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Analysis of BFSA Based Anti-Collision Protocol in LF, HF, and UHF RFID Environments

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ANALYSIS OF BFSA BASED ANTI-COLLISION PROTOCOL IN LF, HF, AND UHF RFID ENVIRONMENTS

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ABSTRACT

Over the years, RFID (radio frequency identification) technology has gained popularity in a number of applications. The decreased cost of hardware components along with the recognition and implementation of international RFID standards have led to the rise of this technology.

One of the major factors associated with the implementation of RFID infrastructure is the cost of tags. Low frequency (LF) RFID tags are widely used because they are the least expensive. The drawbacks of LF RFID tags include low data rate and low range. Most studies that have been carried out focus on one frequency band only. This thesis presents an analysis of RFID tags across low frequency (LF), high frequency (HF), and ultra-high frequency (UHF) environments.

Analysis was carried out using a simulation model created using OPNET Modeler 17. The simulation model is based on the Basic Frame Slotted ALOHA (BFSA) protocol for non-unique tags. As this is a theoretical study, environmental disturbances have been assumed to be null. The total census delay and the network throughput have been measured for tags ranging from 0 to 1500 for each environment. A statistical analysis has been conducted in order to compare the results obtained for the three different sets.

Chapter 1

INTRODUCTION

Radio Frequency Identification (RFID) is a short-range radio technology that uses radio signals to communicate between a stationary location and movable or non-movable objects. Over the years, RFID has become an integral part of daily life, as this technology has been integrated into a number of applications such as theft prevention, toll collection, library book tracking, access control, inventory management, asset tracking, and healthcare. RFID is a relatively new technology that was invented in 1948 [Glover06]. In the decades following its invention, this technology was further researched and developed and was introduced into mainstream applications in the late 1980s. The 1990s gave rise to RFID standards; as a result, this technology started gaining worldwide acceptance and has been growing ever since [Glover06]. The cost of implementation of RFID has declined considerably over the years, making it widely accessible, thereby boosting its popularity further not only amongst consumers but also amongst researchers.

1.1 Radio Frequency Identification (RFID)

A typical RFID setup consists of one or more RFID readers and multiple RFID tags. The RFID identification process involves a reader scanning a tag (or multiple tags) with the help of a radio signal and then updating their status in a database. Figure 1 depicts a general RFID system that comprises of three essential components: the tag, the reader, and the RF module. In RFID systems, the reader sends radio signals to identify the presence of tags. The reader identifies tags that are present in its read area (interrogation zone) during a broadcast session. This process is known as a census [Prodanoff10].

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Figure 2: RFID components [Schuster02]

RFID tags can be *active* or *passive*. Active tags have their own internal power source and continuously transmit information regardless of their proximity to the reader. Active tags are used in applications where the delivery of real-time data is necessary to ensure efficiency and security. Passive RFID tags are not self-powered and transmit only when they are in close proximity to the reader. As passive tags do not transmit continuously, they rely on inductive coupling. Passive tags are used in applications where a tagged item comes in close proximity to a reader.

RFID readers can either be *active* or *passive*. A single active RFID reader can have a very large read area, thereby eliminating the need for it to be in close proximity to the tags. Active readers continuously check for tags within their read area. For example, the

RF Code M250 reader can scan RFID tags from 300 feet away. Passive RFID readers identify tags by either scanning the tagged items through a channel or by manually scanning them. The read range of tags depends on characteristics such as the frequency of operation, the scan range of the reader, and environmental and electrical interference.

1.2 RFID Frequencies

RFID systems operate in the following three frequency ranges: HF (high frequency), LF (low frequency), and UHF (ultra-high frequency). UHF RFID systems have the highest data rate and range but also carry the highest cost of implementation. LF RFID systems have the lowest data rate and read range but are inexpensive to implement [Kingston10].

1.2.1 Low Frequency

Low frequency RFID systems typically operate between 125-134 KHz, and the read range for this band is approximately 2 feet. LF systems have slower read speeds as compared to other frequencies. One of the major benefits of LF RFID systems is that they are the least sensitive to environmental and electrical disturbances. LF RFID systems are also much cheaper to set up than HF and UHF systems [Kingston10]. Typical LF RFID applications include the tracking of animals, vehicle immobilizers, medical applications, and product identification. Although cost effective and popular, the LF spectrum is not considered a universal standard because of variations in frequency standards and power levels from one region to another [Kingston10].

1.2.2 High Frequency

High frequency (HF) systems typically operate at 13.5 MHz and support a larger read range and data rate as compared to LF RFID systems. The typical read range for a HF RFID system is approximately 3 feet. HF RFID systems are more sensitive to environmental and electrical interferences as compared to LF RFID systems but are less sensitive when compared to UHF RFID systems. HF RFID systems find applications in domains such as inventory tracking, healthcare equipment tracking, product authentication, and airline baggage tracking [Kingston10].

1.2.3 Ultra-high Frequency

Ultra-high frequency (UHF) systems operate between 860 and 930MHz. The cost of UHF tags is the same as that of HF tags. Ultra-high frequency systems have a range of up to 10 feet and have the highest data rate amongst the frequency bands. One of the major drawbacks of UHF RFID systems is that they are highly sensitive to environmental and electrical disturbances. UHF systems are also the most expensive to implement; however, they are widely used for such applications as toll collection systems, manufacturing applications, and parking lot access systems due to their large read range [Kingston10].

1.3 RFID Standards

It is critical to have RFID standards in order for applications such as payment systems and supply chain management systems to have universal acceptance. The RFID standards that exist today and those that are being proposed are classified into the following categories: air interference, organization of information, conformance, and application domain. Some examples of these protocols are: the International Organization for Standardization (ISO) 11784 standard that defines the structure of data on tags, ISO 11785 that defines air interference parameters due to environmental and electrical factors, ISO 14443 for smart cards, ISO 15693 for vicinity cards, and ISO 18047 for testing the conformance of RFID tags and readers [Poirer06]. In addition, there are also standards from EPC Global, ASTM International, the DASH7 alliance, and Auto-ID Center [Kingston10].

1.4 RFID protocols

RFID communication protocol is a way of organizing the conversation between a tag and a reader. The most common protocols for RFID tag-reader communication are ALOHA, Slotted Terminal Adaptive Collection, Binary Tree, and the EFP Gen2 specification [Glover06].

1.4.1 ALOHA protocol

ALOHA-based protocols provide collision resolution. When two tags try to identify themselves to a reader at the same instance or when a tag tries to identify itself to a reader while another identification process is taking place, we can say that a collision has taken place. There are three types of ALOHA protocols: simple ALOHA, slotted ALOHA, and Frame-Slotted ALOHA (FSA) [Chemburkar11]. In Simple ALOHA, a tag transmits after a random unsynchronized time interval and continues to do so until all tags are identified. In the slotted version, tags are read in synchronized time intervals, known as slots, after a delay. However, in the frame-slotted ALOHA version, a tag selects a slot randomly and only responds once in a frame. A frame here refers to a fixed number of slots. If collision occurs amongst tags in a given frame, they do not transmit again in the same frame, but wait to respond in the next frame [Chemburkar11]. There are multiple variations of frame-slotted ALOHA. The most common ones include the Basic Frame-Slotted ALOHA (BFSA) and the Dynamic Frame-Slotted ALOHA (DFSA) protocols [Klair10]. In the DFSA protocol, the frame varies over time, whereas in the BFSA protocol, the frame size is kept constant for the entire read cycle [Klair10]. The frame-slotted ALOHA is a collision resolution protocol and is widely implemented and researched due to its simplicity. The existing protocols for FSA include ISO 18000-6:2004 [ISO 18000-6:2004] and ISO15693-3:2000 [ISO15693}3:2000].

1.4.2 Frame-Slotted ALOHA (FSA) protocol

As discussed in the previous section, depending on whether the frame size is static or dynamic, the frame-slotted ALOHA protocol is classified into two main categories: BFSA and DFSA. BFSA and DFSA are further classified depending on the support for features such as muting (the ability of the reader to silence tags successfully after identification) and early-end (the ability of a reader to close the idle slots) [Klair10].

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Figure 2: FSA protocol [Prodanoff10]

The ALOHA protocol is an extension of the Time Division Multiple Access scheme and supports collision resolution. Figure 2 represents the relationship among *read cycles*, *frames* and *slots*. An identification process may consist of a number of *read cycles* as they are repeated until all tags in the read area have been identified. A *slot* is a discrete time interval synchronized by the reader. A collection of slots is grouped into *frames*. A collection of frames comprises of a *read cycle*. In the case of BFSA, the frame size is fixed; hence, in the BFSA scheme, all frames have the same number of slots.

