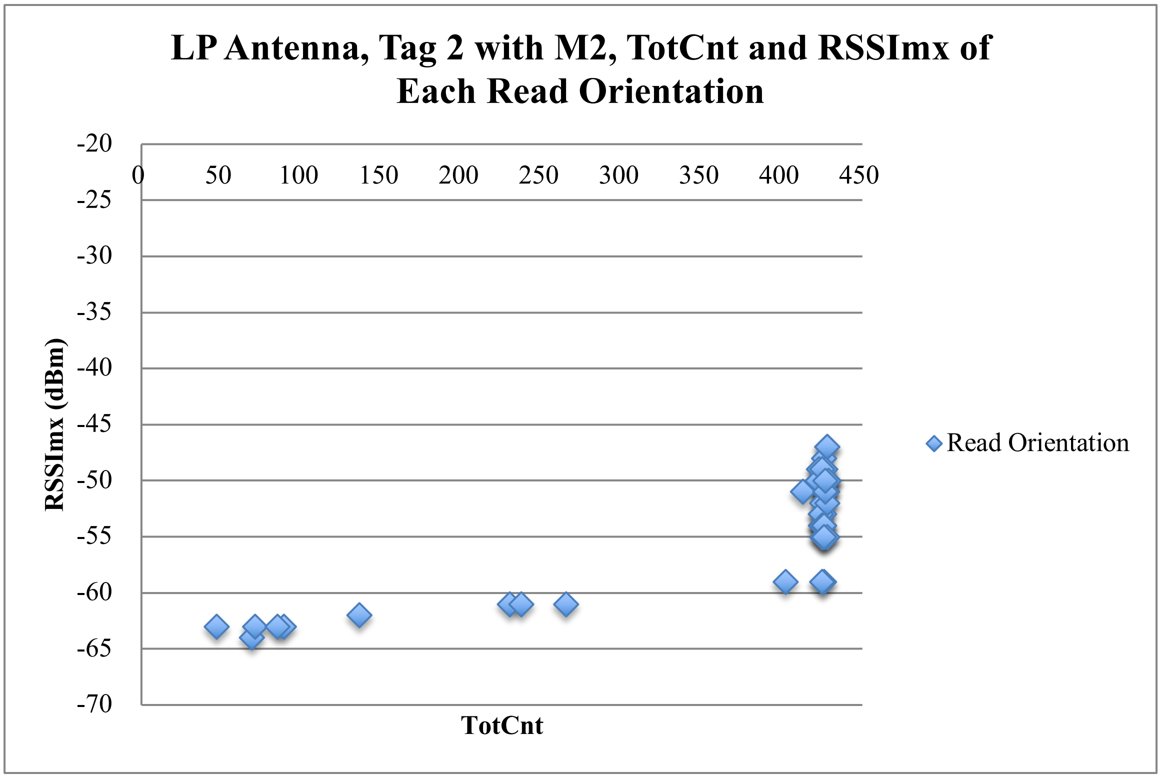


Figure 91 LP Antenna, Tag 2 with M2, TotCnt and RSSImx of Each Read Orientation

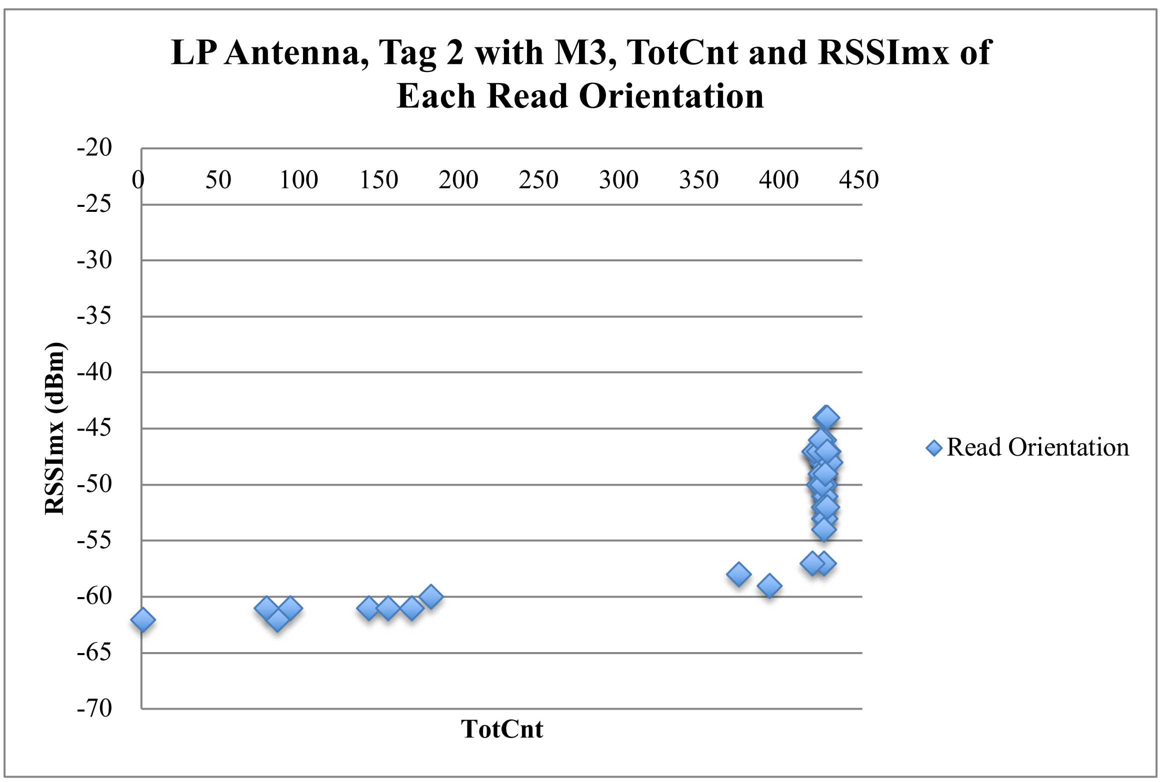


