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DESIGN AND PERFORMANCE ANALYSIS OF A PROGRAMMABLE NEAR FIELD COMMUNICATION ANTENNA ON SOFT MATERIALS

Muhammad Enayetur Rahman
University of Rhode Island, menayet@uri.edu

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DESIGN AND PERFORMANCE ANALYSIS OF A
PROGRAMMABLE NEAR FIELD COMMUNICATION

ANTENNA ON SOFT MATERIALS

BY

MUHAMMAD ENAYETUR RAHMAN

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

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MASTER OF SCIENCE THESIS
OF
MUHAMMAD ENAYETUR RAHMAN

APPROVED:

Thesis Committee:

Major Professor Kunal Mankodiya

Paolo Stegagno

Manbir Sodhi

Nasser H. Zawia
DEAN OF THE GRADUATE SCHOOL

UNIVERSITY OF RHODE ISLAND
2019

ABSTRACT

In the era of ubiquitous computing objects connected to the Internet are increasing day by day. Near Field Communication (NFC) is a perfect example of ubiquitous computing that is secure, short-range, low powered contactless communication. Powerless, single-tapping NFC tag is growing in popularity. Massive demand for NFC requires to study implementing this fast-growing technology onto different materials and places.

In this research study, NFC implementation on flexible material is investigated with different types of materials. NFC antennas were designed with mathematical modeling. Simulation for NFC coil inductance calculation was performed and was verified with mathematical modeling. The NFC antenna was fabricated, and verified according to mathematical modeling and simulation.

NFC antenna has several design parameters on which coil inductance is dependent. In this thesis, these major design parameters are considered, and a factorial design of experiment was conducted to observe which parameters have a substantial effect on the response, i.e., considered here as the read range. After the factorial design of the experiment, it was found that size is the most critical parameter for NFC tag antenna design. Two-way interactions of turn and thickness had the second most significant effect on the read range. Three-way interaction of size, turn, and thickness was the top most influential parameter on the read range. A comparison of available industrial NFC antennas with our fabricated antennas was performed and noticed that our longer sized NFC antennas had a higher reading distance than commercially available tags. The factorial design verifies this comparison result as it depicts size is one of the three main

contributing factors of NFC antenna designing parameters. Besides those experiments, another investigation was conducted from the user standpoint to perceive a user's convenience when using the NFC antennas in posters, and a comparison between two smart posters was concluded. We found that for our NFC poster, 95.5% of users had experienced the longer detection range, and 63.6% of the users believed that our NFC poster had a quicker response. The average NFC poster connection time of the commercial tag was 4.25 seconds, whereas our NFC poster took an average time of 2.04 seconds to connect.

All of the experiments and findings in the thesis illustrate that NFC antennas in flexible materials open up a new area of research which enables everyday connectivity with different materials with the smartphone. Furthermore, this type of research enables interdisciplinary research work that requires a combination of antenna and material science research work and commences advanced antenna technology developments towards next-generation mobile wireless communication systems.

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1. INTRODUCTION

1.1. Introduction

Near Field Communication (NFC) is a wireless communication system which enables two devices to communicate with each other securely. The usage of NFC is the most intuitive and straightforward than any other technology. It is an extremely rapidly growing two-way interactive technology that can link two NFC enabled devices, or an NFC enabled device and a tag. NFC is a low powered contactless connectivity technology. Two compatible NFC devices need to come close enough to transfer data between the devices. Sometimes, this technology delivers power to the NFC-capable energy harvesting microcontroller with sensors. Some examples for the NFC-enabled devices are NFC readers, smartphone, smart tablets, NFC enabled-device as a card emulation mode. This thesis aims to investigate, develop, and test some NFC enabled antennas on some flexible materials.

NFC Forum is a non-profit industry association and is responsible for the NFC standardization and further development and improvement of NFC technology. NFC forum sets the standards for NFC devices and NFC tags to maintain the interoperability among devices and services. So, the devices according to the NFC forum at least maintain the necessary parts of NFC forum protocol stack and interoperability requirements. An NFC Forum Device may support different NFC Forum operating modes: NFC Forum peer mode (mandatory), NFC Forum Reader/Writer mode (mandatory), and NFC Forum card emulation mode (optional) [1]. The NFC Forum device can be a mobile phone, PC, or consumer electronic device. A contactless NFC

Forum Tag is compatible with and can operate according to one of four NFC forum tag platforms called NFC forum type 1-4 tag platforms, the NFC type MIFARE classic tag platform and NFC Type ICODE tag platform or a target according to ISO/IEC 18092 [2]. The main focus of the thesis is on the NFC forum type 2 tag implemented on a flexible material.

1.2. Problem statement

This master thesis research aims to integrate Near Field Communication (NFC) technology on flexible/soft materials. It will aim to increase the range of NFC technology on flexible/soft material beyond its usual range of 4 cm. The research challenge is to design NFC antennas on flexible/soft materials, integrating the antenna with an NFC tag chip. It needs to specify the antenna parameters with material properties so that, maximum energy could be achieved when integrating with the NFC tag-chip.

In this study, research, development, testing, and verification of NFC antennas on different kinds of materials with various antenna parameters will be investigated, especially on flexible materials. The integrated NFC antenna will introduce different shapes, diameters of wires, and sizes. Effects of these parameters on the antenna will be tested in this study. Besides, the research will also explore the development of NFC software and hardware environment to enable the interaction between flexible NFC tag and reader.

1.3. Thesis structure

Chapter 1 presents the introduction, relevant background information, the problem statement of the thesis, and describes the structure of the thesis. Chapter 2 provides detailed theoretical background and some prior literature. Chapter 3 describes the methodology and procedures of the experiments. Chapter 4 has the detailed experimental results and information that was found using the methods described in chapter 3. Chapter 5 summarizes the conclusion, lists some experimental limitations, and discusses possible future work.

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2. BACKGROUND

2.1. Introduction

Wireless communication means transferring information between devices without any physical medium. It is one of the fastest growing technologies that can be categorized as short and long-distance communication. In a wireless communication system, an antenna is a critical part of the communication system because it transfers information in the wireless medium. As wireless communication systems have advanced in the last couple of decades, so have the antenna system developed a lot. For the very high need of a mobile communication system, various new technological challenges have emerged for the antenna designers because of unique performance requirements. For example, the implementation of Radio Frequency Identification (RFID) and Near Field Communication (NFC) antennas on flexible materials need special considerations. Antenna design, substrate materials effect, reader antenna power consideration, and many other different parameters need to be considered other than traditional antennas. This thesis presents the process of making flexible antennas and their testing procedures. It describes a factorial design analysis of NFC antennas and analyzes the results afterward.

2.2. RFID and NFC

Radio Frequency Identification (RFID) uses electromagnetic fields to automatically identify and tracks tags that are attached to objects [1]. The tags hold electronically transmitted data. Passive tags receive power from a nearby RFID reader's

radio waves. Active tags have a local source of energy and can interact with an RFID reader from a longer distance. The tag does not need to be the line of sight of the reader, and it may be embedded in the tracked object [2].

2.2.1. RFID and NFC evolution

Over six decades ago, the British army in World War II started to use RFID to identify objects. At first, in the 1960s, RFID was considered to use commercially and later on 70s and 80s, and it was applied in commercial applications. In 1998, Massachusetts Institute of Technology (MIT) research team started to find new ways to track objects moving in different locations. Later on, NFC technology was developed over RFID. NFC was initiated by Sony and Philips (Now NXP). NFC consists of protocols that are based on RFID, which makes NFC compatible with RFID [3].

2.2.2. Components of an RFID system

An RFID system consists of three main parts: tag, reader, and controller or computation unit. Figure 2. 1 describes the components of an RFID system:

Figure 2. 1 Components of an RFID system [4]

A tag, sometimes called a transponder, consists of an Integrated Circuit (IC) and an antenna. Usually, RFID tags are attached to objects and detected by the RFID reader. Each tag has a unique serial number which helps to communicate and be identified. The reader, on the other hand, is called an interrogator and is capable of both reading and writing to the tag. It is also composed of an antenna, an RF module which is responsible for transmitting and receiving signals, and a control module. A computational unit or control unit is a computer which controls the reader.

2.2.3. Classification of an RFID system

RFID systems are commonly classified according to the attributes of the data carrier. The two main classes of RFID tags are active and passive.

Figure 2. 2 RFID classification [5]

For an active RFID system, active tags have their power sources which generate their RF fields for data transmission. On the other side, in a passive RFID system, tags do not have their power supplies; instead, they use the reader's power to activate their IC's and send a modulated signal back to the reader. As a result, passive tags are cheaper and smaller than active tags.

There are other two modes as well: semi-passive and semi-active. They use a battery to supply the internal operation of the tag, but they depend on the RFID reader power to transmit the signal. Both of these types have some advantages and disadvantages.

2.2.4. RFID frequency bands

The essential differentiation criteria for RFID systems are the operating frequency of the reader, the physical coupling method, and the range of the system. RFID systems are operated at widely differing frequencies, ranging from 135 kHz longwave to 5.8 GHz in the microwave range. Electric, magnetic, and electromagnetic fields are used for the physical coupling. Finally, the possible range of the system varies from a few millimeters to above 15 m [4]. The specific frequency range also depends on country regulations. The figure below shows the different communication range of the RFID system.

Figure 2. 3 Communication range of the RFID system [4]

2.2.5. NFC overview

Near-field communication (NFC) is a radio-frequency identification system (RFID) that enables fast communication between devices over a short range using the 13.56-MHz RFID band [4]. Instead of performing manual configurations, the connection between two NFC devices is automatically established in less than 0.1 seconds. Nowadays, NFC technology is extensively used in the payment system, but it has existed for over a decade. NFC data transmission is measured in Kilo Bits Per Second (kbps). The NFC standard supports varying data rates, again to ensure interoperability between existing infrastructure components. The current data rates are 106 kbps, 212kbps, and 424 kbps [6]. It is a two-way interaction between electronics devices [7] that enables people to perform transactions, accessing coupons in different outlets, or even pairing or connecting two NFC enabled devices with just a single tap. NFC technology avails the Internet of Things (IoT) to expand rapidly as most of the smartphones have NFC readers [8, 9]. Since NFC is a quick and easy way of obtaining data by placing the tag near the reader without any pairing mechanism, it increases the low-cost NFC sensors market.

2.2.5.1. Components of an NFC system

Major parts of an NFC system consist of:

- i. NFC reader
- ii. NFC tag
- iii. Sometimes NFC smartphones also act as an NFC reader.

(i) NFC reader:

An NFC reader is always an active device and is capable of bidirectional information transfer with another NFC device. An NFC reader can be in one of two forms: internal and external. An internal NFC reader can be integrated into an NFC enabled mobile phone, so that when the NFC mobile is touched to an NFC tag, it can read/write data from/to the tag. Thus the interaction between an NFC mobile (with embedded NFC reader) and an NFC tag is, respectively, the interaction between active and passive devices.

In an NFC system, a reader always has the power source, and so is an active device. The reader is capable of exchanging information bidirectional way. The reader could be in two forms: internal and external NFC reader. The internal reader is used inside a smartphone while the external reader usually is outside.