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Figure 3: Tag read cycle [Kang08]

In Figure 3, the x-axis represents a timeline for the read cycle (the time elapsed between two REQUEST commands) whereas the y-axis represents the number of tags within the reader's range. During downlink, the RFID reader transmits a REQUEST signal to the RFID tags that are present in the reader's range. During uplink, the tags that are present within the reader's read range transmit their data packets to the reader. In the case of the simple ALOHA protocol, activated tags share the uplink channel as a result of which partial and complete collisions can occur. This drawback is partially overcome in the slotted ALOHA, where the data is transmitted in slot intervals. Although partial collisions are eliminated, this protocol is still prone to complete collisions. In order to reduce the number of collisions, tags transmit to the reader only once per frame. The frame-slotted ALOHA algorithm uses a discrete time interval known as a frame. A frame is divided into slots. The frame-size is predetermined by the reader, and there may be multiple frames present in a given read cycle. In order to reduce the number of slots with collisions, a tag can transmit only once during the duration of a frame. Figure 4 displays the state transitions of the reader, and Figure 5 displays state transitions of the tag.

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Figure 4: Slotted ALOHA reader state diagram [Glover06]

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Figure 5: Slotted ALOHA tag state diagram [Glover06]

1.4.3 Adaptive Binary Tree protocol

With the Adaptive Binary Tree protocol, the interaction between the reader and tag is more complex than it is with Slotted ALOHA protocol. This protocol uses a state machine. This state machine comprises of four interdependent sections. The first section is a collection of states that can be associated with global commands. This set of commands includes the dormant state. The next section is a state for calibrating communications that is, synchronizing the time-keeping oscillators on the tags with the timing of the reader. Differences in manufacturing, the age of components, and temperature can affect the timing of circuits enough that this calibration is critical to achieving reasonable read rates. The next set of states is concerned with traversing the binary tree, and the last set of states is used for communicating with a tag once it has been identified. Figure 6 shows the state machine.

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Figure 6: Adaptive Binary Tree protocol state diagram [Glover06]

1.4.4 Slotted Terminal Adaptive Collection (STAC) protocol

STAC is defined as a part of the EPCGlobal standard for high frequency tags. This protocol defines up to 512 slots of varying lengths, hence it is well suited for singulation (the method by which RFID readers identify a specific tag from a number of tags present within its range) of large populations of tags, which is necessary in order to minimize collisions. This protocol also allows for the selection of groups of tags based on matching lengths of EPC code beginning with the MSB. This mechanism can only select tags belonging to a particular domain manager or object class because the EPC code is organized by header, domain manager number, object class, and serial number from MSB to LSB. Figure 7 shows the states involved in a STAC protocol interaction.

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Figure 7: STAC protocol state diagram [Glover06]

1.4.5 EPC Gen2 protocol

The EPC Gen2 protocol supports much faster tag singulation than the previous protocols. This specification identifies three steps for communication between readers and tags. Firstly, a reader may broadcast a key and select only those tags that match the key or may inventory tags by signaling them until all tags within the interrogation zone have been identified. Secondly, a reader may also access tags by reading information from a tag, writing information to a tag, truncating a tag, or setting the status for various sections of memory. Figure 8 shows the states involved in an EPC Gen2 protocol interaction.

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Figure 8: Gen 2 protocol state diagram [Glover06]

Chapter 2

PREVIOUS WORK

2.1 Performance Evaluation of Anti-collision Protocols for RFID Networks

The experiment conducted by Baganto *et al.* presents performance evaluation of the various types of RFID protocols such as ALOHA, binary-tree, and query tree improved protocols with the help of a simulation model [Baganto09]. The protocols were compared by evaluating the latency (the duration of the protocol in seconds) and the system efficiency. Latency is also known as total census delay. Total census delay is the time taken to read all tags present within the readers range. Total census delay is a summation of success delay, collision delay and idle delay, which have been discussed further in section 3.1. The system efficiency was calculated as follows:

$$S_{Er} = \frac{R_{id}}{R_{tot}}$$

Here, R_{id} represents the number of identification rounds, and R_{tot} refers to the total number of cycles [Baganto09].

With respect of time, the efficiency of the system was calculated as follows:

$$S_{Et} = \frac{T_{id}}{T_{tot}}$$

Here, T_{id} is the time taken by identification rounds, and T_{tot} is the total time of execution of the protocol [Baganto09].

In this experiment, the total number of tags was varied from 10 to 1000. Also, the channel data rate and frequency were kept constant at 40 Kbps and 866 MHz respectively. Furthermore, the frame-size for the ALOHA protocols was set to a fixed value of 128 slots. The evaluation was conducted for a scenario with an even scatter of tags. The protocols that have been compared are the Query Tree (QT), Query Tree Improved (QTI), Binary Splitting (BS), Tree Slotted ALOHA (TSA), and Enhanced Dynamic Framed Slotted ALOHA (EDFSA) protocols. The QT protocol is a memory-less, anti-collision protocol. The tags do not require additional memory—only enough to store the ID of the tag [Law00]. The QT protocol consists of rounds of key requests and responses. In each round, a reader broadcasts a key as a prefix. Tags with a matching key transmit back with the remaining bits of their ID. When more than one tag responds to a key request, a collision takes place. As a result, the reader realizes that there are multiple tags with the same key. The reader then extends the prefix with an additional bit ('0' or '1') and continues the key request with this longer prefix. The QTI protocol is an extension of the QT protocol that optimizes the number of key requests and avoids the ones that are most likely to result in collisions [Myung06]. The BS protocol is another enhancement of the query tree protocol, where information regarding the previous read cycle is used during a current read cycle [Myung06]. In TSA, tags are assigned to frame slots in a random manner. In this scheme, collision resolution takes place with the help of binary tree splitting. Tags in subsequent slots do not transmit until collisions have been resolved. The EDFSA protocol is an extension of the FSA algorithm, where the number of tags available to be read is first estimated and then the number of tags that are allowed to transmit is adjusted accordingly [Lee05].

In the first experiment, Baganto *et al.* compared the system efficiency of the above protocols (QT, QTI, BS, TSA and EDFSA) for tags ranging from 10-100. The results of this experiment have been presented in Figure 9 where the x-axis represents the number of tags and the y-axis represents the system efficiency.

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Figure 9: System efficiency for 10-100 uniformly distributed tags [Baganto09]

In the second experiment, Baganto *et al.* compared the system efficiency of the protocols (QT, QTI, BS, TSA and EDFSA) for tags ranging from 100-1000. The results of this experiment have been presented in Figure 10 where the x-axis represents the number of tags and the y-axis represents the system efficiency.

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Figure 10: System efficiency for 100-1000 uniformly distributed tags [Baganto09]

In the final experiment conducted by Baganto *et al.,* the time of execution of the different protocols (QT, QTI, BS, TSA and EDFSA) was measured for tags ranging from 100-1000. The results of this experiment have been presented in Figure 11 where the x-axis represents the number of tags and the y-axis represents the time taken for a protocol to complete execution.

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Figure 11: Protocol execution time for uniformly distributed tags [Baganto09]

In terms of system efficiency and protocol execution time, it was noticed that the tree-based algorithms performed better than ALOHA-based algorithms. It was noted that the ALOHA-based algorithms performed poorly due to the fact that the frame length was set to a constant value of 128 bits, which is considered an overestimate for a small number of tags [Baganto09]. The research conducted by Baganto *et al.* does not take into account the optimal frame size while performing an evaluation of the ALOHA-based algorithm. This highly affects the performance of the ALOHA-based protocols. In my thesis, instead of using a constant value for frame size, an optimum value (which is dependent on the number of tags) has been used for all evaluations. The optimal frame size has been discussed further in section 3.3. Also, the system efficiency did not account for idle time or collision time. Hence, the paper by Baganto *et al.* concludes that considering only the total number of identification rounds and not the actual total number of rounds does not provide an accurate measure of performance [Baganto09]. ALOHA-based protocols experience fewer collisions as opposed to the tree-based protocols. Due to the additional overhead introduced by the tag muting mechanism after identification, ALOHA-based protocols have a higher execution time.