Figure 92 LP Antenna, Tag 2 with M3, TotCnt and RSSImx of Each Read Orientation

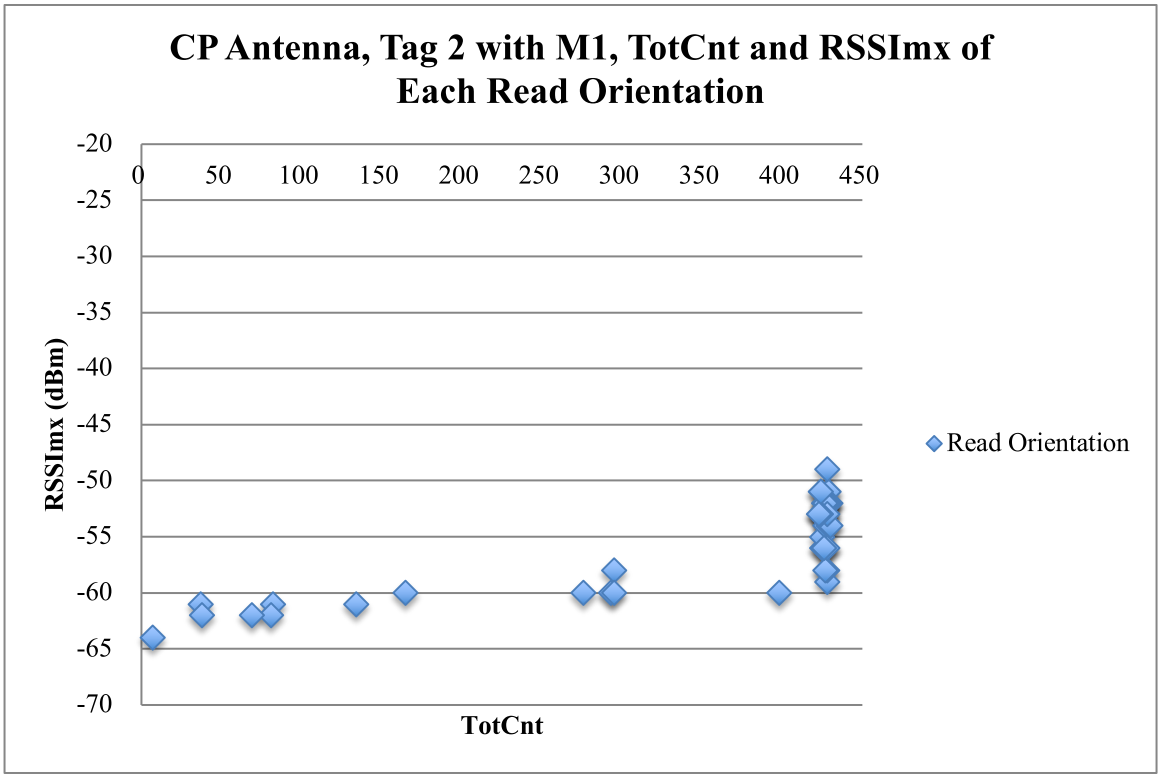


Figure 93 CP Antenna, Tag 2 with M1, TotCnt and RSSImx of Each Read Orientation