(ii) NFC tags:

Usually, NFC tag does not have a power source, and hence, it is a passive object. A small amount of data can be stored inside each of the tags. A large amount of data can be stored inside an expensive tag. The passive tags get the power from an active NFC reader. The reader creates an RF field, and the passive tag gets energized and acts according to the algorithm written to it. Two passive devices cannot communicate with each other as they do not have the power sources.

(iii) NFC enabled mobile phones:

Smartphones with NFC integrated technology are referred to as NFC mobiles. Integration NFC with the mobile phone enhance the Internet of Things (IoT) world. Consumer interaction with the real world creates a new opportunity for different

businesses. Using this feature, users can quickly pay their bill to any store, access the control, and get coupons, and a lot more things can do it using their smartphone [10].

2.2.5.2. NFC operating modes

There are two modes that the NFC device can communicate with other devices; active and passive mode for the initiator and target device communication. Initiator device starts the communication, and the target device responds to it.

Figure 2. 4 NFC operating modes [4]

For example, an NFC tag, smart card, contactless card, or even sometimes an NFC device could be NFC target device. Both the initiator and target generate their electromagnetic field to exchange data in the active mode of communication while in the passive communication mode, only the initiator generates an electromagnetic field and the target uses load modulation to transfer data.

Based on ISO/IEC 18092, NFC IP-1 and ISO/IEC 14443 contactless smart card standards NFC devices can operate in three modes: reader/writer mode, peer to peer mode and card emulation mode [11].

2.2.5.3. Standards and protocols

As the smartphone became the best solution for NFC technology, it is essential to maintain interoperability and compatibility of NFC devices and protocols. Hence, NFC standardization is introduced. Numerous organizations defined different models and standards. The purpose of all standards is to increase the ease of access, security, and interoperability of the NFC technology. NFC standards define data exchange formats, communication protocols, and it is based on RFID standards. Mainly the standard describes the transport protocol, and its activation, data exchange protocol, error detecting code calculation, and protocol deactivation. Some of the organizations with their significant contribution in NFC standards are listed below:

- 1) International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC)*

ISO has the world's largest standardization network and is the most prominent international standard organization. On the other side, IEC is a nonprofit organization;

mostly, they provide standards for electrical, electronic, and relevant technologies. ISO and IEC work together to provide more secure and safer product standards.

2) *NFC Forum*

It is a nonprofit organization set up to spread the NFC technology globally. This standard focuses on spreading short distance communication interaction by using NFC in consumer electronics. In 2004 to advance the RFID technology, some big companies, Nokia, Philips, and Sony formed together and made this organization and later Visa, MasterCard, Samsung, Microsoft, and Motorola joined as well.

3) *ECMA international*

In 1961, a membership-based private organization was formed that is non-profit and non-government. It is open for any size companies that produce, develop, or sell computer systems.

NFC has its standardization based on proximity range communication interface that is different from the RF layer. NFC RF layer is compatible with different standards and is above the standard protocols. In ISO/IEC 18092 defines device-to-device communication for both active and passive modes with the proximity range and 106, 212 or 424 Kbps data rates.

ISO/IEC 14443 is the proximity contactless smart card standard, which defines read to card communication with 106 kbps data transfer rate. Proximity transactions are made by electromagnetic coupling, and it operates at 13.56 MHz frequency.

Parameters	ISO/IEC 18092	ISO/IEC 14443	ISO/IEC 15693
Operating Mode	Peer to Peer	Reader to Card	Reader to card
Communication Mode	Active and passive	Passive	Passive

Parameters	ISO/IEC 18092	ISO/IEC 14443	ISO/IEC 15693
Range	Proximity	Proximity	Vicinity
Dara Rate	106, 212, 424 kbps	106 kbps	≤ 26 kbps

Table 2. 1 Summary of communication interfaces standards [10]

ISO/IEC 14443 standard consists of four parts [10] including physical characteristics, RF power, and signal interface, along with initialization and anti-collision protocols with defining data frame and timing in the third part, and transmission protocol definition in the last section. It also defines two types of cards: Type A and B.

MIFARE, FeliCa, and Calypso are some of the most famous proximity coupling smart card technology that are compatible with ISO/IEC 14443. MIFARE is used by 80% of the contactless smart card in the world. It is a type A standard and developed by NXP semiconductor. This classic card is used in different application areas, i.e., transportation, ticketing, e-payment, road tolling, or access management. FeliCa is the high-speed proximity card developed by Sony and used for mainly money cards. FeliCa currently only belongs to the Japanese Industrial Standard (JIS) X 6319 part 4. Another type of smart card is Calypso, that is used in public transportation in Europe. Type B and European EN 1545 defined the ticketing data for smart cards came from this standard.

2.3. Operating Principles of RFID and NFC

As mentioned before, NFC technology is an extension of the RFID system. To understand the concept of operating principles of these techniques, one needs to understand the physical principles of how they operate. In this section, the theory of

electromagnetic waves and the principles of inductive, capacitive coupling will be discussed to understand the process of power and data transfer of an RFID system.

2.3.1. Magnetic Field Strength H , due to flow of charge

A magnetic field is produced when electricity flows inside a conductor or even in a vacuum. The magnitude of this field is called the field strength, H , regardless of the material properties of the space. In the general form, we can say that: ‘the contour integral of magnetic field strength along a closed curve is equal to the sum of the current strengths of the currents within it,’ and it is given by [4]:

$$\sum I = \oint_{\vec{H}} \vec{ds} \quad (2.1)$$

In a straight conductor, the field strength H along a circular flux line at a distance r is constant. For this case, H can be calculated as:

$$H = \frac{1}{2\pi r} \quad (2.2)$$

Figure 2. 5 Magnetic flux lines around the conductor and a cylindrical coil [4]

The equation below describes the path of field strength along the x-axis of a round coil that is similar to inductively coupled RFID transmitter antennas.

$$H = \frac{I \cdot N \cdot R^2}{2\sqrt{(R^2 + x^2)^3}} \quad (2.3)$$

Where N is the number of windings, R is the circle radius, and x is the distance from the center of the coil in the x-direction. The boundary condition is when $d \ll R$ and $x < \frac{\lambda}{2\pi}$. The electromagnetic far field begins when x exceeds $\frac{\lambda}{2\pi}$. For a rectangular conductor loop with edge lengths a x b the field strength path would be:

$$H = \frac{N \cdot I \cdot ab}{4\pi\sqrt{\left(\frac{a}{2}\right)^2 + \left(\frac{b}{2}\right)^2 + x^2}} \cdot \left(\frac{1}{\left(\frac{a}{2}\right)^2 + x^2} + \frac{1}{\left(\frac{b}{2}\right)^2 + x^2} \right) \quad (2.4)$$

For an inductively coupled RFID system if there are three different sizes of antennas the largest one has the lowest magnetic field strength while the smallest one has the highest field strength at the center of the antenna, but for the largest antenna, it remains constant for a greater distance compared to other small antennas.

2.3.2. Magnetic Flux and Magnetic Flux Density

The total number of magnetic lines passing through a coil is denoted as magnetic flux and if the measurement of the magnetic field which passes through a surface, it is magnetic flux density B.

Figure 2. 6 Relationship between magnetic flux and flux density [4]

The equation below defines the relationship between flux density B and field strength H , and it is material relationship:

$$B = \mu_0 \mu_r H = \mu H \quad (2.6)$$

μ_0 is the magnetic field constant ($\mu_0 = 4\pi \times 10^{-6}$ Vs/Am), and it describes the magnetic conductivity (.ie., permeability) of a vacuum. μ_r is the relative permeability and explains the permeability of a material relative to μ_0 .

2.3.3. Inductance

When the current flows inside of a conductor, a magnetic field is generated, and this field intensifies when there are N loops to form a coil of the same area A . Total flux Ψ will be the sum of flux Φ generated by N number of coil loops.

$$\psi = \sum_N \phi_N = N \cdot \phi = N \cdot \mu \cdot H \cdot A \quad (2.7)$$

Figure 2. 7 Inductance definition [4]

The ratio of total magnetic flux to the current is called the inductance and given by equation 2.8, where it depends on the geometry and the permeability of the medium.

$$L = \frac{\psi}{I} = \frac{N \cdot \phi}{I} = \frac{N \cdot \mu \cdot H \cdot A}{I} \quad (2.8)$$

2.3.4. Mutual Inductance

Mutual inductance occurs when the two or more coils are magnetically linked together; they are arranged so that the change in current in one causes a voltage drop to be induced in the other. The relative position between the two coils defines the amount of mutual inductance. If the second conductor with area A_2 located with first conductor area A_1 where the current flows into it then, the second conductor will be affected by the magnetic flux generated by A_1 . The flux that connects inductively between two coils is called coupling flux. The amount of inductive coupling depends on the geometry, position and the permeability of the medium of the two coils. Mutual inductance M_{21} of conductor 2 relative to conductor 1 is defined as the ratio of partial flux Ψ_{21} enclosed by conductor 2 to the current I_1 in conductor 1.

Figure 2. 8 Mutual inductance, M_{21}

$$M_{21} = \frac{\psi_{21} I_1}{I_1} = \oint \frac{B_2(I_1)}{I_1} dA_2 \quad (2.9)$$

The same relation is applied to for coil 1 and we find:

$$M = M_{12} = M_{21} \quad (2.10)$$

Assuming a homogeneous magnetic field and using 2.9 we get:

$$M_{12} = \frac{B_2(I_1) \cdot N_2 \cdot A_2}{I_1} = \frac{\mu_0 \cdot H(I_1) \cdot N_2 \cdot A_2}{I_1} \quad (2.11)$$

Using 2.3 and A_2 with $(\pi \cdot r^2)$, we obtain:

$$M_{12} = \frac{\mu_0 \cdot N_1 \cdot R_1^2 \cdot N_2 \cdot R_2^2 \cdot \pi}{2 \sqrt{(R_1^2 + x^2)^3}} \quad (2.12)$$

For the homogeneity of the magnetic field in the area, A_2 the condition $A_2 \leq A_1$ and x-axes of the two coils should be on the same plane. By 2.10 and $A_1 \leq A_2$ we get:

$$M_{21} = \frac{\mu_0 \cdot N_1 \cdot R_1^2 \cdot N_2 \cdot R_2^2 \cdot \pi}{2 \sqrt{(R_2^2 + x^2)^3}} \quad (2.13)$$

2.3.5. Coupling Coefficient

To define the coupling between the two coils, we define the coupling coefficient. It defines how well the flux link between the two coils. If the coupling between the two coils is functional, then, the flux link to another coil will be active. On the other hand, if the coupling between the two coils is weak, then the linked flux will also be affected. The coupling coefficient is the fraction of total flux, which links the other coil is called the coupling coefficient, k . If Φ_1 is the total flux generated by coil 1 and Φ_{12} is the flux that is linked to the coil 2 then,

$$K = \frac{\phi_{12}}{\phi_1} = \frac{\phi_{21}}{\phi_2}$$

K always varies between $0 \leq k \leq 1$. $k = 0$ means two coils are decoupled and $k = 1$ means both coils have the same magnetic flux. The relation between the coupling coefficient and the mutual inductance is given by [4]:

$$K = \frac{M}{\sqrt{L_1 \cdot L_2}} \quad (2.14)$$

Where L_1 and L_2 are the inductance values of the two coils.