2.2 RFID Systems and Rapid Prototyping

The study conducted by Angerer *et al.* highlights the need for developing more versatile RFID systems that are capable of supporting a number of frequency ranges as well as domains on both readers as well as tags [Angerer10].

Traditional RFID systems have been limited to just one frequency domain such as low frequency, high frequency, or ultra-high frequency. Challenging demands originating from technologically improving applications demand high performance in terms of data throughput, read distances, data rates, and reliability. In order to meet these needs, complex protocols on both the physical as well as the logical layer are required. In order to design and develop an interoperable high-performance RFID system, researchers, designers, developers, and engineers need to further study the performance of various RFID environments. This includes the study of performance evaluation of different RFID frequency environments, the study of compatibility of RFID equipment, and the study of the impact of physical system parameters on performance. Traditionally, studies comparing RFID protocols and analyzing the performance of RFID environments have only been conducted across one frequency spectrum. The authors of this study recommend that in order to create more versatile RFID systems for the future, studies need to be conducted across all frequency spectrums. This need has been addressed in this thesis, where the performance of the frame-slotted ALOHA protocol has been evaluated for the low frequency, high frequency, and the ultra-high frequency spectrums.

2.2.1 Compatibility of present day RFID Systems

The various radio frequency tags and readers, whether active or passive, along with different frequency spectrums and the wide variety of RFID specifications have led to compatibility, reusability, and interoperability issues in today's applications. Varying policies, standards, and specifications across different parts of the world enhance the complexity of designing and developing a universal framework [Angerer10]. RFID components are widely being developed to support one specific application well-suited to a certain frequency domain, following one particular standard, and most studies are focused on frequency domain as well. As a result of this, components designed for a given environment (e.g., LF) are not suitable for other environments (e.g., HF). The challenge of overcoming these complexities and developing interoperable RFID components is the future of this technology, and this paper, presented by Angerer *et al.*, highlights the immediate need to start working towards this.

2.3 Performance of BFSA-based Anti-collision Protocols

The study performed by Chemburkar evaluated the performance of the BFSA protocol, supporting non-unique tags with the help of a simulation model created using OPNET Modeler 14.5 [Chemburkar11]. The results of this study were compared against those obtained in the study performed by Kang, in which the performance of BFSA muting protocol for unique tags was evaluated [Kang08]. This study focused on the UHF spectrum, and the parameters evaluated were network throughput and total census delay. Figure 12 displays the results obtained for total census delay for this study. It was found that the total census delay increased with the number of tags. It was also noticed that the total census delay for every number of tags was greater in the case of unique tags as opposed to non-unique tags.

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Figure 12: Total census delay [Chemburkar11]

Figure 13 shows the results obtained for the network throughput for this study. It was found that the network throughput decreased as the total number of tags was increased. It was also found that the network throughput of the unique tags was higher for the scenario that included non-unique tags as opposed to unique tags.

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Figure 13: Network throughput [Chemburkar11]

The statistical analysis of the results by Chemburkar revealed a significant difference between the non-unique tags and unique tags for the results obtained for network throughput and total census delay [Chemburkar11].

2.4 H. Vogt's Algorithm

The study conducted by Vogt focusses on estimating the number of tags that can be successfully read within a read cycle by using the frame size and analyzing the outcome of the read cycle [Vogt02]. In this mathematical analysis, the lower bound and Chebyshev's inequality have been used in order to analyze the number of tags. The lower bound simply estimates that the number of tags is greater than the summation of the number of slots filled with one tag and two times the number of slots that incurred collision [Vogt02]. When the lower bound is used, the real value of the number of tags is underestimated.

On the other hand, Chebyshev's inequality measures the inequality between the actual values and the expected values in order to estimate the number of tags for which the difference become minimal. The number of tags is calculated with the help of the frame size, denoted by *N*, and the results of the read cycle, c_0, c_1, and c_k, where c_0 represents the number of empty slots, c_1 represents the number of filled slots, and c_k represents the number of collided slots. According to this study, the lower bound estimation function provides more accurate estimations for low values of the number of tags as compared to Chebyshev's inequality. Although Chebyshev's inequality did not prove to be as accurate as the lower bound estimation, it was noted that it provided steadier estimations for a wider range of tags [Vogt02].

$$\varepsilon_{vd}\left(N, c_0, c_1, c_k\right) = \min \left| \begin{pmatrix} a_0^{N,n} \\ a_1^{N,n} \\ a_{\geq 2}^{N,n} \end{pmatrix} - \begin{pmatrix} c_0 \\ c_1 \\ c_k \end{pmatrix} \right|$$

Chapter 3

METHODOLOGY

This study compares simulation results in LF, HF, and UHF RFID environments. An evaluation of the total census delay and network throughput was conducted under the condition that the scope of this study is theoretical, assuming ideal conditions. Ideal conditions indicate that a constant frame size and slot duration have been used for a given iteration. Also, it has been assumed that there are no anomalies caused by environmental or electrical disturbances.

3.1 Evaluating Total Census Delay

The total census delay consists of three different delays, which include success delay, collision delay, and idle delay. The summation of these three delays is known as the total census delay and can be represented as

$$T[n] = n + C[n] + I[n],$$

where n represents the success delay, $C[n]$ represents the collision delay, and $I[n]$ represents the idle delay [Cappelletti06]. The delays $C[n]$, $I[n]$, and n can be measured as

$$C[n] = N\, p_0\, RT$$

$$I[n] = NRT\,(1 - p_0 - p_1)$$

$$n = NRT,$$

where N is the frame size, T is the slot duration, and R is the number of read cycles required to identify a group of tags. Here, p_0 represents the probability of having idle slots and p_1 represents the probability of having successful slots.

In addition, the slot duration represented by T (in seconds) and can be calculated as

$$T = \frac{ID}{data\_rate},$$

where ID (in bits) represents the size of the packet containing the tag's ID, and data_rate (in bps) is the data rate from the tag to the reader.

Assurance level, which is denoted by α, is the probability of identifying all tags in the reader's interrogation range [Vogt02]. It is necessary that the evaluation of read cycles satisfies α, since it is used to determine the total census delay. For example, a value of $\alpha = 0.99$ means that 99% of tags were present and only 1% or less were missing. Muting decreases the number of tag responses after every read cycle. Hence, the number of responding tags in the read cycle is less than or equal to those in the read cycle. The number of responding tags in the read cycle has been evaluated by Bin *et al.*, and a solution for the minimum total census delay has been proposed [Bin05].

3.2 Evaluating Network Throughput

Network throughput can be defined as the ratio of the number of successfully transmitted packets (one per given read cycle) to the total number of packets sent by the tags during the census [Cappelletti06]. If there are n tags to be read, the total number of packets sent by the tags during a census for non-muting BFSA can be represented as

$$P[n] = nR,$$

where R represents the number of required read cycles needed to identify a set of tags with confidence level α. The tags can transmit only once in a read cycle. The network throughput can be calculated as

$$S[n] = \frac{\alpha n}{P[n]} = \frac{\alpha}{R},$$

where α represents the confidence level, n represents the total number of identified tags, and $P[n]$ represents the total number of packets sent by the tags during the census.

3.3 Optimal Frame Size

In the evaluation of total census delay and network throughput, an optimal frame size has been used for a given number of tags. According to a study conducted by Prodanoff, for n number of tags, the optimal frame size can be evaluated as follows [Prodanoff10]:

$$N_{opt} = \frac{n}{\ln(2)},$$

where N_{opt} represents the optimal frame size and $ln(2)$ represents the natural logarithm of the integer 2. The optimal frame size is kept constant for the duration of a census.

Chapter 4

OPNET SIMULATION

4.1 Simulation Model

An OPNET simulation model developed using OPNET Modeler 17 was used in this study, implementing the frame-slotted ALOHA protocol. Three different environments have been studied (low frequency, high frequency, and ultra-high frequency). Each environment contains one reader and 10-1000 tags. In this simulation, the assurance level has been set to 0.99, the frame size selected is optimal, and the tags emulated are non-unique. The reader and tags have been modeled against current RFID standards (Table 1).