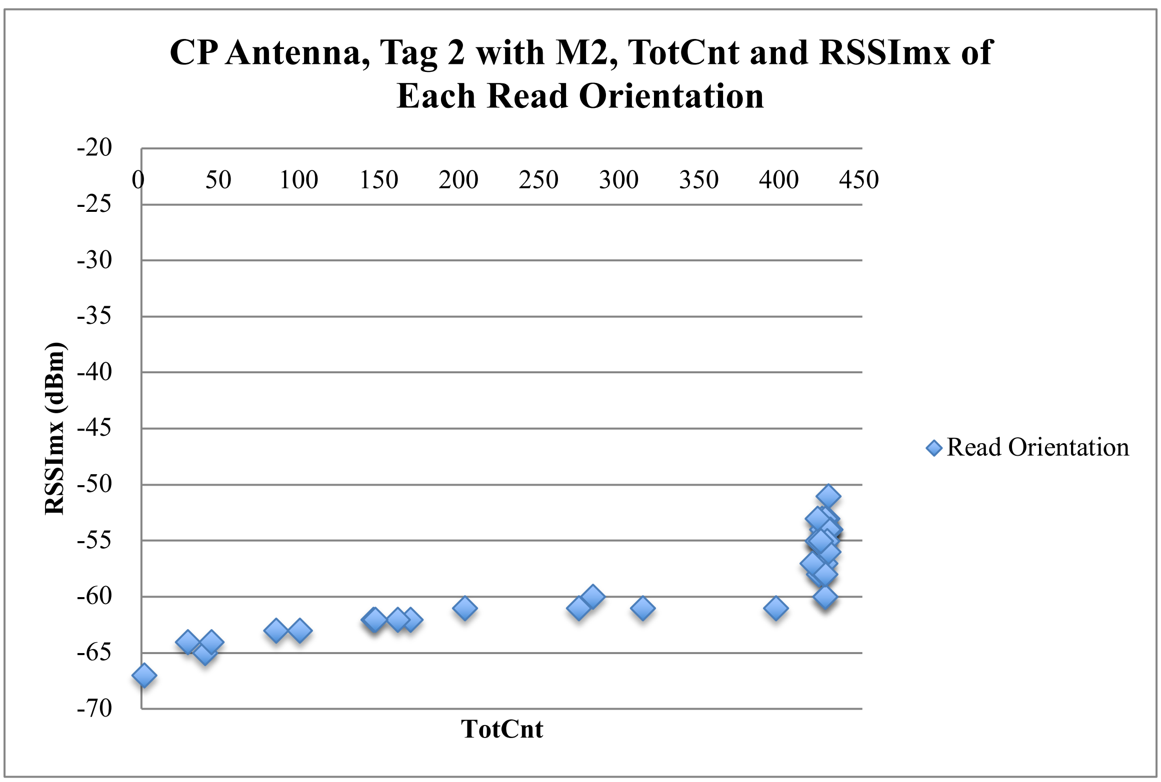


Figure 94 CP Antenna, Tag 2 with M2, TotCnt and RSSImx of Each Read Orientation

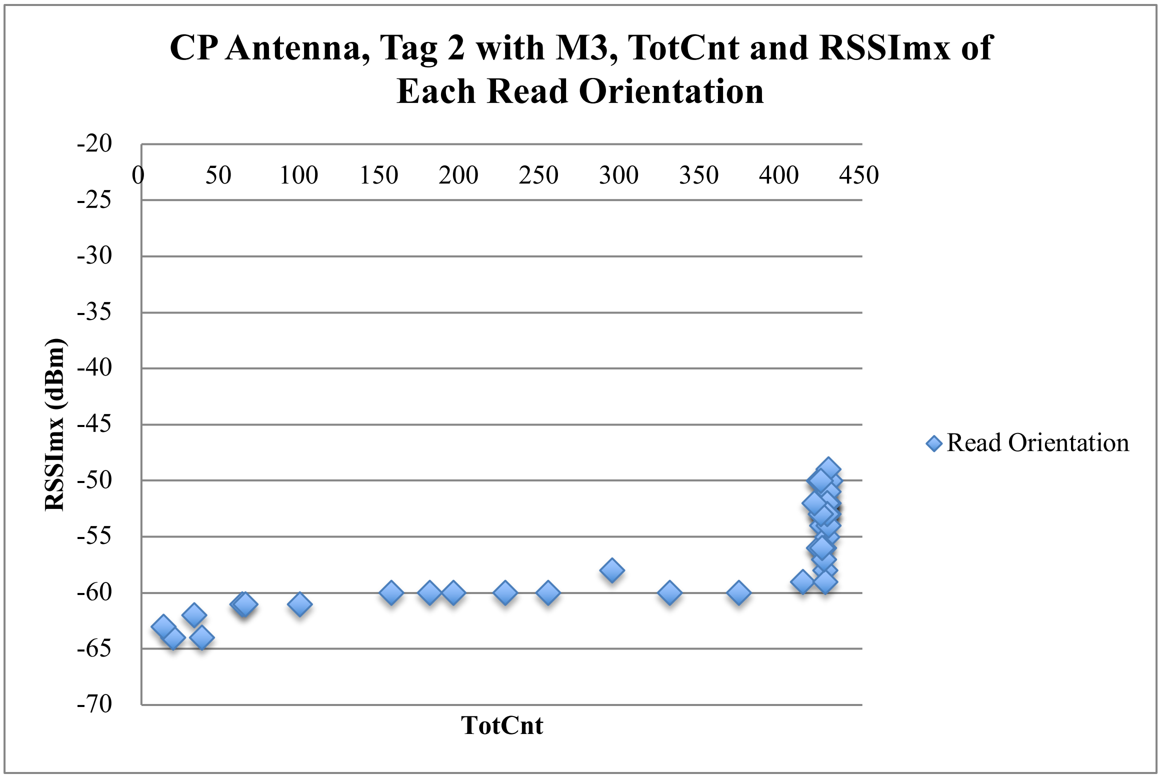