2.4. Flexible Antennas of RFID and NFC

Flexible antennas have a great extent of usage, especially in wearable applications. The main challenges of antennas in wearable electronics including but not limited to the realization of flexible antennas, ubiquitous, robust and low cost where the antennas are on the body-worn and perform almost similar features like regular antennas. Wearable electronics are gaining much popularity day by day in healthcare, consumer electronics, child monitoring, sports, and other sectors. Integration of wearable antennas on those areas has different challenges including, flexibility and conformability, robustness and tolerance in different environmental or mechanical conditions, cost consideration, weight consideration, simplicity, recyclability, and maintaining RF performance similar to the traditional antennas.

2.4.1. Types and fabrication process

When flexible antennas are considered, two categories are mainly discussed [15]:

- a) Thin-film based flexible antennas
- b) Fabric-based flexible antennas

2.4.1.1. Thin-film based flexible antennas

Thin-film based wearable antenna substrate could be Polyethylene terephthalate (PET), Kapton, paper, or polydimethylsiloxane (PDMS) [15]. Selection of these type of flexible material is an issue considering flexibility, light-weight, low-cost, and

robustness. Usually, metal is deposited onto these kinds of materials to form flexible antennas. Several procedures to fabricate the antennas on these types of materials comprise of screen-printing, inkjet-printing, sputtering, photolithography, manual deposition of conductive polymers, injection of liquid metal alloy.

Screen-printing is the additive stencil-based process, and the conductive ink is printed by a patterned fabric process [16]. It is easy to implement and very much cost-effective way to produce flexible antennas. Environment-friendly and high printing solution makes it very popular [17]. The limitation of this process is limited control of the thickness of the metal, and it is susceptible to ink viscosity changes [18].

Figure 2. 9 Thin-film antennas [15]: a) screen printing, b) inkjet printing, c) photolithography

In the *inkjet* printing method, using an inkjet printer that uses inks with silver or gold nanoparticles (2-50 nm in diameter) on the flexible substrates to make the antenna [19]. This method is also pretty much typical for flexible antenna realization, but it does not

have good conductivity and robustness. However, this problem can overcome by applying multilayer printing process.

Photolithography and sputtering is another type of flexible antenna-making process that uses microfabrication equipment. This process involves sputter-deposition of copper in a controlled manner onto the flexible substrate and then dipping the whole structure inside the acetone bath. This method is low-cost and straightforward to use. In [20] authors illustrated 450nm thick conductive layer that is printed on a PET substrate using photolithography to realize UHF RFID antennas. However, the problem of this process is the prototypes are sensitive to extreme flexibility and mechanical pressure.

2.4.1.2. Fabric-based flexible antennas

In this process usually, a conductive thread or metal is woven or deposited onto the fabric substrate. Example fabric substrate could be Cordura, felt, lycra, cotton, polyester, polycot, etc [21, 22]. These types of fabric have low permittivity and tangent values [15]. Fabrication technique could be, adhesive, screen printing, inkjet printing, embroidery of conductive threads, and electro-textiles.

Figure 2. 10 Fabric based flexible antennas, a) adhesive copper tape on fabric b) embroidery of E-threads c) Electrotexiles [15]

The *adhesive* of flexible copper tape onto the fabric based material is one of the very basic traditional methods realizing flexible antennas onto textile material. The adhesive material may affect the antenna's performance and should take into account its permittivity along with the substrate material when simulation and testing will be done. The shortcoming would be manual cutting of the metal adhesive will not be the perfect desired shape, and the antennas are not mechanically robust. It is low-cost, fast, and easy to produce that acts similar properties of the traditional copper antennas. Adhesives are required to provide interconnections between the antenna subcomponents, such as conducting components, substrates, connectors, vias, walls, and wires. The two frequent interconnections needed in the fabrication of textile antennas are:

- 1) Grasping the conductive/flexible metallic parts to the substrate
- 2) Allowing a high-frequency galvanic connection

Metallic tapes or textiles with rear adhesive are employed to make the antennas. *Advanced dimensioning or laser cutting* is another method besides hand-operated tools that are used to dimension textiles substrate. To ensure accurate dimension precision antennas at higher frequencies need advanced machines and equipment. For example, Ultra Wide Band (UWB) textile antenna is developed in [23] utilizing a laser-cutting method.

Figure 2. 11 Epilog Zing 24 laser-cutting machine [23]

In this study, they described, antenna-design was done by a laser cutter machine, the Epilog Zing 24 laser system, to orderly form the antenna design. The work stated, in [11] used a picosecond pulsed laser to accurately dimension off-the-shelf e-textile sheets. Alternatively, copper foils can be bound onto a textile substrate earlier to dimensioning using a laser tool to assure accuracy [24].

Embroidery is a direct way of implementing of conductive fibers onto designated substrates can be used to manufacture wearable antennas. A home-based digital embroidery machine is enough for this technique [25]. To make textile surface hundreds of e-fibers are tightly bundled and, automatic embroidery was applied with high-density stitching. The fabricated conductive textile covers were then utilized to form the radiating parts, ground planes, and transmission channels.

Conductive and screen printing is an alternative method for flexible antenna fabrication. For example, authors in [26] described the printing of spiral lines that is consisted of five turns on a denim substrate and were printed using silver ink. The fabrication was then kept at 90 °C for nearly 5–10 min. Such a fabrication system requires the usage of a highly resistive silicone from MG Chemicals, which was spread onto the substrate.

Inkjet printing process onto the textile is an alternative way of textile antenna making that is described in [27]. They used an interface layer to form an interface layer. Lint-Free clean-room wipes soaked in deionized water before silver inkjet printing is used when the fabrication is started. The conductive model was kept for 10 min at 150 °C. To enhance the fabrication cohesiveness and decrease fabric roughness, inkjet printing technique has been improved to add screen printed interface layer [28]. Another second coat of ink was appended to boost the robustness of bending. The fabrication process is summarized in the figure.

Figure 2. 12 Flow diagram of inkjet-printed textile antenna fabrication process [28]

2.4.2. Prior work of flexible RFID antennas

A list of study of RFID and NFC antennas are mentioned below:

RFID Based Location Tracking [29]

This paper represents an overview of RFID-based localization and tracking technologies, including tag-based (e.g., LANDMARC), reader-based (e.g., reverse RFID), transceiver-free, and hybrid approaches. These technologies mainly use the readily available resource of radio signal strength information or RSS change information to localize the target objects. A number of well-known approaches and their limitations are introduced. This article also indicates the challenges and possible solutions in the near and long terms. The challenges include multipath propagation, interference, and localizing multiple objects, among others. Most of these challenges exist not only for RFID-based localization but also for other RF-based localization technologies.

Textile Antenna for Wearable Radio Frequency Applications [30]

In this research article, authors embroidered Radio Frequency circuits and antennas in textile.

Figure 2. 13 Textile E-thread [30]

They used integrated conductive fiber (Metal coated high strength polymer fibers) E-Fibers. Silver coated Amberstrand fibers were used. The diameter was 15 μm , composed of a 10 μm high strength p-phenylene-2, 6-benzobisoxazole (PBO [Toyobo 2005]) core, and 2-3 μm thick metallic coating.

Fabrication process and performance

The performance comparison with copper antenna shows that if the performance is excellent compared with the conventional copper antenna. It has very low Electrical loss (0.2 dB/cm), excellent mechanical flexibility and radio frequency up to 3 GHz.

Figure 2. 14 Fabrication process [30]

Figure 2. 15 Testing the textile antenna [30]

Colorful Textile Antennas Integrated into Embroidered Logos [31]

In this literature, the authors presented a method to create colorful textile antennas that could be embroidered within logos or other aesthetic shapes. The embroidery process uses an e-thread in the bobbin case of the sewing machine to embroider the antenna on the back side of the garment.

Figure 2. 16 Colorful textile antenna [31]

Beam Switching Conformal Antenna Array for mm-Wave Communication [32]

In this study, 3 Antenna arrays with 16 patch elements each were used. The main beam direction can be changed by switching a semiconductor. RT/Duroid 5880 material is used, high-frequency laminates with PTFE composites reinforced with glass microfibers. Substrate thickness is 127 μm . SP3T semiconductor switch is used.

Figure 2. 17 Conformal beam antenna [32]

2.5. Resonant circuits

In an RFID system, most of the cases inductively coupled tags are passive tags [4]. These inductively coupled tags are made with an IC (microchip) and an antenna coil. All the energy to activate the IC comes from the RFID reader antenna. Whenever the emitted field from the reader penetrates the tag coil, a voltage is induced in tag's coil that drives the tag IC. The tag IC and tag antenna acts as a resonant circuit. Below section provides the basics of series and parallel resonant circuits, and some of their properties are discussed.

2.5.1. Series resonant circuit

In electrical circuits, series resonance has many uses and one of the most important circuit. Series resonant circuits are specially used for frequency selective circuits (such as in radio or television), noise filters and act as a bandpass filter. For frequency selective capability this circuit is used extensively.

Figure 2. 18 Series resonant circuit [13]

Characteristics of the series resonance circuit: [14]

- Minimum impedance
- Maximum circuit current
- $\cos(\phi) = 1$, hence current and voltage becomes in phase.
- Circuit current becomes proportional to circuit resistance i.e. $I \sim 1/R$

2.5.2. Parallel resonant circuit

When inductor and capacitor are in parallel then this type of resonance occurs. The parallel resonant circuit is also known as the rejector circuit. The uses might be as a band stop filter, tank circuits in an oscillator, and many other cases.

Characteristics of the parallel resonance circuit: [14]

- Maximum impedance
- Minimum circuit current

- $\cos(\phi) = 1$, hence voltage and the current become in phase
- Circuit current depends on circuit impedance, $Z = L/C$ or $I \sim -(1/R)$

Figure 2. 19 Parallel resonant circuit [13]

At resonance, there will be a high circulating current between the inductor and the capacitor due to the energy of the oscillations; then parallel circuits produce current resonance [13]. In the parallel resonant circuit theoretically, the energy between the inductor and the capacitor moves back and forth, which does not require any external power source.

At the resonant frequency, capacitive and inductive reactance are same: $X_C = X_L$ for both series and parallel resonant circuit. That is, at resonant frequency:

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (2.15)$$

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3. METHODS AND DEVELOPMENTS

In this chapter, preliminary work of the NFC antenna on a flexible substrate is discussed, which includes RFID antennas on soft material and some other related communication ways for considering a smart billboard system. To identify a specific person, by using traditional technologies, NFC is the best technology because of its availability in most of the smartphones and its implementation on the flexible material is desirable. The NFC antenna equivalent circuit system is discussed. Fabrication of NFC antenna on different substrate variation is reported, and some prototypes of NFC antennas are made. Furthermore, with copper and aluminum, two types of materials are used for the fabrication of NFC antennas. Different fabrication methods are also described to manufacture NFC antennas, and some working prototypes are produced. Later on, design parameters of NFC antennas are observed, and the relevant parameters that are essential for making NFC antenna coil are discussed. In the end, a statistical method is described to find out which parameters have a critical effect on designing NFC antennas.