Environment	Standard	Frequency	Data Rate
UHF	Gen2 standard	900 MHz	640kbps
HF	ISO 15693	13.56 MHz	26kbps
LF	ISO 14223	125 KHz	5kbps

Table 1: RFID standard used for simulation

Consider the following example, where the simulation parameters are as follows:

Number of tags	5
Data rate	640kbps
Number of slots	8
Slot duration	0.0001 sec
Read cycle duration	0.001 sec
REQUEST packet size	88 bits
SELECT packet size	72 bits
Response packet size	80 bits

Table 2: Sample simulation parameters

In this example, at the beginning of the census, the reader sends a REQUEST in order to identify tags within its range. At 0.14ms, the request is received, and it is found that tags 1, 2, 3, 4, and 5 are present within the reader's range, thereby starting the read cycle. At the beginning of slot 2, that is, at 0.27ms, tags 1 and 3 transmit to the reader at the same time, thereby causing a collision. Hence, no tags are successfully identified at this point. At the beginning of slot 3, tag 1 transmits to the reader again and succeeds, as no other tags are present to cause collisions with. The first read cycle consists of only 8 slots. At the end of the first read cycle, only 3 tags are identified. Figure 14 displays the timeline for the first read cycle.

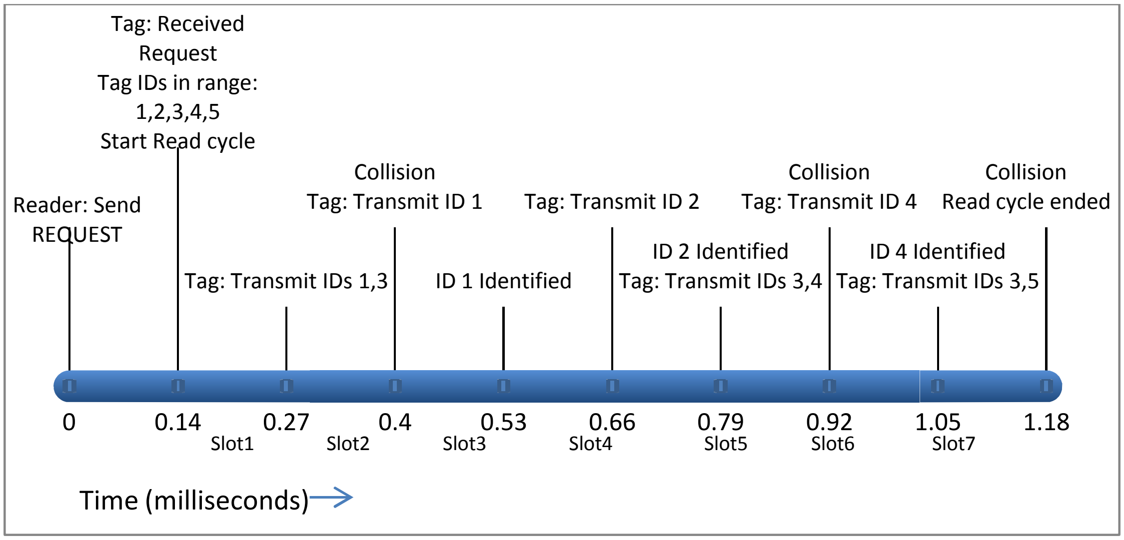

Figure 14: Read cycle 1

At the end of the first read cycle, there are two more tags, 3 and 5, that are yet to be identified. The reader sends out a SELECT signal, thereby causing the tags to mute. At 1.29ms, the reader sends out a REQUEST to the tags present in its read range. Tags 3 and 5 are found to be in the read range, thereby starting the second read cycle. A collision occurs at 1.69ms. Tags 3 and 5 then transmit independently at the beginning of slots 5 and 6 respectively. At this point, all tags found at the beginning of the census have been identified. There are still two slots left before the end of the read cycle. As all tags have already been identified, slots 7 and 8 are idle. The census is completed at the end of slot 8, and it was found that the total census delay was 2.34ms. Figure 15 represents the second read cycle.

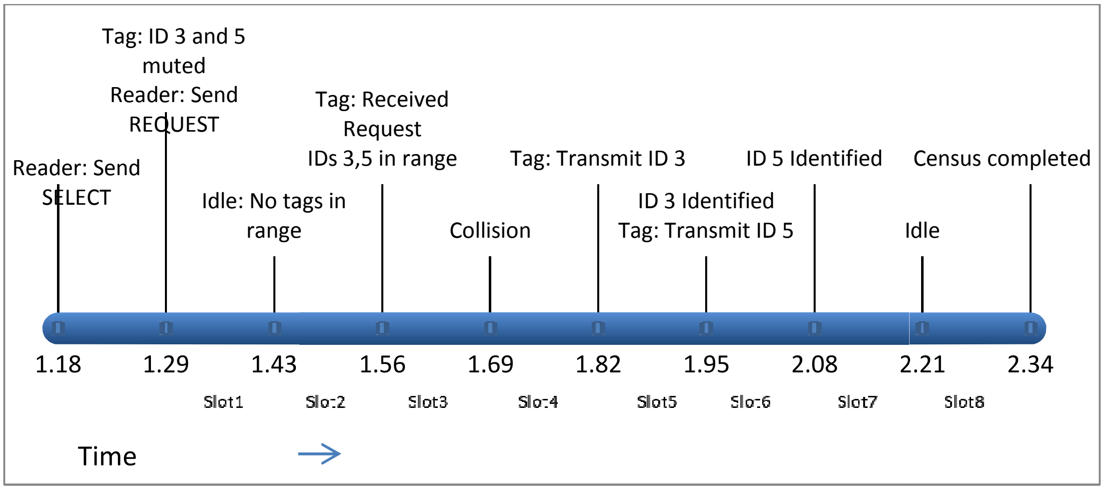

Figure 15: Read cycle 2

In this thesis, the OPNET modeler has been used to evaluate the total census delay and network throughput of LF, HF, and UHF RFID environments. Table 3 displays the experiments, control variables, and response variables that have been measured, and Chapter 5 discusses the result.

Experiment	1	2
Purpose	Analysis and comparison of total census delay in LF, HF and UHF in RFID environments	Analysis and comparison of network throughput in LF, HF and UHF in RFID environments
Control Variables	Packet Size, Data Rate, Collision Delay, Idle Delay, Frequency	Total number of tags, Required Reads, Assurance Level, Frequency
Response Variables	Total Census Delay	Network throughput

Table 3: Experiments conducted

Chapter 5

EVALUATION AND RESULTS

5.1.1 Total Census Delay

The total census delay was calculated using an OPNET model for the low-frequency, high-frequency, and ultra-high-frequency bands. This experiment was performed in two parts. For the first part, the number of tags was varied from 10 to 200, and for the second part, the total number of tags was varied from 200 to 1500. The results have been presented in Figures 16 and 17 where the x-axis represents the number of tags and the y-axis represents the total census delay in seconds.

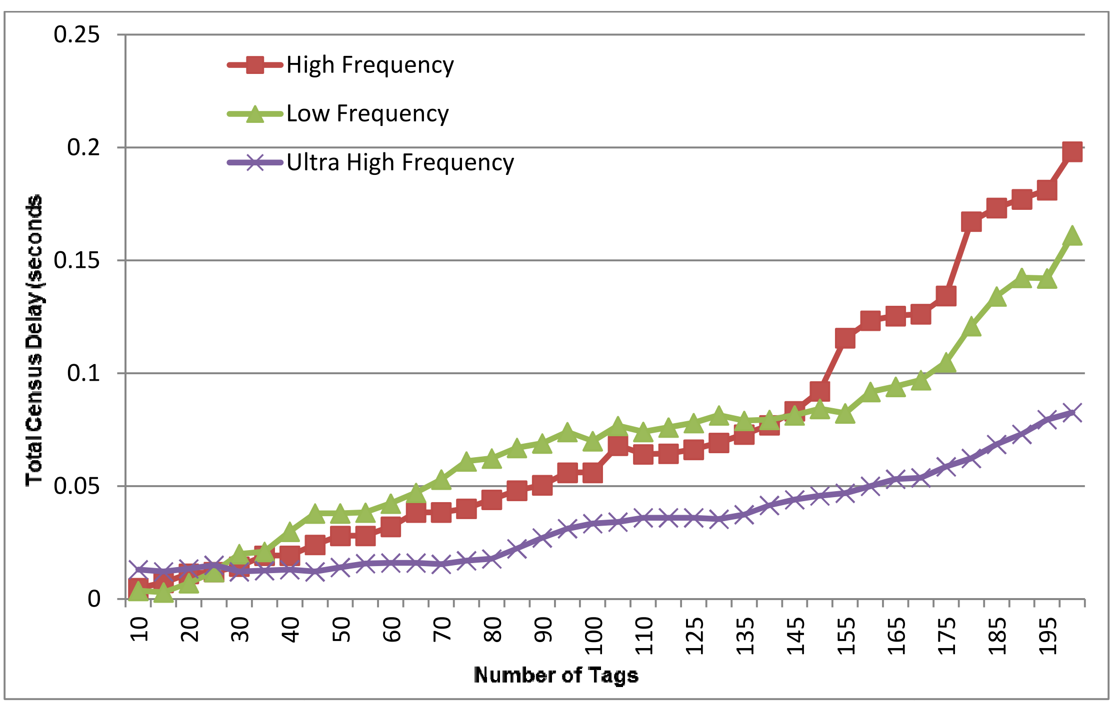

Figure 16: Total census delay versus number of tags (10-200)