Figure 95 CP Antenna, Tag 2 with M3, TotCnt and RSSImx of Each Read Orientation

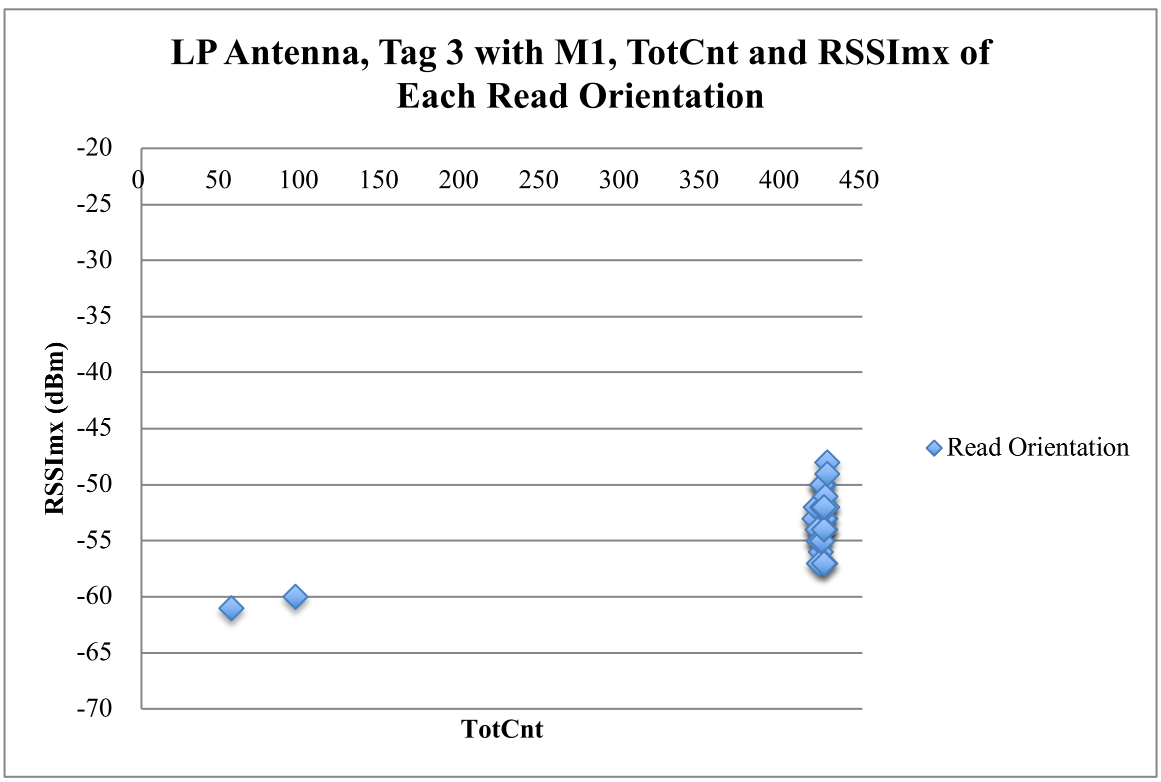


Figure 96 LP Antenna, Tag 3 with M1, TotCnt and RSSImx of Each Read Orientation

