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Investigation of inductively coupled RFID systems compatibility in proximity to metals

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INVESTIGATION OF INDUCTIVELY COUPLED RFID SYSTEMS COMPATIBILITY IN PROXIMITY TO METALS

By Natkeeran Ledchumikanthan, B.Eng (Ryerson).

A project presented to Ryerson University in partial fulfillment of the requirements for the degree of Master of Engineering in the Program of Electrical and Computer Engineering.

Toronto, Ontario, Canada, 2007

Author's Declaration Page

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Abstract

The high frequencies range, inductively coupled Radio Frequency Identification (RFID) systems are widely used for product identification. The effectiveness of RFID systems diminishes near metals. The objective of this work was to investigate how the magnetic field values were affected by the metallic disc, and how the physical parameters of the metal impact the electromagnetic values. The RFID system simulation models consisting of a reader coil, a circular metallic disc and a tag coil were developed using COMSOL software. The flux at different positions over the disc was compared to the flux at the same positions when the disc was not present, for discs of different radius and thickness. For models developed, the ratio of electric field when metal is present to electric field when metal is not present increased away from the metal. The radius and position where values are recorded impact the value of the magnetic field notably.

Acknowledgement

I primarily want to thank my supervisor Dr. Farah Mohammadi for having provided the opportunity to work with her in this project. She has continuously challenged, engaged, and advised me on this project. Without her understanding and guidance, it would have been difficult to come this far.

I also would like to thank my family for continuous support they provided throughout this project.

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1 Chapter: Introduction

Radio Frequency IDentification (RFID) is a method of storing and retrieving information using electromagnetic waves of radio frequency range [1]. An RFID system typically consists of a tag, a reader and a processing system. Data is embedded in the RFID tag, and when sensed by the RFID reader, the tag relays the data to the reader. The processing system processes the data received by the reader according to application requirements. RFID technology has a range of applications including tracking, identification, data logging and communication. An important area of RFID application is the retail industry. The RFID technology is being widely adapted by the retail industry to uniquely identify and track each product from manufacturing to checkout. The industry is shifting from the current Universal Product Code (UPC) to RFID based Electronic Product Code (EPC). The technology is expected to result in labour efficiency, better product and business management, thus providing for an overall cost effectiveness for consumers and businesses.

The retail industry is widely adopting RFID based EPC; however, there are limitations in the application of RFID systems. One particular scenario where the deployment of RFID systems becomes problematic is in commercial liquid packaging. The packing contains layers of plastic, paper and metallic items as shown in the Figure 1. The product can vary, and the tag must be placed on the product.

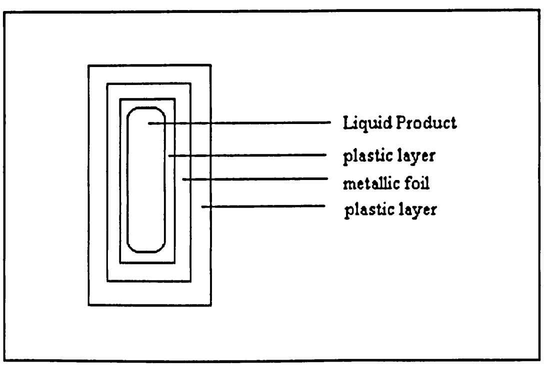


Figure 1: Commercial Liquid Packaging

The RFID systems have reduced reliability near the metals. This is due to "the decrease in read range at perpendicular incidence in close proximity to metals or dielectrics (such as water), due to the decrease in electric field near the surface required to meet the boundary conditions" [3]. The near range RFID systems are tuned to or optimized to operate at resonant frequency. The optimization is done by impedance matching. Metals change the impedance of the RFID system. This offsets the resonant frequency or the optimum design frequency.

Metals in the vicinity cause eddy currents, which absorbs RFID energy, "thus reducing the overall effectiveness of the RFID field. These eddy currents also create their own magnetic field that is perpendicular to the metal surface. This perpendicular magnetic field "cancels" the reader field" [4]. This project focuses on these limitations of the RFID system.

1.1 Project Objectives

As noted above, the RFID systems are less reliable in the vicinity of metals. While literature identifies several causes such as eddy currents, the electromagnetic background and how exactly metals impact the RFID tags or systems is not fully understood [5]. The general objective of this project is to investigate how metals impact the magnetic field, and thus the performance of the tag. It will focus on how eddy currents can be taken into consideration in the RFID System model. While various geometric configurations of the metallic foil layer are possible, the study will restrict itself to the geometric configuration as seen in Figure 2.

The aims were to model the inductive coupling operating principle behind RFID systems in the context of Figure 2 geometry, and to do simulation to study the electromagnetic behavior (determining the electric field values) for different sizes of the metallic discs.