3.1. Preliminary work

RFID (UHF range) communication using Cooley's EnviroFlex PE material

In this work, an Ultra High Frequency (UHF) RFID system was developed, and Cooley's [1] EnviroFlex PE material [2] was utilized to wrap over an RFID-UHF 915 MHz aluminum foil antenna. The following hardware were used:

- a) Simultaneous RFID reader
- b) Arduino form-factor compatible microcontroller

- c) Ultra-High Frequency (UHF) RFID tags
- d) Integrated Antenna bounded to Cooley EnviroFlex material with graphics.

The overall system of our RFID system looks like:

Figure 3. 1 Demo RFID-UHF antenna with Cooley's EnviroFlex PE.

Here, each location picture is a specific tag for the RFID system. We programmed the microcontroller to send the Unique ID (UID) of the tag (here, location tag) to the user. The user then receives this UID using a Java program with Swing for User Interface. Based on this specific UID, the program shows the picture of the location picture, description of this location and plays audio related to this location.

Antenna description

Aluminum foil tape was used to make the antenna. Then we wrapped the antenna with Cooley provided EnviroFlex PE material [2].

Figure 3. 2 Antenna bounded with Cooley's EnviroFlex PE material.

3.2. NFC tag explanation

NFC IC was chosen from NXP semiconductor [3]. Among the two major categories of NFC tag IC: NTAG and ICODE [4], NTAG I²C tag IC was selected due to its various features. For example, NTAG is very secured, low priced, and also capable of energy harvesting to a microcontroller. NTAG data transmission is very high 106 kbps compared to ICODE, which is 26.5 kbps [7]. So, the NTAG I²C Plus IC was used for this thesis work. A detailed NXP[®] tag IC comparison chart is mentioned in appendix A.

3.2.1. NFC tag equivalent circuit

From the datasheet of NTAG I²C Plus IC [6], the internal capacitance of the IC is 50 pF. An NFC tag is nothing but an antenna, i.e. (inductor), an IC and a resonant capacitor in series or parallel based on the resonant frequency and inductor

requirements. Equivalent circuits of NFC tag antenna, IC and the entire circuit is described below.

3.2.1.1. Series and parallel equivalent circuit of the antenna

NFC antenna can be represented as an inductor L_{sc} in series to a loss resistance R_{sc} . The antenna capacitance C_{coil} is in parallel to this series circuit. This capacitance consists of the inter-turn capacitance, and a probably produced tag capacitance. Alternatively, the NFC antenna could be presented as a parallel circuit as below:

Figure 3. 3 Series and parallel equivalent NFC antenna [7]

3.2.1.2. NFC IC equivalent circuit

NFC IC equivalent circuit is a parallel circuit of a resistor and a capacitor. The resistor represents the energy consumption of the IC, and the capacitor value is 50 pF.

Figure 3. 4 Equivalent circuit of NTAG IC [7]

3.2.1.3. Equivalent circuit of the NFC tag

If we consider the antenna as a parallel circuit, the following sketch reveals the equivalent circuit of the total NFC inlay tag:

Figure 3. 5 NFC tag equivalent circuit [7]

A resonance circuit is developed with the antenna inductance L_{PC} and other parallel capacitors, i.e., NTAG IC capacitance C_{IC} , antenna capacitance, and the parasitic connection capacitance. The NTAG IC input resistance R_{IC} unitedly with the loss resistance of the antenna and the connection resistance represents the quality factor of the whole tag. This quality factor determines the threshold field strength of the tag. R_{Con} should be kept as low as possible because of the high connection resistance will lower the total parallel quality factor and reduce the communication range.

A simplified version of the above figure when the product delivered in the package is given below:

Figure 3. 6 Equivalent NFC antenna tag [8]

The total antenna impedance is $Z_{ant} = C_{ant} \parallel R_{ant} \parallel L_{ant}$. For a given antenna C_{ant} , R_{ant} , and L_{ant} are constant, but Z_{ant} is frequency dependent. At the self-resonance frequency, the imaginary part of the antenna impedance is null, and the antenna is purely resistive. Below the self-resonance frequency, the imaginary part of the antenna impedance is positive, and the antenna behavior is inductive [8].

3.2.2. Mathematical model and coil inductance calculation

In the closeness of a magnetic field, the equivalent circuit of the NFC tag is:

Figure 3. 7 NFC tag in the presence of a magnetic field [8]

Here, the model includes the following parameters:

- V_{oc} is the open circuit voltage delivered by the antenna which depends on the magnetic field strength and designing of the antenna.
- L_A is the antenna coil inductance defined as $L_A = X_A / \omega$; X_A is the antenna reactance.
- R_S is the equivalent power consumption
- C_S is the serial equivalent tuning capacitance.

When the self-resonance frequency is low ($f < f_{self}/10$), the stray capacitance C_{ant} is negligible and $L_A = L_{ant}$ and the reactance is $X_A = jL_A\omega$. At 13.56 frequency, C_{ant} becomes in a range of some pF and $L_A > L_{ant}$. The antenna impedance is $Z_{ant} = R_A + jL_A\omega$.

The NFC / RFID chip impedance is $Z_S = R_S + j.1 / C_S\omega$. For the equivalent RLC circuit, the total impedance is $Z_{tot} = Z_{ant} + Z_S$ and the resonant frequency is given by the condition $L_A C_S \omega^2 = 1$ [8].

At the resonant frequency, the total impedance is minimal and reduced to $Z_{tot} = R_A + R_S$ which is purely resistive. The current inside the antenna and the voltage delivered to the NFC / RFID chip are maximum. The maximum energy is provided to the device [8].

Self-inductance of particular shapes

At 13.56 MHz depending on different shapes the major parameter is the equivalent inductance L_A . The stray capacitance is in a few pF. Below some formulas are mentioned [8]

1. Inductance of a circular antenna

$$L_{ant} = \mu_0 N^{1.9} r \ln\left(\frac{r}{r_0}\right) \quad (3.1)$$

Where r is the average coil radius in millimeters, r_0 is the wire diameter in millimeters, N is the number of turns, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m

2. Inductance of a spiral antenna

$$L_{ant} = 31.33\mu_0 N^2 \frac{d}{8d + 11c} \quad (3.2)$$

Where d is the average coil diameter in mm, c is the thickness of the winding in μm , N is the number of turns of the coil, $\mu_0 = 4\pi \cdot 10^{-7}$ H/m, L is in Henry

3. Inductance of a square antenna [26]

$$L_{ant} = k1\mu_0 N^2 \frac{d}{1 + k2p} \quad (3.3)$$

Where d is the mean coil diameter, $d = (d_{out} + d_{in})/2$ in mm, d_{out} = outer diameter, d_{in} = inner diameter, $p = (d_{out} - d_{in})/(d_{out} + d_{in})$ in mm. $K1$ and $K2$ constants depend on the layout:

Layout	K1	K2
Square	2.34	2.75
Hexagonal	2.33	3.82
Octagonal	2.25	3.55

Table 3. 1 K1 and K2 values of different layouts [8]

Figure 3. 8 Square coils [8]

3.3. NFC antenna fabrication

Justifying the proof of concept of NFC antenna on the flexible material, it is necessary to make some prototypes of NFC antenna that can be made with some flexible material with different material choice. In this section, substrate variation, antenna material choice, and antenna fabrication process are discussed.

3.3.1. Substrate variation

A lot of research work has already been performed to flexible antennas on different substrate variation such as electro-textile [9], paper-based [10], fluidic [11], and synthesized flexible substrate [12]. A 150 mm ×180 mm flexible electro-textile antenna based on a 4 mm felt fabric is introduced in [9] where the antenna acts in ISM 2.45 GHz band. A flexible antenna printed on a 46mm×30mm paper-based substrate was recommended for synthesis into flexible displays for the WLAN applications in [10]. The problem of the paper-based substrate is that it is not strong enough, and there are discontinuities if there is high bending. In this thesis, NFC antennas are produced with four types of flexible substrates. Paper, plastic, fiberglass, and textile were considered onto the NFC antennas were developed.

3.3.2. Antenna material choice

Three types of metals are considered for the fabrication of NFC antennas.

- 1) Copper
- 2) Aluminum

- 3) Conductive thread: 2-Ply [18] stainless steel thin conductive thread, 3-Ply stainless steel medium conductive thread [17], and stainless steel thick conductive thread [19].

3.3.3. NFC antenna fabrication ways

NFC antennas are produced by four different techniques.

1. Hand making process
2. Robotic cutting
3. Embroidery machine
4. Chemical etching process

Hand making process

It is a manual process. In this process, some NFC coil antenna patterns are drawn using Microsoft office power-point tool. Rectangular, circular spiral, and hexagonal spiral antennas drawings are made and then printed on a simple paper. Aluminum or copper foil are attached on the back side of the printed paper. Later, the paper was cut down according to the traces of the drawing.

Figure 3. 9 Hand-made NFC coil antennas

Robotic cutting

The hand making process was not accurate enough to cut NFC antennas properly. Even though the design was perfect when the scissor was used at the corner or edges of antenna shapes, it was challenging to maintain a perfect and good shape antenna. So, a robotic machine was necessary for this purpose. In this method, we used the ‘Makerspace’ facilities at the library of the University of Rhode Island. We used Silhouette Cameo [11] to make perfect shaped antennas onto paper and vinyl paper.

Figure 3. 10 NFC antennas made by Silhouette Cameo

Embroidery machine

When it came to making the NFC antenna onto the textile material, a traditional way is hand stitching method. Using an automated embroidery machine is a better choice for making a perfect shaped antenna. We used Brother CS6000i [14] for this purpose. We made square antennas on textile material with conductive thread.

Figure 3. 11 Embroidery NFC antenna

Chemical etching process

We used the chemical etching method when we need to make the antenna onto the flexible fiberglass [15] material. We used single sided PCB board. There are two steps: i) Making PCB design on Eagle PCB designing software [16] ii) Fabrication on flexible fiberglass material.

i) Making PCB design on Eagle PCB software

The steps required:

1. Download footprint of the IC [NTAG I²C Plus: NT3H2211]
2. Making a library
3. Design in Schematic and Board in Eagle

ii) Fabrication of flexible fiberglass material

The steps required:

1. Print the Eagle Board file to a glossy heat transfer paper [20] using a laser printer.
2. Iron the printed paper onto the flexible copper substrate so that, the ink sticks onto it.
3. The last step is to sink the flexible copper substrate into the FeCl₃ [21] solution for about 15 to 20 minutes and etch the copper part.
4. After etching, wash the substrate into room temperature water. Dry it.
5. Later, using pure acetone [20] clean the ink part of the substrate that is our desired antenna.

Figure 3. 12 Three etched NFC antennas

3.4. NFC antenna coil design parameters

As explained before in sections 3.2.1 and 3.2.2 the critical parameter of NFC coil design is the equivalent inductance L_A of the antenna at 13.56 MHz. The stray capacitance is usually a scale of few pico-farads for regular NFC products. According to [8] the inductance of the NFC antenna depends on:

- a) Antenna geometry parameters
- b) Conductor parameters
- c) Substrate parameters

a) Antenna geometry parameters include the number of coil turns, antenna length, width and number of layer.

b) Conductor parameters are specifying for the antenna conductors. Width of the track, the spacing between turns and the thickness of the conductor, are main parameters here.

c) Substrate parameters include the thickness and dielectric permittivity of the substrate.