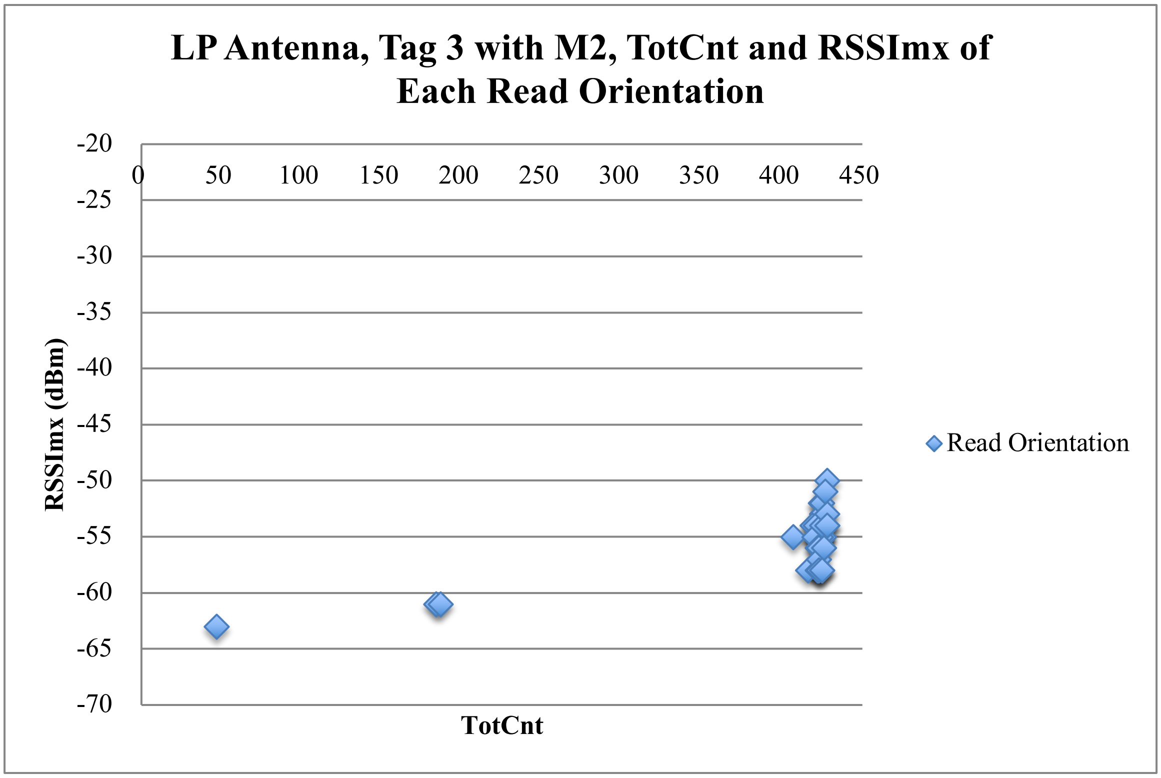


Figure 97 LP Antenna, Tag 3 with M2, TotCnt and RSSImx of Each Read Orientation

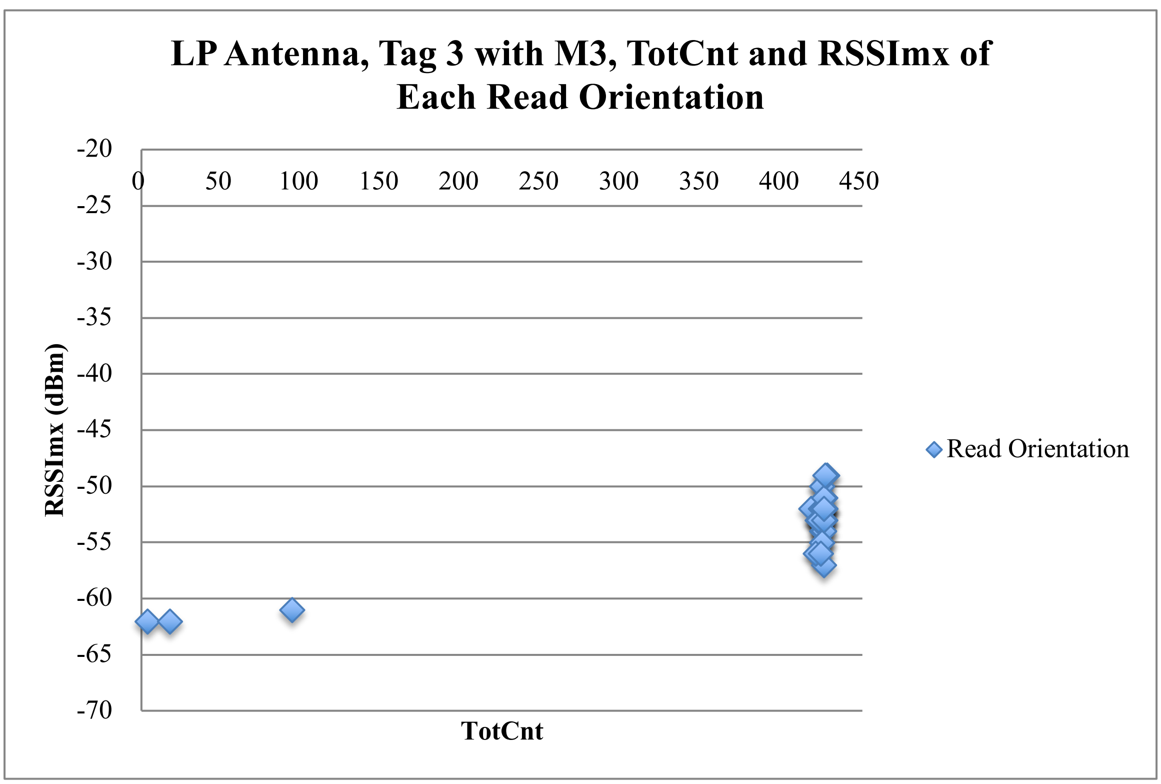