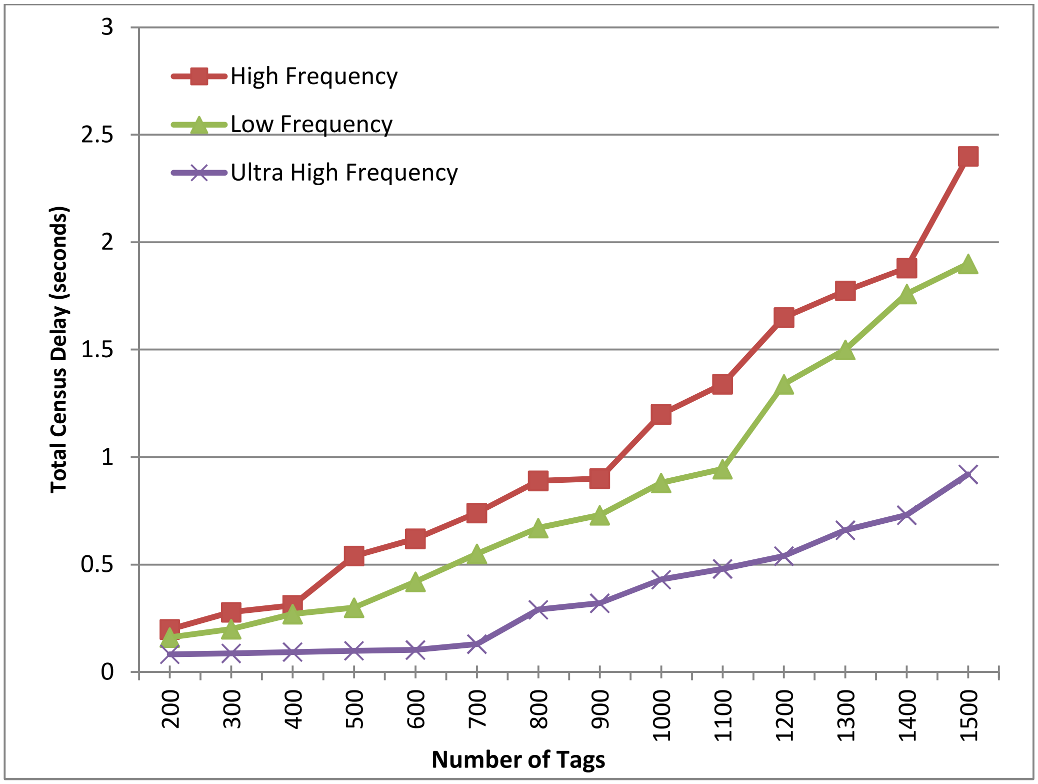

Figure 17: Total census delay versus number of tags (200-1500)

From the results presented in Figure 16, where the number of tags ranges from 10-200, it can be observed that the ultra-high frequency environment has the least total census delay as compared to the high frequency and low frequency environments. From Figure 16, it can also be observed that the total census delay is the highest for the low frequency environments for number of tags less than 150. For tags greater than 150, it was observed that the high frequency environment has the highest total census as compared to the low frequency and the ultra-low frequency environments.

From the results presented in Figure 17, where the number of tags ranges from 200-1500, it can be observed that the ultra- frequency environment has the least total census delay whereas the high frequency environment has the highest.

In order to analyze the results presented in Figures 16 and 17, an analysis of variance (ANOVA) analysis was performed for the results obtained for the three groups. For this experiment, a one-way ANOVA analysis was performed. A one way ANOVA analysis is used to determine whether there are significant differences between the means of three or more unrelated groups. ANOVA analysis is performed by calculating the mean for each of the groups (group mean), the mean for all of the groups combined (overall mean), the total deviation from the individual mean (within group variation) and the deviation from the group mean (between group variations). The final outcome of an ANOVA analysis is the ratio between the "between group variation" and the "within group variation." If the "between group variation" is significantly greater than the "within group variation," then it is likely that there is a statistically significant difference between the means of the groups.

In the case of this analysis, we have three unrelated groups (high frequency, ultra-high frequency, and low frequency). For each group, a set of total census delay has been calculated for a varying number of tags. As we have three groups, an ANOVA analysis is applicable in this scenario. The results of this test are shown in Table 4 for 10-200 tags and in Table 5 for 200-1500 tags.

Groups	*Count*	*Sum*	*Average*	*Variance*
HF	40	2.76014	0.069004	0.003078
LF	40	2.644	0.0661	0.001674
UHF	40	1.3198	0.032995	0.000446

Variation Source	*SS*	*df*	*MS*	*F*	*p-value*	*F crit*
Between Groups	0.032013	2	0.016007	9.239448	0.000188	3.073763
Within Groups	0.202693	117	0.001732			
Total	0.234706	119				

Table 4: ANOVA analysis results—total census delay (10-200)

Groups	*Count*	*Sum*	*Average*	*Variance*
HF	14	14.7202	1.051443	0.4585
LF	14	11.6262	0.830443	0.342717
UHF	14	4.964	0.354571	0.077572

Variation Source	*SS*	*df*	*MS*	*F*	*p-value*	*F crit*
Between Groups	3.550981	2	1.77549	6.061155	0.005103	3.238096
Within Groups	11.42424	39	0.292929			
Total	14.97523	41				

Table 5: ANOVA analysis results—total census delay (200-1500)

In this experiment, the confidence level assumed is 95%, hence $\alpha = 0.05$. The results in Table 4 and Table 5 indicate that the *p-value* is less than α for both scenarios, that is, tags ranging from 10-200 and tags ranging from 200-1500. The null hypothesis here is that there is no significant difference in the means among the three groups that have been tested (high frequency, low frequency, and ultra-high frequency) under several assumptions: (1) response variable residuals are normally distributed (or approximately normally distributed); (2) samples are independent; (3) variances of populations are equal; (4) responses for a given group are independent and identically distributed normal random variables. Assumptions (1) and (4) hold, as the sample sizes are not unbalanced and are relatively large with size greater than 25, so that the central limit theorem applies, and approximate normality is expected. As samples are independent by experiment design, assumption (2) holds as well. To better understand, if assumption (3) is met, F-tests were conducted for the following pairs of total census delay values obtained for this scenario in order to further isolate the statistical difference: (high frequency, low frequency), (high frequency, ultra-high frequency), and (low frequency, ultra-high frequency). The value of α used for these tests is 0.05. The pair-wise F-test (see Tables 6, 7, and 8) revealed values of F ranging from 1.84 to 6.91. As assumption (3) has not been met, ANOVA tests do not appear to be applicable for the scenario with tags ranging from 10-200. We still present the results from the ANOVA analysis for that scenario in Table 4 in order to emphasize that even though the ANOVA p-value appears to be lower than α, statistical significance cannot be concluded.