Authors in [21] described some factors that have the communication distance between NFC tag and reader. They explained coil shape, the number of turns, wire diameter, inner diameter are the main factors that affect significantly on communication range.

In this thesis, five major design parameters are considered, as these have a significant effect on the antenna inductance.

- 1) Antenna shape
- 2) Antenna size
- 3) Number of turns
- 4) Antenna material thickness or wire diameter and
- 5) Type of antenna material

3.5. A statistical analysis of the NFC antenna's design parameters

In this section, a statistical experiment was done to identify the significant impacts of the NFC antenna design parameters on the response. The Factorial design is considered foremost as an NFC antenna design requires two or more factors. In general, factorial designs are most efficient for this type of experiment.

3.5.1. The theory behind the statistical investigation

3.5.1.1. Factorial design

A factorial design is the study of the effects of two or more factors in an experiment. A factor is a discrete variable to distinguish experimental units. For example, our NFC antenna designing case, we have five main parameters those are discrete variables or factors. Each factor can have different levels. These levels can be

either discrete or quantitative. Discrete level, for example, ‘Large antenna’ or ‘Small antenna.’ Quantitative could be any specific numbers.

The factorial design shows two or more factors in a single experiment and is classified by the number of levels of each factor and the number of factors. Factorial designs have several benefits. They are more potent than one-factor-at-a-time experiments. Besides, a factorial design is essential when interactions may be present to avoid misleading conclusions. Lastly, factorial designs provide the effects of a factor to be determined at several levels of the other factors, yielding results that are valid over a range of experimental conditions [24].

3.5.1.2. 2^k factorial design

The 2^k factorial design is a particular case of among different factorial designs. In this design, each k factor has only two levels. These levels may be quantitative or may be qualitative. A complete replicate of such a design requires $2 \times 2 \times \dots \times 2 = 2^k$ observations and is called a 2^k *factorial design*. For this design, it is necessary to assume that, i) the factors are fixed ii) the designs are entirely randomized iii) the usual normality assumptions are satisfied [24].

The statistical model for a 2^k design would include k main effects, two-factor interactions, three-factor interactions, . . . , and one k -factor interaction. That is, the complete model would contain $(2^k - 1)$ effects for a 2^k design [24].

3.5.1.3. Two-level fractional factorial design: $2^{(k-1)}$ factorial design

When the number of factors (k) in a 2^k factorial design increases, the number of experimental runs multiplies for a complete replicate. For example, for 6 factors requires $2^6 = 64$ runs. Among 63 degrees of freedom, only 6 of them corresponds to the main effects, 15 degrees of freedom are two-factor interactions. So, only 21 of 63 interactions are likely to be considered of major interest. The remaining 42 are associated with three or and higher interactions. If the higher order interactions are negligible, information on the main effects and low-order interactions may be obtained by running only a fraction of the complete factorial experiment. Then, fractional factorial designs are considered one of the most useful methods.

3.5.2. Antenna parameters set

A total of thirty-three NFC antennas are considered for the experiment, and the antennas are numbered from 1 to 33. As discussed previously, five major factors are considered for the experiment, and two levels for each of the factors are considered. So, by the 2^k factorial design, it has a total of $2^5 = 32$ runs. For each type of run, if there are three experiments, it would be a total of $32 \times 3 = 96$ experiments. Below figure shows the total of 32 categories of antennas and each category has three experiments.

		Circular shape				Rectangular shape			
		small size		large size		small size		large size	
		Low # turns	High # turns	Low # turns	High # turns	Low # turns	High # turns	Low # turns	High # turns
Low thickness	Aluminum	1 19	2 14, 17, 18	3	4 29	5	6 16, 25	7	8 20
	Copper	9 12	10 10, 11	11	12	13 6, 7	14	15 9, 13	16
High thickness	Aluminum	17	18 21, 23	19 30, 31, 32, 33	20	21	22 6, 15, 22, 24	23 26	24 27, 28
	Copper	25	26	27	28	29 5	30	31 1, 2, 3, 4	32

Table 3. 2 NFC Antenna category

There are only a total of 33 antennas, and two or more antennas belong to one category, there are almost half of the categories that did not have any NFC antennas. On the above figure, in each cell, the big numbers represent the category number and below the small numbers represents the antenna number of that category. The white space numbers do not have any antennas. For example, category 3, which means: circular shape, large size, low number of turns, low thickness (conductor width), and the aluminum category does not have any antennas. On the other hand, all the green cells with numbers have one or more antennas. For example, category 31 has four antennas: 1, 2, 3 and 4. For this reason, two-level fractional design $2^{(k-1)}$ or one-half fraction design is considered. As a result, now the total number of run or category would be $2^{(5-1)} = 16$ categories or runs. If each run or category has three independent experiments, then the total number of experiments would be $3*16 = 48$.

Factor name	Levels	Sign/High-Low
Antenna shape	i) Rectangular	+
	ii) Circular	-
Antenna size	i) Large	+
	ii) Small	-

Factor name	Levels	Sign/High-Low
Number of turns	i) High	+
	ii) Low	-
Antenna material thickness	i) High	+
	ii) Low	-
Type of material	i) Copper	+
	ii) Aluminum	-

Table 3. 3 Factors, levels, and corresponding sign

Randomly numbers from 1 to 48 are generated, and three numbers are taken from it and placed through each category. These numbers are considered the experiment number sequence. The figure below describes each experiment numbers with sign/high-low values. Here, green cell values have the antennas and grey cells do not have the antennas and are not counted for any categories.

		Circular shape -												Rectangular shape +											
		small size -						large size +						small size -						large size +					
		Low # turns -			High # turns +			Low # turns -			High # turns +			Low # turns -			High # turns +			Low # turns -			High # turns +		
Low thickness -	Aluminum -	22	18	30	8	39	14				16	40	47				12	19	24				28	27	9
	Copper +	36	41	13	15	25	34							4	37	45				23	21	42			
High thickness +	Aluminum -				29	31	26	20	38	6							46	1	11	3	44	2	32	33	43
	Copper +													17	5	10				35	7	48			

Table 3. 4 Experimental numbers considering factors

3.5.3. Reading Range (Distance) Measurement System

The response is the distance of this experiment. For 48 experiments, 48 different responses are the distance. The readers are smartphones that have NFC features. Three phones are used for each category so that, the NFC reading distances are not dependent on a specific phone. The phones are Samsung Galaxy S7, LG G5, and Google Pixel 2 those have NFC features. Now, each category is phone independent and also NFC antenna independent as the experiment numbers are randomly distributed. An NFC distance measurement tool is made from Styrofoam, a plastic pipe, and some flat plastic plates.

Figure 3. 13 NFC distance measurement tool with phone and tag

First of all, all the NFC tags are written the same text content: 'Hello URI' using an android application 'NFC Tools Pro'. Each NFC tag is placed on the flat surface of the Styrofoam. Then, the NFC smartphone is kept on the top surface of the plastic plate, which can be moved along with the plastic PVC pipe. Two indicators are attached to the same level as the plastic plate. A scale is vertically placed onto the Styrofoam.

The plastic plate, along with the smartphone with the 'NFC feature' turned on, was sliding down from the top until the NFC data can be read thoroughly. Each

experiment was done at least five times to get an accurate result. Each phone has an NFC reader on its back side of the phone but at a different location. First, this location was identified by using an app called ‘NFC Ring Control’ where the approximate location of the NFC reader was marked as red-area. Each tag was aligned at the same area and placed on the Styrofoam surface as depicted on the above picture. In this way, NFC readings of all the 48 experiments were measured and placed on each cell experiment.

		Circular shape -												Rectangular shape +											
		small size -						large size +						small size -						large size +					
		Low # turns -			High # turns +			Low # turns -			High # turns +			Low # turns -			High # turns +			Low # turns -			High # turns +		
Low thickness -	Aluminum -	1.3 22	3.5 18	2.5 30	1.9 8	2.8 39	2.9 14				3.9 16	7.3 40	2.7 47				2.3 12	3.2 19	3 24				2.6 28	3.2 27	2.5 9
	Copper +	1.5 36	2.7 41	2.7 13	1.5 15	3.3 25	2.8 34							2.3 4	3.9 37	2.9 45				3.4 23	5.4 21	4 42			
High thickness +	Aluminum -				2.1 29	3 31	2.4 26	3.9 20	5.6 38	4.3 6							2.6 46	4 1	1.5 11	3.4 3	4.5 44	3.5 2	5.3 32	8.5 33	1.5 43
	Copper +													2.9 17	3.8 5	3.3 10				2 35	2.8 7	2 48			
		S7	G5	Pixel 2	S7	G5	Pixel 2	S7	G5	Pixel 2	S7	G5	Pixel 2	S7	G5	Pixel 2	S7	G5	Pixel 2	S7	G5	Pixel 2	S7	G5	Pixel 2

Table 3. 5 NFC reading values

All the experimental values are measured in centimeters. Large cell numbers represent the response of the experiments, i.e., the reading distance while small cell numbers denote the experiment number sequence. Later, according to the high/low values of each five parameters, these values are fed through a Minitab [25] software to analyze these data.

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4. NFC ANTENNA EXPERIMENTS AND RESULTS

In this chapter, tools for NFC antenna inductance calculation simulation are used for finding the inductance of NFC antennas. After finding the inductance from mathematical calculation and simulation, a simple resonant circuit simulation was done to find out the proper resonant capacitor value for NFC resonant frequency at 13.56 MHz. After the attached the resonant capacitor the antenna was tested using an impedance analyzer and vector network analyzer (VNA) to verify that the entire circuit is resonating at 13.56 MHz. Later, the statistical analysis was done to find out the most critical parameters of the NFC antenna design parameters and the interactions between them. These results are presented at the end of this chapter.

4.1. Inductance calculation simulation

First NFC antenna design parameters were taken into account. In this thesis, 2 antennas are considered to make. One is the possible most giant NFC antenna that is rectangular 160x80 mm², and another one is the square shape 80x80 mm². For design simulation, eDesignSuite NFC antenna design tool [1] was used, which takes into various variables such as, antenna geometry, conductor, and substrate parameters. The geometry only considers rectangular shaped antenna, but the inputs of length, width, and the number of turns can be given. Conductor parameters such as width, spacing, and thickness can also be given on conductor parameter section. The default value of the thickness is considered here. According to the specification of [3] the antenna parameters are set and are listed to the below table:

The major design parameters are given below:

Parameter Type	Design Parameters	Antenna 1	Antenna 2
Antenna Geometry	Antenna length (mm)	160	80
	Antenna width (mm)	80	80
	Number of turns	4	3
Conductor	Conductor width (mm)	0.5	0.6
	Spacing between turns (mm)	2	2
	Thickness (μm) [2]	17.5	17.5
Substrate	Thickness (mm)	0.127	0.127
	Permittivity	4.6	4.6

Table 4. 1 NFC flexible antenna design parameters

Figure 4. 1 Screenshot of the online simulation tool from ST Electronics

4.2. Antenna experiment with impedance meter and vector network analyzer

After the antenna fabrication, a resonant capacitor value was calculated according to the equation (2.15) assuming that, antenna capacitance and equivalent parasitic connection capacitance is negligible. The capacitance value is 50 pF for NTAG I²C plus IC that is from the datasheet. The frequency is 13.56 MHz for NFC. A tuning capacitor is connected in series or parallel.