Figure 98 LP Antenna, Tag 3 with M3, TotCnt and RSSImx of Each Read Orientation

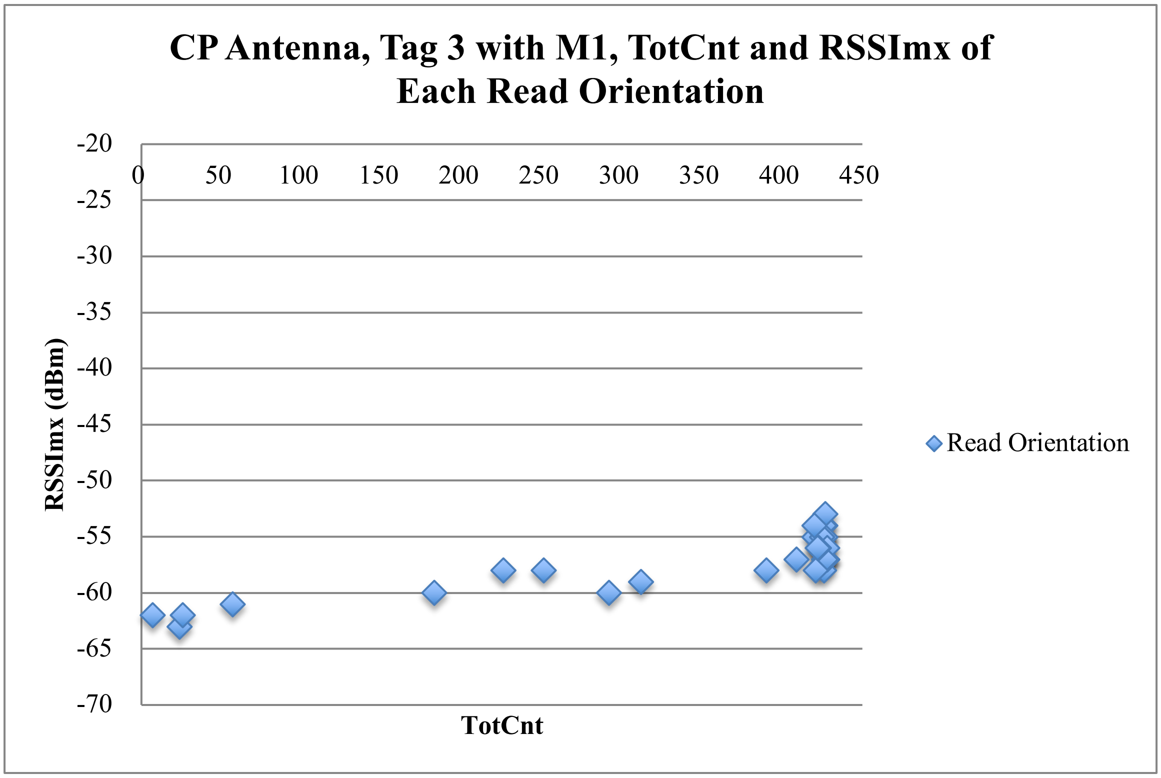


Figure 99 CP Antenna, Tag 3 with M1, TotCnt and RSSImx of Each Read Orientation