	HF	*LF*
Mean	0.0690035	0.0661
Variance	0.003077817	0.001673843
Observations	40	40
Df	39	39
F	1.838773329	
P(F<=f) one-tail	0.030359087	
F Critical one-tail	1.704465067	

Table 6: F-test for HF and LF pair—total census delay (10-200)

	HF	*UHF*
Mean	0.0690035	0.032995
Variance	0.003077817	0.000445585
Observations	40	40
df	39	39
F	6.907368736	
P(F<=f) one-tail	1.01E-08	
F Critical one-tail	1.704465067	

Table 7: F-test for HF and UHF pair—total census delay (10-200)

	LF	*UHF*
Mean	0.0661	0.032995
Variance	0.001673843	0.000445585
Observations	40	40
df	39	39
F	3.756509095	
P(F<=f) one-tail	3.59E-05	
F Critical one-tail	1.704465067	

Table 8: F-test for LF and UHF pair—total census delay (10-200)

Since the ANOVA null hypothesis appeared to be rejected for the scenario with tags ranging from 200-1500 as indicated by the analysis presented in Table 5 (again, based on a p-value less than α), F-tests were conducted for the following pairs of total census delay values obtained for this scenario in order to test assumption (3): (high frequency, low frequency), (high frequency, ultra-high frequency), and (low frequency, ultra-high frequency). The value of α used for these tests was 0.05. The pair-wise F-test (see Tables 9, 10, and 11) revealed values of F ranging from 1.34 to 5.9 with unequal variances. The value of α used for these tests was 0.05. As assumption (3) was not met, ANOVA does not appear to be applicable for the scenario with tags ranging from 200-1500, even though the p-value was less than α (see Table 5).

	HF	*LF*
Mean	1.051442857	0.830442857
Variance	0.458499546	0.342716592
Observations	14	14
df	13	13
F	1.337838776	
P(F<=f) one-tail	0.303682926	
F Critical one-tail	2.576927084	

Table 9: F-test for HF and LF pair—total census delay (200-1500)

	HF	*UHF*
Mean	1.051442857	0.354571429
Variance	0.458499546	0.077571919
Observations	14	14
df	13	13
F	5.910638165	
P(F<=f) one-tail	0.00149313	
F Critical one-tail	2.576927084	

Table 10: F-test for HF and UHF pair—total census delay (200-1500)

	LF	*UHF*
Mean	0.830442857	0.354571429
Variance	0.342716592	0.077571919
Observations	14	14
df	13	13
F	4.418049673	
P(F<=f) one-tail	0.005838711	
F Critical one-tail	2.576927084	

Table 11: F-test for LF and UHF pair—total census delay (200-1500)

From the graphs in Figures 16 and 17, it can be inferred that the plot seems linear in nature for all three groups. From the result set, it was also observed that for all frequency environments, the total census delay seemed directly proportional to the number of tags; that is, with an increase in the number of tags, there was an increase in the total census delay. In order to justify this observation, standard deviation was calculated for each individual set in order to determine the degree of relationship between the records of a given group. The R factor has been calculated for each result set (low frequency, high frequency, and ultra-high frequency). The results of this test are shown in Tables 12 and 13.

Groups	*R*	*Relationship*
High Frequency	0.950570653	Strong
Low Frequency	0.96656479	Strong
Ultra High Frequency	0.955185141	Strong

Table 12: R factors—total census delay (10-200)

Groups	*R*	*Relationship*
High Frequency	0.677125	Strong
Low Frequency	0.58542	Weak
Ultra High Frequency	0.2785173	Weak

Table 13: R factors—total census delay (200-1500)

Table 12 indicates that there is a strong linear relationship between the number of tags and total census delay for all groups when the number of tags is between 10 and 200. Table 13 indicates that there is a strong linear relationship between the number of tags and total census delay for the high-frequency spectrum but a weak linear relationship for low- and ultra-high-frequency spectrums when the number of tags is between 200 and 1500.

5.2 Network Throughput

The network throughput was calculated using an OPNET model for the low-frequency, high-frequency, and ultra-high-frequency bands. This experiment was conducted in two parts. For the first part, the number of tags was varied from 10 to 200, and for the second part it was varied from 200 to 1500. The results have been plotted in Figures 18 and 19 where the x-axis represents the number of tags and the y-axis represents the total network throughput.

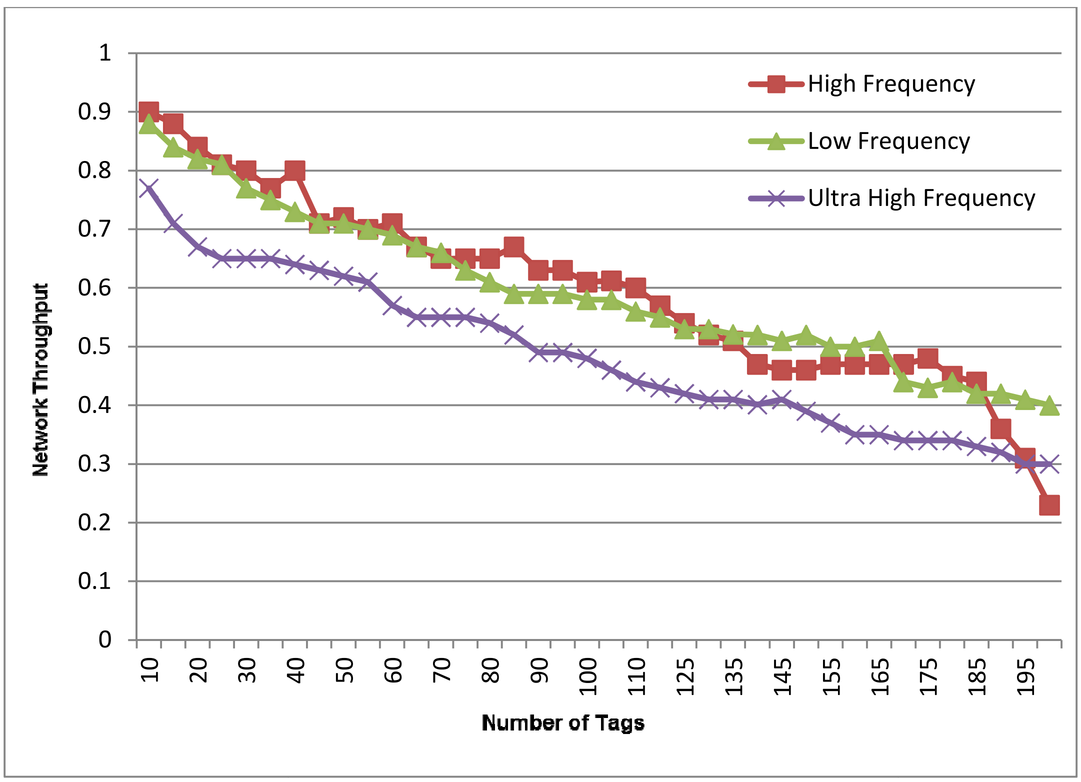

Figure 18: Network throughput versus number of tags (10-200)

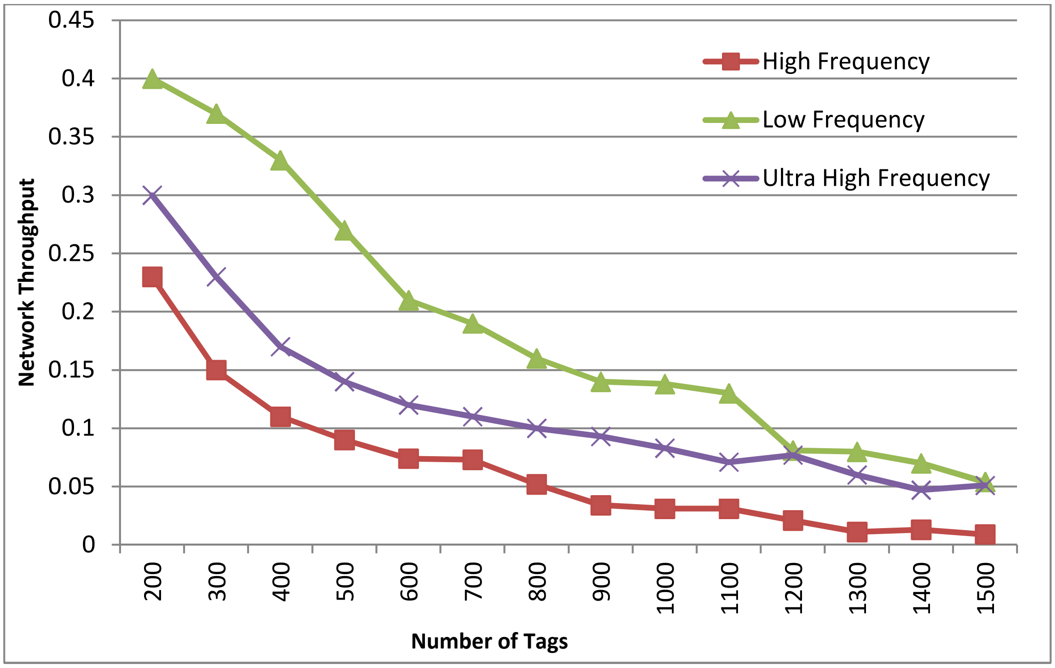

Figure 19: Network throughput versus number of tags (200-1500)

From the results presented in Figure 18, where the number of tags ranges from 10-200, it can be observed that the ultra-high frequency environment has the least network throughput. From Figure 19, where the number of tags ranges from 200-1500, it can be observed that the high frequency environment has the least network throughput and the low frequency environment the highest.