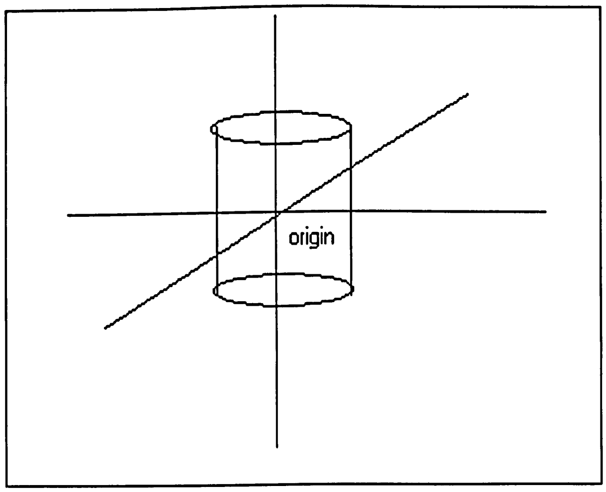


Figure 2: Geometric configuration of the metal – a cylindrical disc (Also see Figure 14)

1.2 Project Outline

In this research we have provided coverage of important subjects required for study of RFID systems compatibility in the vicinity of metals. Therefore, it focuses on the key issue of unreliability or degraded performance of RFID systems near metals.

The first four chapters are designed to present the fundamental building blocks for RFID system simulation. Chapter 2 discusses a general introduction to electromagnetic theory. Chapter 3 discusses the system components of typical RFID systems, classifies the systems, and outlines the physical principals upon which RFID systems are based.

Chapter 4 highlights the various applications, and limitations of the RFID System. Chapter 5 reviews approaches to RFID modeling found in the literature. The available methodologies to solve the governing electromagnetic equations are elaborated in this chapter. Then it briefly outlines the criteria for an RFID model in relation to the thesis. In trying to take the eddy current into the model, various methods of calculating eddy currents are discussed.

The development of a finite element electromagnetic model to perform analysis of RFID system compatibility in the vicinity of metals to predict magnetic field distribution using finite element model has been described in Chapter 6.

The degradation in performance of RFID systems near metals is examined through comprehensive simulation as well as analysis of the results for various configurations in chapter 7. This chapter also provides the results of the parametric study. Finally, the conclusions and suggested future works are summarized in chapter 8.

2 Chapter: Electromagnetic Theory

In this chapter an overview of the fundamental Electromagnetic theory is provided. RFID theory and technology drives from the electromagnetic theory, and an understanding of electromagnetic theory is essential to understanding RFID theory and technology. In addition, antenna theory is also reviewed since it is an important component of the RFID System.

2.1 Electromagnetic Field Theory

2.1.1 Maxwell Equations

Four Maxwell equations establish the fundamental nature of electromagnetic waves. They are as follows:
Electric field from magnetic flux density (Faraday's Law):

$$\nabla \times \vec{E} = -\frac{\overrightarrow{dB}}{\overrightarrow{dt}}$$

Magnetic field from electric flux density (Ampere's Law):

$$\nabla \times \vec{H} = \vec{J} + \frac{\overrightarrow{dD}}{dt}$$

Gauss Law:

$$\nabla \bullet \vec{D} = \rho$$

No magnetic charges:

$$\nabla \bullet \vec{B} = 0$$

Where
$\vec{E}$ - Electric Field Intensity (V/C)
$\vec{D}$ - Electric Flux Density (C/m^2)
ψ - Electric Flux (C)
$\vec{B}$ - Magnetic Flux Density (Wb/m^2)
$\vec{H}$ - Volume Current Density (A/m)
ψ - Magnetic Flux (T)
ρ - Electric Charge Density (C/m^3)
$\vec{J}$ - Volume Current Density (A/m^2)
t - time
dx - small change

The important contribution by Maxwell is introducing the ~ J into equation 3. The relationship is expressed by the Continuity Equation, which expresses the Law of Conservation of Charges.

$$\nabla \cdot \vec{J} + \overrightarrow{\frac{d\rho}{dt}} = 0$$

The current equation $i = \overrightarrow{\frac{dq}{dt}}$ is important.

The relationship between Electric Field Intensity and Electric Flux Density for most practical purposes can be defined by the following equation.

$$\vec{D} = \varepsilon \vec{E}$$

where ε = permittivity

Similarly, the relationship between Magnetic Field Intensity and Magnetic Flux Density can be defined as:

$$\vec{B} = \mu \vec{H}$$

where μ = permeability

Electromagnetic waves can be described as a function of space and time as $\overrightarrow{EM} = f(x, y, z, t)$. Generally, the analysis involves electromagnetic waves moving in one dimension, thus the equation becomes $\overrightarrow{EM} = f(z, t)$ [6]. As noted before, electromagnetic waves can be described in terms of electric and magnetic wave components. It is analogous to describing a line vector in plane using its x and y components.

2.1.2 Electric and magnetic vortex interpretation

Electric current causes magnetic vortex. Electric field vector E can have vortices caused by changing magnetic flux. Also, electric flux density can have sources caused by conduction charge density, and magnetic flux density can have no sources. Illustrations of electrostatic field sources and vortex nature of a magneto dynamic field are shown in Figure 3 and Figure 4.