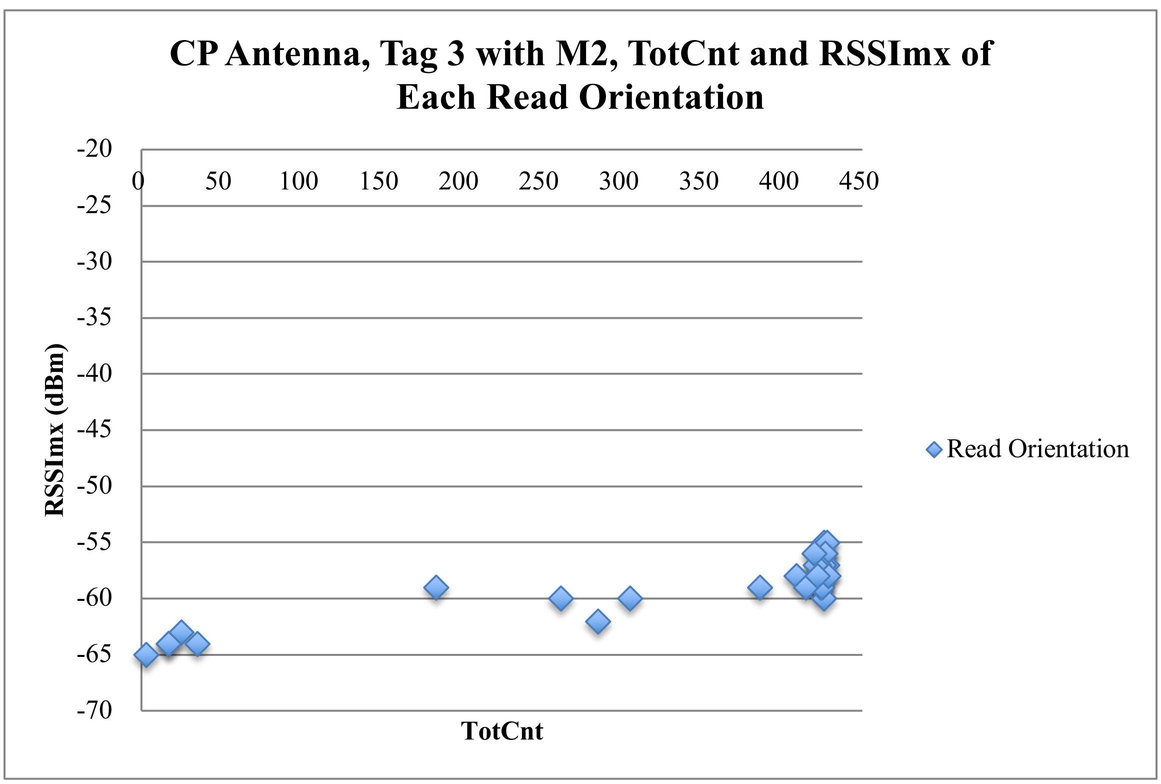


Figure 100 CP Antenna, Tag 3 with M2, TotCnt and RSSImx of Each Read Orientation

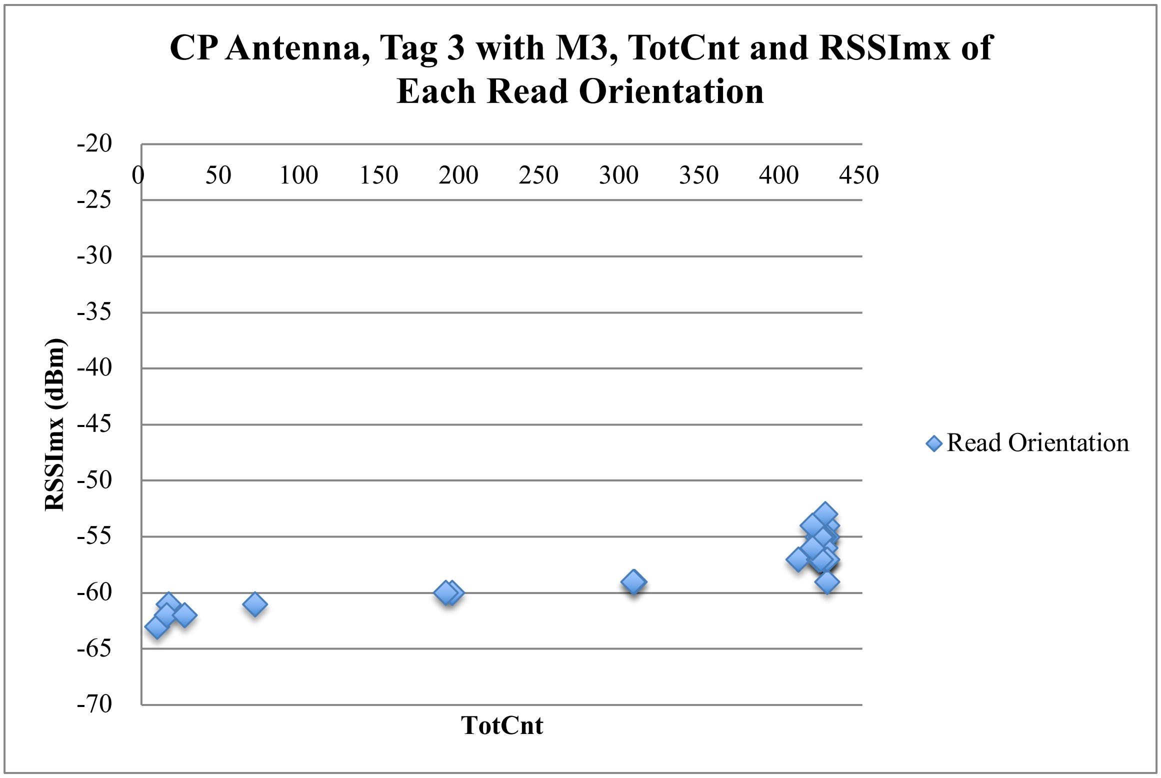


Figure 101 CP Antenna, Tag 3 with M3, TotCnt and RSSImx of Each Read Orientation

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REFERENCES

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