Figure 4. 2 Antenna 1 testing (R-X value measuring) using impedance analyzer 4294A

Figure 4. 3 Antenna 2 (R-X value measuring) testing using impedance analyzer 4294A

Antenna	Inductance (μH)	Series equivalent	IC capacitor (pF)	Tunable capacitor (pF)	Tuned Capacitor placement	Resonating frequency (MHz)
Antenna 1	4.85	10	50	56	Series	14.06
Antenna 2	1.62	2	50	30	Parallel	13.98

Table 4. 2 Verification of NFC fabricated antennas

On the above table, it can be seen that the antennas are resonating very close to 13.56 MHz and using the smartphones the antennas were correctly working.

4.3. The factorial design analysis result

In this thesis, a statistical experiment was conducted to see the influence of the parameters on the reading distance. The details of experimental methods are mentioned in chapter 3, section 3.5. The data is the reading distance found from different industrial NFC antennas with three different phones. To analyze the data set, this is fed to the Minitab software [4].

4.3.1. Definitions

A concise definition and explanation are mentioned below [5].

Distribution fitting: Distribution fitting aims to predict the probability or to forecast the frequency of occurrence of the magnitude of the phenomenon in a specified interval. On the normal probability plot of the effects, effects that are further from 0 are statistically significant. For positive effects, changes from the low level to the high level of the factor the response increases.

Pareto chart: The Pareto chart shows the absolute values of the standardized effects from the most substantial effect to the smallest effect. The reference line for statistical significance depends on the significance level (denoted by α or alpha). Bars that cross

the reference line are statistically significant. Because the Pareto chart displays the absolute value of the effects, one can determine which effects are significant but cannot determine which effects increase or decrease the response.

Histogram: In regression analysis, the difference between the observed value of the dependent variable (y) and the predicted value ($\hat{y}$) is called the residual (e). Each data point has one residual. Residual = Observed value - Predicted value or, $e = y - \hat{y}$. The histogram shows the distribution of the residuals for all observations. The histogram is used to determine whether the data are skewed or include outliers.

Versus order: Use the residuals versus order plot to verify the assumption that the residuals are independent of one another. Ideally, the residuals on the plot should fall randomly around the center line.

Fitted values: Fitted values are also called predicted values. The residuals-versus-fit graph plots the residuals on the y-axis and the fitted values on the x-axis. To verify the assumption that the residuals are randomly distributed and have constant variance (The average of the squared differences from the Mean). Ideally, the points should fall randomly on both sides of 0, with no recognizable patterns in the points.

Normal probability plot: The normal probability plot of the residuals displays the residuals versus their expected values when the distribution is normal. To verify the assumption that the residuals are normally distributed. The normal probability plot of the residuals should approximately follow a straight line.

DF: The total degrees of freedom (DF) is the amount of information in the data. The analysis uses that information to estimate the values of unknown population parameters. The total DF is determined by the number of observations in the sample. The DF for a

term shows how much information that term uses. Increasing the sample size provides more information about the population, which increases the total DF. Increasing the number of terms in the model uses more information, which decreases the DF available to estimate the variability of the parameter estimates.

Seq SS: Sequential sums of squares are measures of variation for different components of the model. Unlike the adjusted sums of squares, the sequential sums of squares depend on the order the terms are entered into the model.

Seq MS: Sequential mean squares measure how much variation a term or a model explains. The sequential mean squares depend on the order the terms are entered into the model. Unlike sequential sums of squares, sequential mean squares consider the degrees of freedom.

F-value: An F-value appears for each term in the Analysis of Variance table. The F-value is the test statistic used to determine whether the term is associated with the response. Minitab uses the F-value to calculate the p-value, which is used to make a decision about the statistical significance of the terms and model.

P-Value: The p-value is a probability that measures the evidence against the null hypothesis. Lower probabilities provide stronger evidence against the null hypothesis. To determine whether the association between the response and each term in the model is statistically significant, compare the p-value for the term to your significance level to assess the null hypothesis.

$P\text{-value} \leq \alpha$: *The association is statistically significant*: If the p-value is less than or equal to the significance level, one can conclude that there is a statistically significant

association between the response variable and the term. Minitab retains the term in the model.

P-value > α : *The association is not statistically significant* If the p-value is greater than the significance level, you cannot conclude that there is a statistically significant association between the response variable and the term. Minitab removes the term from the model.

S: S represents the standard deviation of the distance between the data values and the fitted values. S is used to assess how well the model describes the response. S is measured in the units of the response variable and represents how far the data values fall from the fitted values. The lower the value of S, the better the model describes the response. However, a low S value by itself does not indicate that the model meets the model assumptions. One should check the residual plots to verify the assumptions.

R-sq: R^2 is the percentage of variation in the response that is explained by the model. It is calculated as 1 minus the ratio of the error sum of squares (which is the variation that is not explained by the model) to the total sum of squares (which is the total variation in the model). Use R^2 to determine how well the model fits the data. The higher the R^2 value, the better the model fits the data. R^2 is always between 0% and 100%.

R-sq (adj): Adjusted R^2 is the percentage of the variation in the response that is explained by the model, adjusted for the number of predictors in the model relative to the number of observations. Adjusted R^2 is calculated as 1 minus the ratio of the mean square error (MSE) to the mean square total (MS Total). Adjusted R^2 is used when someone wants to compare models that have different numbers of predictors. R^2 always increases when one adds a predictor to the model, even when there is no real

improvement to the model. The adjusted R^2 value incorporates the number of predictors in the model to help you choose the correct model.

R-sq (pred): Predicted R^2 is calculated with a formula that is equivalent to systematically removing each observation from the data set, estimating the regression equation, and determining how well the model predicts the removed observation. The value of predicted R^2 ranges between 0% and 100%. Predicted R^2 is used to determine how well the model predicts the response for new observations. Models that have larger predicted R^2 values have better predictive ability.

A predicted R^2 that is substantially less than R^2 may indicate that the model is over-fit. An over-fit model occurs when someone adds terms for effects that are not important in the population. The model becomes tailored to the sample data and, therefore, may not be useful for making predictions about the population. Predicted R^2 can also be more useful than adjusted R^2 for comparing models because it is calculated with observations that are not included in the model calculation.

4.3.2. $\frac{1}{2}$ factorial design of experiments (with outliers)

A design of experiments statistical method was created to explore 2-level factorial design. As discussed in chapter 3, section 3.5 five factors shape, size, number of turns, wire thickness, and type of material were considered. $\frac{1}{2}$ fraction factorial design was chosen with three number of replicates in each category results in a total of $3 \cdot 2^{5-1} = 48$ experiments. After feeding through the values to the software, the design of the experiment was analyzed using the software. The result is given below.

Factorial Regression: Range versus Shape, Size, Turns, Thickness, Material

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	15	40.1281	2.67521	1.63	0.120
Linear	5	21.6784	4.33568	2.64	0.041
Shape	1	0.5704	0.57042	0.35	0.560
Size	1	8.7552	8.75521	5.33	0.028
Turns	1	0.4335	0.43350	0.26	0.611
Thickness	1	0.0919	0.09187	0.06	0.814
Material	1	1.7633	1.76333	1.07	0.308
2-Way Interactions	9	16.0470	1.78300	1.09	0.400
Shape*Size	1	3.5208	3.52083	2.14	0.153
Shape*Turns	1	0.5104	0.51042	0.31	0.581
Shape*Thickness	1	0.0075	0.00750	0.00	0.947
Shape*Material	1	0.1008	0.10083	0.06	0.806
Size*Turns	1	0.0372	0.03720	0.02	0.881
Size*Thickness	1	0.0104	0.01042	0.01	0.937
Size*Material	1	0.0833	0.08333	0.05	0.823
Turns*Thickness	1	5.7038	5.70375	3.47	0.072
Turns*Material	1	0.0133	0.01333	0.01	0.929
3-Way Interactions	1	8.5204	8.52042	5.19	0.030
Size*Turns*Thickness	1	8.5204	8.52042	5.19	0.030
Error	32	52.5267	1.64146		
Total	47	92.6548			

Table 4. 3 Analysis of Variance table with outliers

Model Summary:

S	R-sq	R-sq(adj)	R-sq(pred)
1.28119	43.31%	16.74%	0.00%

Table 4. 4 Model summary table

4.3.2.1. Analyzing the result with plots

If we plot the Normal plot of the standardized effect, Pareto chart, Normal probability plot, Residual versus fits, Histogram, residual versus order and residuals versus factors are given below:

Figure 4. 4 Pareto chart and Histogram

Here, the size, size*turn*thickness is the significant effect on the read range or response.

Figure 4. 5 Normal probability and Versus fits

Clearly, normal probability plot of the residual with the outliers far away from the line and residual versus fitted values with outliers that are far away from zero.

Figure 4. 6 Residual versus observation order

Figure 4. 7 Residual versus shape

Figure 4. 8 Residual versus size

Figure 4. 9 Residual versus turns

Figure 4. 10 Residual versus thickness

Figure 4. 11 Residual versus material

Figure 4. 12 Residual versus range

It can be seen from all the above figures there are outliers there in all of the figures those are red circled. An outlier is an unusually large or small observation. Outliers can have a disproportionate effect on statistical results, such as the mean, which can result in misleading interpretations [5]. If the outliers are removed and then rerun the factorial design analysis, the result is discussed in the section below. Residual versus variables with outliers have adjacent values graphs because of the outliers.

4.3.3. $\frac{1}{2}$ factorial design of experiments (excluding outliers)

Factorial Regression: Range versus Shape, Size, Turns, ... ness, Material

Analysis of Variance

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	15	26.6898	1.77932	2.98	0.006
Linear	5	12.2968	2.45935	4.12	0.006
Shape	1	0.0035	0.00353	0.01	0.939
Size	1	2.8602	2.86017	4.79	0.037
Turns	1	0.3068	0.30682	0.51	0.479
Thickness	1	0.1350	0.13500	0.23	0.638
Material	1	1.7633	1.76333	2.96	0.096

Source	DF	Adj SS	Adj MS	F-Value	P-Value
2-Way Interactions	9	10.3474	1.14971	1.93	0.088
Shape*Size	1	0.4630	0.46296	0.78	0.386
Shape*Turns	1	0.0098	0.00980	0.02	0.899
Shape*Thickness	1	0.0075	0.00750	0.01	0.911
Shape*Material	1	0.0655	0.06545	0.11	0.743
Size*Turns	1	0.1334	0.13339	0.22	0.640
Size*Thickness	1	0.0403	0.04033	0.07	0.797
Size*Material	1	0.7273	0.72727	1.22	0.279
Turns*Thickness	1	5.0430	5.04300	8.45	0.007
Turns*Material	1	0.0133	0.01333	0.02	0.882
3-Way Interactions	1	7.4003	7.40033	12.41	0.001
Size*Turns*Thickness	1	7.4003	7.40033	12.41	0.001
Error	29	17.3000	0.59655		
Total	44	43.9898			

Table 4. 5 Analysis of Variance table with outliers

Model Summary:

S	R-sq	R-sq(adj)	R-sq(pred)
0.772368	60.67%	40.33%	*

Table 4. 6 Model summary table

4.3.3.1. Analyzing the result with plots

Figure 4. 13 Normal plot of standardized effect

Figure 4. 14 Pareto chart of standardized effects

Figure 4. 15 Normal probability plot of residuals

Figure 4. 16 Residual versus fits

Figure 4. 17 Histogram of residuals

Figure 4. 18 Residual versus observation order

Figure 4. 19 Residual versus shape

Figure 4. 20 Residual versus size

Figure 4. 21 Residual versus turns

Figure 4. 22 Residual versus thickness

Figure 4. 23 Residuals versus material

Figure 4. 24 Residual versus range

It can be seen from the above figures after excluding the outlier values all of the plots have their regular behaviors. For example, for normal probability plot should approximately follow a straight line, which appears here. Residual versus fitted values should randomly be distributed along with the zero lines with no recognizable pattern

and no extreme values and this is found here. The histogram is a more normal curve after removing the outliers. There is no any specific trend or pattern for residual versus order that means residuals are independent to one another. Also, residual versus variables (factors) are more dispersed after removing the outliers.