In order to analyze the results presented in Figures 18 and 19, an ANOVA analysis, as described in section 5.1, was performed for the results obtained for the three groups. The results for this test are shown in Tables 14 and 15.

Groups	Count	Sum	Average	Variance
HF	40	24.532	0.6133	0.02894
LF	40	24.401	0.610025	0.020636
UHF	40	20.151	0.503775	0.022608

Variation Source	SS	df	MS	F	p-value	F crit
Between Groups	0.310607	2	0.155303	6.45438	0.002193	3.07376
Within Groups	2.81522	117	0.024062			
Total	3.125827	119				

Table 14: ANOVA analysis results—network throughput (10-200)

Groups	Count	Sum	Average	Variance
HF	14	0.929	0.066357	0.00395
LF	14	2.623	0.187357	0.013029
UHF	14	1.652	0.118	0.005222

Variation Source	SS	df	MS	F	p-value	F crit
Between Groups	0.103219	2	0.05161	6.973824	0.002575	3.238096
Within Groups	0.288618	39	0.0074			
Total	0.391838	41				

Table 15: ANOVA analysis results—network throughput (200-1500)

In this experiment, the confidence level was assumed is 95%, hence $\alpha = 0.05$. The above results indicate that for both scenarios (that is, tags ranging from 10-200 and tags ranging from 200-1500) the p-value < α. The null hypothesis here is that there is no significant difference in the means among the three groups that have been tested (high frequency, low frequency, and ultra-high frequency) under several assumptions: (1) response variable residuals are normally distributed (or approximately normally distributed); (2) samples are independent; (3) variances of populations are equal; (4) responses for a given group are independent and identically distributed normal random variables. Assumptions (1) and (4) hold, as the sample sizes are not unbalanced and relatively large with size greater than 25, so that the central limit theorem applies and approximate normality is expected. As samples are independent by experiment design, assumption (2) holds as well. To better understand, when assumption (3) was met, F-tests were conducted for the following pairs of network throughput values obtained for both scenarios in order to further isolate the statistical difference: high frequency and low frequency; high frequency and ultra-high frequency; and low frequency and ultra-high frequency. The value of α used for these tests is 0.05. For the scenario with 10-200 tags, assumption (3) appears to hold, as the F-tests revealed similar small F-values for all three cases: LF, HF, and UHF. The ANOVA null hypothesis has been rejected for the scenario with tags ranging from 10-200. The F-test results have been presented in Tables 16, 17, and 18.

	HF	*LF*
Mean	0.6133	0.610025
Variance	0.028940215	0.020636435
Observations	40	40
df	39	39
F	1.402384425	
P(F<=f) one-tail	0.147611229	
F Critical one-tail	1.704465067	

Table 16: F-test for HF and LF pair (network throughput, 10-200 tags)

	HF	*UHF*
Mean	0.6133	0.503775
Variance	0.028940215	0.022608487
Observations	40	40
df	39	39
F	1.280059828	
P(F<=f) one-tail	0.222112777	
F Critical one-tail	1.704465067	

Table 17: F-test for HF and UHF pair (network throughput, 10-200 tags)

	LF	*UHF*
Mean	0.610025	0.503775
Variance	0.020636435	0.022608487
Observations	40	40
df	39	39
F	0.912773848	
P(F<=f) one-tail	0.388545505	
F Critical one-tail	0.586694336	

Table 18: F-test for LF and UHF pair (network throughput, 10-200 tags)

For the scenario with 200-1500 tags, the variances are not the same (assumption (3) does not appear to hold), as the pair-wise F-test (see Tables 19, 20, and 21) revealed values of F ranging from 0.3 to 2.5. As assumption (3) was not met, ANOVA is not applicable for the scenario with tags ranging from 200-1500, even though the p-value (0.002575) is less than α.

	HF	*LF*
Mean	0.066357143	0.187357143
Variance	0.003950247	0.013029478
Observations	14	14
df	13	13
F	0.303177706	
P(F<=f) one-tail	0.020004885	
F Critical one-tail	0.388059098	

Table 19: F-test for HF and LF pair (network throughput, 200-1500 tags)

	HF	*UHF*
Mean	0.066357143	0.118
Variance	0.003950247	0.005221692
Observations	14	14
df	13	13
F	0.75650709	
P(F<=f) one-tail	0.311112617	
F Critical one-tail	0.388059098	

Table 20: F-test for HF and UHF pair (network throughput, 200-1500 tags)

	LF	UHF
Mean	0.187357143	0.118
Variance	0.013029478	0.005221692
Observations	14	14
df	13	13
F	2.495259631	
P(F<=f) one-tail	0.055839075	
F Critical one-tail	2.576927084	

Table 21: F-test for LF and UHF pair (network throughput, 200-1500 tags)

From the graphs in Figures 18 and 19, it can be inferred that the plot seems linear in nature for all three groups. From the dataset, it was also observed that the network throughput seemed inversely proportional to the number of tags; that is, as the number of tags increased, the throughput decreased. In order to justify this observation further, standard deviation was calculated for each individual set in order to determine the degree of relationship between the records of a given group. The R factor has been calculated for each result set: low frequency, high frequency, and ultra-high frequency. The result is shown in Tables 22 and 23.

Groups	*R*	*Relationship*
High Frequency	−0.976628993	Strong
Low Frequency	−0.977838636	Strong
Ultra High Frequency	−0.969709853	Strong

Table 22: R factors—network throughput (10-200)

Groups	*R*	*Relationship*
High Frequency	−0.152876608	Weak
Low Frequency	−0.149588419	Weak
Ultra High Frequency	−0.116554626	Weak

Table 23: R factors—network throughput (200-1500)

Table 22 indicates that there is a strong negative relationship between the number of tags and throughput for all groups when number of tags is between 10 and 200. Table 23 indicates that there is a weak negative relationship between the number of tags and throughput for all groups when number of tags is between 200 and 1500.

Since the ANOVA null hypothesis has been strongly rejected for the scenario with tags ranging from 10-200, we conducted further pairwise t-tests in order to better understand how the means of each sample relate to each other. The results presented in Tables 25 and 26 indicate that there is a statistically significant difference in the means of HF vs. UHF and UHF vs. LF, as the corresponding p-values are less than α for both these scenarios. Table 24 indicates that for HF vs. LF, the p-value is greater than α, hence the results obtained for this pair are not statistically significant.

	HF	*LF*
Mean	0.6133	0.610025
Variance	0.028940215	0.020636435
Observations	40	40
Pooled Variance	0.024788325	
Hypothesized Mean Difference	0	
df	78	
t Stat	0.093025649	
P(T<=t) one-tail	0.463060856	
t Critical one-tail	1.664624645	
P(T<=t) two-tail	0.926121713	
t Critical two-tail	1.990847069	

Table 24: Pairwise t-test (HF, LF) for network throughput (10-200)

	HF	*UHF*
Mean	0.6133	0.503775
Variance	0.028940215	0.022608487
Observations	40	40
Pooled Variance	0.025774351	
Hypothesized Mean Difference	0	
df	78	
t Stat	3.050945085	
P(T<=t) one-tail	0.001558422	
t Critical one-tail	1.664624645	
P(T<=t) two-tail	0.003116845	
t Critical two-tail	1.990847069	

Table 25: Pairwise t-test (HF, UHF) for network throughput (10-200)

	LF	*UHF*
Mean	0.610025	0.503775
Variance	0.020636435	0.022608487
Observations	40	40
Pooled Variance	0.021622461	
Hypothesized Mean Difference	0	
df	78	
t Stat	3.231404879	
P(T<=t) one-tail	0.000902586	
t Critical one-tail	1.664624645	
P(T<=t) two-tail	0.001805172	
t Critical two-tail	1.990847069	

Table 26: Pairwise t-test (UHF, LF) for network throughput (10-200)

Chapter 6

CONCLUSION

In this thesis, network throughput and total census delay were evaluated for high frequency (HF), low frequency (LF), and ultra-high frequency (UHF) environments using OPNET Modeler 17. For each environment, a set of results was obtained for a small number of tags (10-200), and another set of results was produced for a large number of tags (200-1500). Those results were plotted with the total number of tags depicted on the x-axis and network throughput and total census delay on the y-axis. For a range of tags from 10-1500, it was observed that the total census delay increased as the number of tags increased for all environments. It was also observed that, generally, network throughput decreased as the number of tags increased.