4.3.3.2. Mean of response (Range) for individual factors

Figure 4. 25 Main effects plot for Range

Above figure explains the mean of range for individual factors. It can be seen that the shape and thickness do not have any major effect on the range. On the other hand, size is the biggest powerful factor, which is the positive standardized effect that is when the size has increased, the range is also increased. Interestingly, the number of turns has a negative standardized effect on the range. If the turns are increased or high the average range is decreased but for a lower turn the range is higher than that is found for the higher turns. The plot shows a very big difference when the aluminum material is selected rather than copper. But for this case, it can be said that most of the available industrial NFC antennas that were experimented were aluminum. As a result, in this case, we can ignore this result.

4.3.3.3. Interaction plot for response (Range)

Figure 4. 26 interaction plot for range

The interaction plots for the five factors are given here. Some concluding remark could be mentioned:

- Shape with other factors:** Large circular shapes have a greater range than large size rectangular antennas. The opposite is true for smaller sized antennas. Circular or rectangular shapes do not have an effect on either high or low number of turns. Same is applicable for shape and material interaction. Circular aluminum has much better performance than circular copper antennas, but rectangular aluminum or rectangular copper have almost similar performance.
- Size with other factors:** For all cases, if the size is bigger than the read range also increases. For smaller sized antennas, turns, thickness, and material's high or low value do not have any effect on the read range. For bigger sized antennas a low

number of turns have high performance than the high number of turns. Aluminum performs much better at the same size rather, copper has an almost equal performance for both the sizes.

- c) **Turns with other factors**: Performance of low turn and low thickness is better than high turn and high thickness. Low turn performs better for both aluminum and copper.
- d) **Thickness and material** do not have any interaction plot.

4.4. User survey experiment using NFC posters

A user survey experiment was done to get feedback and compare our etched antenna and the commercial antenna. A total of 22 users participated in this experiment.

4.4.1. Poster making

At this stage, we aim to test the tags with end-users. We fabricated two identical posters: poster A contains the commercial tag 'C' mentioned in table number TN, and poster B contains our fabricated best-performing tag (antenna 1 – 160x80 mm²) since it has a greater range compared to antenna 2. Both posters are introduced to the users so that they could interact with them using their phones.

Figure 4. 27 Back side of poster A and B

Figure 4. 28 (a) Cork sheet to attach the posters (b) Complete posters

4.4.2. Smartphone application development

Users were asked to use their smartphones to find the NFC tag. An Android app was developed to measure the duration of detecting NFC poster successfully. If the user has other than Android, we measured the timing using a stopwatch.

In Appendix B details of this Android app development is mentioned.

Figure 4. 29 Android User Interface

4.4.3. Conveying the survey

A total of 22 users participated in the survey. Finally, users were asked to fill out a survey form that consists of eight questions and it summarizes their experience about using the two posters. All the questions were mandatory for each user to fill-up the survey. The questions are listed below:

1. Have you ever used Near Field Communication (NFC) in anywhere before?

If 'Yes' where did you use it?
2. Make and model of your mobile phone?
3. Do you have any mobile phone cover when you used the posters?
4. Which NFC poster you think is detectable from a longer range, Poster A or Poster B?
5. Which poster do you think you got a quick response?
6. Which NFC poster you think is easy to detect, poster A or poster B?
7. Your rating for poster A? [From 1 to 10, where 1 is the lowest and 10 is highest]
8. Your rating for poste B? [From 1 to 10, where 1 is the lowest and 10 is highest]

When the survey is conveyed, the timing for each poster was also recorded using an Android app who had used Android phone. A stopwatch was used to get the time if the user had other than Android phone. Each users' timing is listed in Appendix C.

4.5. Result analysis

4.5.1. Analysis of key results from the factorial design

After removing three outliers from the first design of the experiment, the Pareto chart shows three terms contribute the most to the variability in the response ie. reading range. The highest significant effect on the range is the three interaction-level: BCD (from the figure), which is size*turns*thickness. Two-level interaction, CD (from the figure), turns*thickness is the second most significant value. The third most prominent term is the size that is one of the primary factors. As the p-values ≤ 0.05 of these three terms, it can be said that there is a statistically significant association between the response variable and the terms. The S value is measured that has the units of the response variable and represents how far the data values fall from the fitted values. The lower the value of S, the better the model describes the response. It has only 0.772368 which is very low. After removing the outliers, the residual plots were again observed and found all of them met the expected plots.

4.5.2. Comparison results

After measuring the distance of different industrial NFC antennas as described in section 3.5.3, if we consider only the reading distance as the only criteria for antenna performance, then, the best performing antenna is the 27, 28 number antenna, 24 number category among 32 categories as shown in figure number FN. The antennas have the best performing reading distance is 8.5 cm for LG G5 phone. But if we observe that, this is the NXP's ICODE IC [6] which is ISO 15693/ISO 18000-3 compliant

infrastructure IC. It requires a very low magnetic field intensity compared to other category and data transmission rate is also low. So, we can exclude this one.

Name [Antenna Number]	Antenna category	Experiment number	Standard	Phone	Reading range (cm)
A [27 or 28]	24	33	ISO 15693/ISO 18000-3	LG G5	8.5
B [29]	4	40	ISO 15693/ISO 18000-3	LG G5	7.3
C [31]	19	38	ISO 14443	LG G5	5.6

Table 4. 7 The best performing industrial antennas

The next best performing antenna is antenna C, its standard is the same as all other antennas ISO 14443 and the distance is found 5.6 cm. We can compare this with our own made antenna.

Antenna name	Standard	Phone	Range (cm)	Size
C	ISO 14443	LG G5	5.6	
Our antenna 1	ISO 14443	LG G5	8.1	160x80
Our antenna 2	ISO 14443	LG G5	5	80x80

Table 4. 8 Comparison of antennas

Clearly, it can be seen that our NFC antennas are better-performing antennas compared to all other industrial NFC antennas despite ignoring antenna material and other properties. So, if only copper is considered the performance of industrial ones are even worse than antenna 'B'. One of the main reason is that because of the antenna dimension and antenna parameters that is explained in full details in section 4.4.

4.5.3. User survey

We got the survey result from 22 users. There were eight questions related to user experience while using the posters. 14 users had smartphone cover and the other 8

users did not have. 9 users used Android phones and the other 11 users used iPhone. While experimenting, we also calculated the duration of NFC poster detection of each individual poster with individual users. The time was recorded and found that the average NFC detection time of the commercial tag was 4.25 seconds, whereas antenna 1 took an average time of 2.04 seconds to connect. The detailed timing for all of the users are given in Appendix C.

Figure 4. 30 User's rating (0 means lowest and 10 means highest) for posters A and B. Poster B that is our tag received a higher rating.

The figure shows the user's rating on the overall performance of both tag posters. Our flexible tag (poster B) received a distinctly higher rating compared to the commercial counterpart. The figure shows the results of two questions included in the survey. All the other survey result is listed in Appendix D. It can be observed that users were more satisfied with our flexible tag than the commercial one.

Figure 4. 31 Which poster (a) is detectable from a longer range (b) has a quick response (c) is easy to detect?

95.5% of users had experienced the longer detection range for poster B. 63.6% of the users believed that poster B had a quicker response. 77.3% of users easily detected poster B. All of the above results show the user experience while using the two identical posters.

Bibliography:

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5. CONCLUSION AND DISCUSSION

The thesis discussed the background of antennas that were fabricated on the flexible and soft material was discussed in various applications. The potential advantages of NFC and RFID usage and applications were mentioned. Preceding research work on RFID antenna on flexible material was also considered to represent the proof of concept. The fundamental operational principles, mathematical modeling, and equations for coil inductance calculation were also discussed. After that, the NFC antenna fabrication process and the factors that have the most substantial effect on the reading range were discussed. An experiment was conducted to discover which factors and their correlation between them have a significant effect on the reading distance. A comparison of our own NFC antenna and the best performing industrial antenna was also mentioned. A user survey was also conveyed to get a response from the user perspective.

5.1. Conclusion of the thesis

In this thesis, mathematical modeling, simulation, and fabrication of two NFC antennas on the flexible fiberglass were discussed in detail. A comparison of our best performing antenna with the industrial NFC antennas are made. It is observed that our NFC antennas are performing much better than the industrial available NFC antennas. One of the primary reasons is that the antennas are much longer than the traditional industrial available NFC antennas and this is supported utilizing the statistical factorial design methods where it can be seen that, size is one of the essential parameters on the read range.

5.2. Limitations of the work

While performing the experiments, there were some limitations and constraints. First of all, the NFC antennas we fabricated were only on fiberglass, and the conductor was copper. A combination of different substrates with different conductor materials is desirable for the experiments to come up to a generalized conclusion. Secondly, measuring the inductance value and resonating frequency with the impedance meter and PNA network analyzer requires much expertise to handle different situations. The factorial designing method was conducted on all of the industrial NFC antennas where most of the antennas were made with aluminum. The high and low levels on each parameter were based on the average values that were calculated using the approximate values because of the lack of datasheet of the available NFC antennas that we have. Most of the industrial antennas were made of aluminum while the factorial design was considered. Flexibility and bending test for the antennas have not experimented. Despite these limitations, this research guides us with a generalized design consideration of NFC antennas.

5.3. Future research

This research work could be further carried out by improving the limiting factors of the thesis. For example, a comparison of different NFC antennas fabricated to a different flexible substrate with different material could have experimented. Multiple NFC tag antennas covering a large area on the flexible material is another research area. For cost minimization, a single IC implementation with covering a large area should be considered. Antenna power circuitry may be considered for this research area. The

extent of the NFC antenna's design factors is another future research possibilities. For instance, the maximum or minimum factors such as length/width, the gap between turns, number of turns, different shapes, thickness for a specific material of a particular NFC IC to accurately detect the tag from an NFC reader or smartphone. On the other hand, research on NFC reader antenna is another research area.

APPENDICES

Appendix A

NXP® NFC tag IC solution is given in the below table [1]

NFC TAG IC SOLUTIONS					
NFC Forum compliance	Type 2 Tag	Type 2 Tag	Type 2 Tag	Type 4 Tag	Type 5 Tag
ISO/IEC standard compliance	ISO/IEC 14443-3A	ISO/IEC 14443-3A	ISO/IEC 14443-3A	ISO/IEC 14443-4A	ISO/IEC 15693
Input capacitance [pF]	50	50	50	70	23.5
NFC tag type baudrate [kbit/s]	106	106	106	106	26.5 (up to 53)
PRODUCT	NTAG®	NTAG F	NTAG I^{PC} plus	NTAG 413 DNA	ICODE
Product description	Passive NFC tag for smart inlays, labels and tags	Passive NFC tag with field-detection output signal	Passive NFC tag with I ^{PC} interface, energy harvesting, password protection, originality check and high pass-through mode	Passive NFC tag with AES authentication and SUN feature	Passive NFC tag for smart inlays, labels and tags
Product name	NTAG 213/215/216	NTAG 213F/216F	NTAG I ^{PC} plus 1k/2k	NTAG 413 DNA	ICODE SLIX 2
User memory [Bytes]	144/504/888	144/888	888/1912	160	316
SRAM [Bytes]	-	-	64	-	-
Operating distance up to [mm] ⁽¹⁾	100	100	100	100	1500
Package	Wafer, MOA8	Wafer, HXSON4	Wafer, XQFN8, TSSOP8, SO8	Wafer	Wafer, SOT1122, MOA8
Temperature range [°C]	-25 to +70	-25 to +70	-40 to +105	-25 to +70	-40 to +85
Energy harvesting [mW]	-	-	up to 15	-	-
RF Silence	-	via FD pin	via config bit	-	-
Field-detection signal output	-	Yes	Yes	-	-
Pass-through mode using SRAM	-	-	Yes	-	-
Host interface	-	-	I ^{PC}	-	-
Clock frequency [kHz]	-	-	100/400	-	-
Supply voltage host interface [V]	-	-	1.67 to 3.6	-	-
Security features					
UID ASCII mirror & NFC counter ASCII mirror	Yes	Yes	-	Yes, plus CMAC	-
Authentication via ECC	Yes	Yes	Yes	Yes	Yes
Access keys	32 bit	32 bit	32 bit	3 x AES 128 bit	32 bit
Read/Write protection	NFC	NFC	I ^{PC} /NFC	NFC	NFC
Password authentication counter	Yes	Yes	Yes	Yes	-
Product support & ordering information					
Product type	213: NT2H1311G 215: NT2H1511G 216: NT2H1611G	213F: NT2H1311F 216F: NT2H1611F	1k: NT3H2111 2k: NT3H2211	NT4H1321G	SL252602
12NC	MOA8: 213: 9353 046 24118 215: 9353 046 25118 216: 9353 046 26118	HXSON4: 213F: 9353 015 88125 216F: 9353 000 51125	XQFN8: 1k: 9353 069 39125 2k: 9353 069 43125	Wafer 75µm: 9353 515 45005	MOA8: 9353 083 52118
	Wafer 120µm: 213: 9352 999 12005 215: 9352 999 27005 216: 9352 999 29005	Wafer 120µm: 213F: 9353 015 87005 216F: 9353 009 52005	TSSOP8: 1k: 9353 069 32118 2k: 9353 069 33118	Wafer 120µm: 9353 473 47005	SOT1122: 9353 080 29115
	-	-	SO8: 1k: 9353 070 09115 2k: 9353 070 16115	-	Wafer 120µm: 9353 073 26003
	-	-	Wafer 150µm: 1k: 9353 069 56005 2k: 9353 069 57005	-	-
	-	-	15 years (NTAG I ^{PC} plus 2k)	-	-
Product longevity program	-	-	-	-	-
Development boards	-	NTAGFCL6 9353 045 64699	OM5569/NT322E 9353 078 49699	-	-
	-	NTAGFCL5LED 9353 045 68699	OM5569/NT322ER 9353 078 48699	-	-
	-	-	OM23221ARD 9353 393 71598	-	-
Software	Android™: NFC TagInfo, TapLinX iOS: NFC TagInfo by NXP PC: TagXplorer		Binaries and source code for Windows® and Android™ applications, Peek & Poke GUI, LPCXpresso controller FW example, Bluetooth pairing example based on NXP KW4412, TapLinX, Android™ app.	Android™: NFC TagInfo, TapLinX iOS: NFC TagInfo by NXP PC: TagXplorer	

Table A. 1 NXP® NFC tag IC solution

List of references:

[1] “NXP ® NFC and Contactless Reader Solutions NFC TAG IC SOLUTIONS.”

Appendix B

The Android code is given for determining the time required to detect an NFC poster.

A helper class ‘*NfcHelper*’ is used for the easy implementation.

```
public class MainActivity extends AppCompatActivity {

    private NfcAdapter nfcAdapter;
    NfcHelper nfcHelper;

    // For timing things
    TextView timer ;
    Button start, pause, reset;
    long MillisecondTime, StartTime, TimeBuff, UpdateTime = 0L ;
    Handler handler;
    int Seconds, Minutes, MilliSeconds ;

    @Override
    protected void onCreate(Bundle savedInstanceState) {
        super.onCreate(savedInstanceState);
        setContentView(R.layout.activity_main);
        nfcAdapter = NfcAdapter.getDefaultAdapter(this);
        nfcHelper = new NfcHelper(this);

        if (!nfcHelper.isNfcEnabledDevice()) {
            //Dialog for Alert Device has no NFC feature
            showNoNFCDeviceAlertDialog();
        } else {
            if (!nfcHelper.isNfcEnabled()) {
                //Dialog for NFC Enable settings
                showEnableNFCAlertDialog();
            }
        }

        // For timing things:

        timer = (TextView) findViewById(R.id.tvTimer);
        start = (Button) findViewById(R.id.btStart);
        pause = (Button) findViewById(R.id.btPause);
        reset = (Button) findViewById(R.id.btReset);
        handler = new Handler() ;

        start.setOnClickListener(new View.OnClickListener() {
            @Override
            public void onClick(View view) {

                StartTime = SystemClock.uptimeMillis();
                handler.postDelayed(runnable, 0);

                reset.setEnabled(false);

            }
        });

        pause.setOnClickListener(new View.OnClickListener() {
            @Override
            public void onClick(View view) {

                TimeBuff += MillisecondTime;

                handler.removeCallbacks(runnable);

                reset.setEnabled(true);

            }
        });
    }
}
```



```

        reset.setOnClickListener(new View.OnClickListener() {
            @Override
            public void onClick(View view) {

                MillisecondTime = 0L ;
                StartTime = 0L ;
                TimeBuff = 0L ;
                UpdateTime = 0L ;
                Seconds = 0 ;
                Minutes = 0 ;
                MilliSeconds = 0 ;

                timer.setText("00:00:00");

            }
        });

    }

    // For timing things
    public Runnable runnable = new Runnable() {

        public void run() {

            MillisecondTime = SystemClock.uptimeMillis() - StartTime;

            UpdateTime = TimeBuff + MillisecondTime;

            Seconds = (int) (UpdateTime / 1000);

            Minutes = Seconds / 60;

            Seconds = Seconds % 60;

            MilliSeconds = (int) (UpdateTime % 1000);

            timer.setText("" + Minutes + ":"
                + String.format("%02d", Seconds) + ":"
                + String.format("%03d", MilliSeconds));

            handler.postDelayed(this, 0);

        }

    };

    private void showEnableNFCAlertDialog() {
        AlertDialog.Builder alertDialog = new AlertDialog.Builder(this);
        alertDialog.setTitle("Enable NFC");
        alertDialog.setMessage("Would you like to enable NFC? Select NFC Settings");
        alertDialog.setPositiveButton("NFC Settings", new
            DialogInterface.OnClickListener() {
                @Override
                public void onClick(DialogInterface dialogInterface, int which)
            {
                if (Build.VERSION.SDK_INT >= Build.VERSION_CODES.JELLY_BEAN)
            {
                Intent intent = new
            Intent(Settings.ACTION_NFC_SETTINGS);
                startActivity(intent);
            }
            else {
                Intent intent = new
            Intent(Settings.ACTION_WIRELESS_SETTINGS);
                startActivity(intent);
            }
            }
        });
        alertDialog.setNegativeButton("Close", new DialogInterface.OnClickListener()
        {
            @Override

```

```

        public void onClick(DialogInterface dialogInterface, int which) {

            return;
        }
    });
    alertDialog.show();
}

private void showNonNFCDeviceAlertDialog() {
    AlertDialog.Builder alertDialog = new AlertDialog.Builder(this);
    alertDialog.setTitle("NFC Error!!");
    alertDialog.setMessage("Your Device Has No NFC Feature, Please Upgrade Your Device");
    alertDialog.setNegativeButton("Close", new DialogInterface.OnClickListener()
    {
        @Override
        public void onClick(DialogInterface dialogInterface, int which) {

            return;
        }
    });
    alertDialog.show();
}

@Override
protected void onNewIntent(Intent intent) {
    Toast.makeText(this, "NFC intent received", Toast.LENGTH_SHORT).
        show();
    super.onNewIntent(intent);

    TimeBuff += MillisecondTime;

    handler.removeCallbacks(runnable);

    reset.setEnabled(true);
}

@Override
protected void onResume() {
    super.onResume();

    Intent intent = new Intent(this, MainActivity.class).
        addFlags(Intent.FLAG_RECEIVER_REPLACE_PENDING);
    PendingIntent pendingIntent = PendingIntent.getActivity(this, 0,
        intent, 0);
    IntentFilter[] intentFilter = new IntentFilter[] { };
    nfcAdapter.enableForegroundDispatch(this, pendingIntent,
        intentFilter, null);
}

@Override
protected void onPause() {
    super.onPause();
    nfcAdapter.disableForegroundDispatch(this);
}
}

```

Appendix C

User ID	Time for Poster A	Time for Poster B
1	19.284	3.134
2	19.763	0.918
3	2.31	2.17
4	61.22	61.63
5	8.666	1.692
6	1.375	1.153
7	5.33	1.92
8	3.458	0.9
9	9.133	4.585
10	4.28	1.72
11	1.753	1.568
12	2.13	1.9
13	6.51	1.78
14	6.76	1.92
15	2.43	1.33
16	1.37	1.866
17	4.22	1.95
18	6.82	4.42
19	2.89	2.999
20	3.17	2.175
21	2.97	1.28
22	3.17	1.53

Table A. 2 Timing to detect poster A and B

Appendix D

Figure A. 1 Question 1

If 'Yes', where did you use it?

13 responses

Figure A. 2 Question 2

3. Do you have any mobile phone cover when you used the posters?

22 responses

Figure A. 3 Question 3

Question 4. Which NFC poster you think is detectable from a longer range, Poster A or Poster B?

Poster A Poster B

Figure A. 4 Question 4

5. Which poster do you think you got a quick response?

22 responses

Figure A. 5 Question 5

6. Which NFC poster you think is easy to detect, poster A or poster B?

22 responses

Figure A. 6 Question 6

7. Your rating for poster A

22 responses

Figure A. 7 Question 7

8. Your rating for poster B

22 responses

Figure A. 8 Question 8

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