The results on the data sets obtained for the large number of tags (200-1500) indicate that the UHF environment performs better than the LF and HF environments because the total census delay corresponding to a given number of tags has the smallest value among all environments. Similarly, the datasets obtained for the HF and LF environments for the small number of tags (10-200) indicate that the total census delay for HF environments is less than for the LF environment. From the dataset obtained for the analysis of network throughput with a small number of tags (10-200), it was observed that the UHF environment had the lowest network throughput compared to the HF and LF environments. From the dataset obtained for the analysis of network throughput with a large number of tags (200-1500), it was observed that the HF environment had the least network throughput.

In order to evaluate these results for statistical significance, an ANOVA analysis and pairwise F-tests were conducted for each dataset. The ANOVA analysis indicated that the results obtained for total census delay and network throughput for both types of environments (small number of tags and large number of tags) appeared to indicate statistical significance, based on p-values lower than α. To further analyze the scenarios for statistical significance, pair-wise F-tests were conducted. The results of F-test were interesting, as it was determined that for total census delay, the variances in the datasets were different even though the ANOVA p-values were low. Hence, ANOVA was not found to be applicable for those scenarios. From the F-test conducted for network throughput for a small number of tags, it was determined that the variances in the datasets were within the acceptable range, hence the ANOVA null hypothesis was rejected for this scenario. On the contrary, from the F-test conducted for network throughput for a large number of tags, it was determined that the variances in the datasets were different; hence, ANOVA is not applicable for that scenario. In order to analyze how the means of the three different frequencies (for the network throughput scenario with a small number of tags) relate to each other, pairwise t-tests were conducted. From these tests, it was found that there is a statistically significant difference between the means of HF vs. UHF and UHF vs. LF for network throughput with a small number of tags.

Future work may include studying the effect of assurance level on network throughput. Additionally, in this thesis, the data rate within a given frequency environment was kept constant for all iterations. A given frequency environment can support a range of data rates. Future research needs to be conducted in order to determine an optimal data rate for a given frequency and also study the effect of data rate on the volume of tags within an environment. Similarly, additional future work may include evaluating the performance of the ALOHA-based protocol across a wide spectrum of frequencies for each type of environment (HF, LF, and UHF). In this study, only one frequency was used for each environment.

REFERENCES

Print Publications:

[Chemburkar11]
Chemburkar, K., "Performance of BFSA Based Anti-Collision Protocols for RFID Networks Supporting Identical Tags," Thesis (M.S. in Computer and Information Sciences), University of North Florida, (2011)

[Glover06]
Glover, B., Bhatt, H., “RFID essentials,” O'Reilly Media, Inc., ISBN 0596009445, (2006)

[ISO 15693-3:2000]
Identification Cards - Contactless Integrated Circuit Cards - Vicinity Cards – Part 3: Anticollision and Transmission Protocol, ISO/IEC 15693-3, (10th March, 2000)

[ISO 18000-6:2004]
Information technology – Radio Frequency Identification for Item Management – Part 6: Parameters for Air Interface Communications at 860 MHz to 960 MHz, ISO/IEC 18000-6, (15th August 2004)

[Kang08]
Kang, S., “Framed Slotted ALOHA: Multi-Tag Identifying Anti-Collision RFID Protocol Simulation Using OPNET Modeler 14”, Thesis (M.S. in Computer and Information Sciences), University of North Florida, (2008)

[Kingston10]
Kingston, P., "RFID Applications: An Introductory and Exploratory Study," International Journal of Computer Science Issues (IJCSI) 7.1, (2010)

[Klair10]
Klair, D., Chin, K., Raad, R. "A survey and tutorial of RFID anti-collision protocols," IEEE Communications Surveys & Tutorials, vol.12, pp. 400-421, (2010)

[Law00]
Law, C., Lee, K., Siu, K., “Efficient memory less protocol for tag identification,” Proceedings of the 4th international workshop on discrete algorithms and methods for mobile computing and communications, pp. 75-84, New York, USA, ISBN: 1-58113-301-4, (2000)

[Lee05]
Lee S., Sung-Don J., Lee C., "An enhanced dynamic framed slotted ALOHA algorithm for RFID tag identification," Mobile and Ubiquitous Systems: Networking and Services, vol. 166, no. 172, pp. 17-21, (July 2005)

[Myung06]
Myung, J., Lee, W., "Adaptive binary splitting: A RFID tag collision arbitration protocol for tag identification," Mobile Network Applications, vol. 11, number 5, pp. 711–722, (2006)

[Poire06]
Poirer, C., McCollum D., "RFID: Strategic Implementation and ROI," J. Ross Publishing, New York, ISBN 1-932159-47-9, (2006)

[Prodanoff10]
Prodanoff, Z. G., "Optimal Frame Size Analysis for Framed Slotted ALOHA Based RFID networks", Computer Communication, vol. 33, no. 5, pp. 648-653, (March 2010)

[Schuster02]
Schuster, E. W., Allen, S. J., Brock, D. L., "Global RFID: The Value of the EPCglobal Network for Supply Chain Management," Springer-Verlag, ISBN: 3540356541, (2007)

Electronic Sources:

[Angerer10]
Angerer, C., Bueno-Delgado, M. V., Vales-Alonso, J., Rupp, M., "A comparative study of RFID schedulers in dense reader environments," Industrial Technology (ICIT), 2010 IEEE International Conference, vol. 1373, no. 1378, pp. 14-17, (March 2010) http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5472512&isnumber=5472440, last accessed April 14, 2014.

[Baganto09]
Bagnato, G., Maselli, G., Petrioli, C., Vicari, C., "Performance analysis of anti-collision protocols for RFID systems," IEEE Vehicular Technology Conference, vol. 1, no. 5, pp. 26-29 (April 2009) http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=5073775&isnumber=5073272, last accessed April 14, 2014.

[Bin05]
Bin, Z., Mamoru, K., and Masashi, S., “Framed ALOHA for Multiple RFID Objects Identification,” IEICE Transactions on Communication, vol.E88–B, No.3, (March 15, 2005.), http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.102.2078&rep=rep1&type=pdf, last accessed May 17, 2014.

[Cappelletti06]
Cappelletti, F., Ferrari, G., and Raheli, R. “A Simple Performance Analysis of Multiple Access RFID Networks Based on the Binary Tree Protocol,” ISCCSP, (March, 2006), www.eurasip.org/proceedings/ext/isccsp2006/defevent/papers/cr1211.pdf, last accessed May 17, 2014.

[Vogt02]
Vogt, H., “Multiple Object Identification with Passive RFID Tags,” Proceeding of the IEEE International Conference on Systems, Cybernetics, vol. 3, 6-9, (October 2002), http://ieeexplore.ieee.org.dax.lib.unf.edu/stamp/stamp.jsp?tp=&arnumber=1176119&isnumber=26388, last accessed April 14, 2014.

[Zürich04]
Zürich, E., Burdet, L. A., “RFID Multiple Access Methods,” Seminar “Smart Environments“, (August 15, 2004) http://www.vs.inf.ethz.ch/edu/SS2004/DS/reports/06_rfid-mac_ report.pdf, last accessed April 14, 2014.

VITA

Varun Bhogal holds a Bachelor of Engineering degree in Computer Science from the University of Pune (India), 2006. He is expected to receive a Master of Science degree in Computer and Information Science from the University of North Florida in August 2014. Varun is currently employed as a Quality Assurance Engineer at Fanatics, Jacksonville, where he is responsible for implementing software testing procedures and developing test automation tools. Prior to Fanatics, Varun worked with IxReveal, Jacksonville as a Systems Analyst for a period of two years.

Varun has extensive experience in creating automated tests and developing automation tools for web services and application on multiple platforms such as Windows, UNIX, iOS and Android. He is proficient in C#, C++, C, Python, VB script, JavaScript, SQL, Selenium WebDriver, WinRunner, LoadRunner, CodedUI and SoapUI.