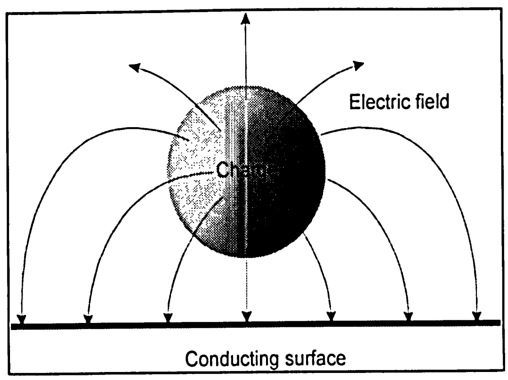


Figure 3: Electric field near a conducting surface;

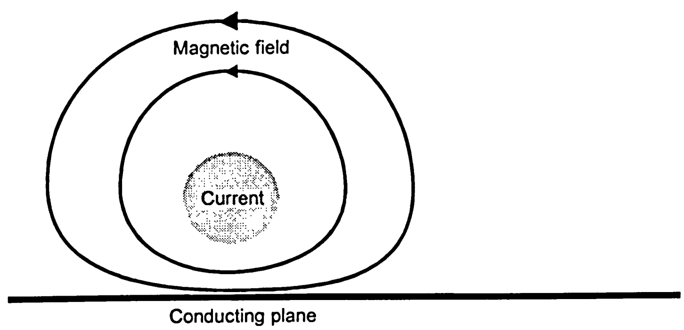


Figure 4: Oscillating magnetic field near a conducting surface (Note the vortex nature of the magnetic field)

2.1.3 Boundary Conditions

There are four mediums through which EM waves travel. The four mediums are as follows:

1. Free space ($\sigma = 0$, $\varepsilon = \varepsilon_0$, $\mu = \mu_0$)
2. Lossless dielectrics ($\sigma = 0$, $\varepsilon = \varepsilon$, $\mu = \mu$)
3. Lossy dielectrics ($\sigma \neq 0$, $\varepsilon = \varepsilon$, $\mu = \mu$)
4. Good conductors ($\sigma = \infty$, $\varepsilon = \varepsilon_0$, $\mu = \mu$)

When EM waves cross the boundaries of different mediums their behavior does change. The way the behavior changes is governed by the following four equations:

$$\overrightarrow{E_{1t}} - \overrightarrow{E_{2t}} = 0$$
$$\overrightarrow{D_{1n}} - \overrightarrow{D_{2n}} = \rho_s$$
$$\overrightarrow{H_{1t}} - \overrightarrow{H_{2t}} = \overrightarrow{J_s} \times \overrightarrow{a_n}$$
$$\overrightarrow{B_{1n}} - \overrightarrow{B_{2n}} = 0$$

Note that Electric fields tangential component does not change as the EM waves travel from one medium to another. However, the normal component does change. If we assume there are no external charges at the boundary, that is $\rho_s = 0$, then the relationship of the normal component would be $\overrightarrow{E_{1n}} = \frac{\varepsilon_2}{\varepsilon_1}\overrightarrow{E_{2n}}$. Furthermore, the tangential component of the magnetic field does not change, assuming $\overrightarrow{J_s} = 0$. The normal component is related as $\overrightarrow{H_{1n}} = \frac{\mu_2}{\mu_1}\overrightarrow{H_{2n}}$.

2.1.4 Poynting Vector

As the wave travels, we are interested in its direction. Also, we are interested in its energy. Poynting Vector points in the direction the EM wave travels, and helps us to determine the energy. The Poynting Vector is defined as: $\vec{P} \equiv \vec{E} \times \vec{H}$.

Note that the above is only a definition and not an equation. If the electric field and magnetic field have the same frequency, then the Poynting Vector becomes: complex $\vec{P} \equiv \vec{E} \times \vec{H}^*$.

The direction of electromagnetic wave is termed the direction of propagation of the wave. Propagation of the wave is pointed by the Poynting Vector. Also, the direction of time varying electric field is wave polarization. The plane of polarization is defined as the plane that contains the electric field and the axis of propagation. A uniform plane wave can be defined as follows: $e^i = |e|\cos(wt - \vec{k} \cdot \vec{r})\overrightarrow{ar}$, where direction of propagation is $\vec{r}$.

2.1.5 Polarization

Polarization is similar to filtration. Polarization refers to electric field pointing in the same direction. The type of polarization is determined by the angular pointing of the electromagnetic field. If electric field only consists of one component then it is linearly polarized (horizontal or vertical). If the electric field consists of two plane waves differed by 90 degrees difference (and equal amplitudes), then it is circular polarization. If the electric field consists of two planes that differ by other than 90 degrees, that is said to be elliptical polarization.

2.2 Wave Equations

Wave equations are partial differential equations that describe the nature of electromagnetic waves. The wave equations can be derived from the fundamental Maxwell laws. The concepts of phasors and vector identities are useful in simplifying the derivation. Depending on the medium the final form of the wave equations would differ. For lossless, source free, linear, homogeneous, isotropic, and time invariant medium the wave equation can be traced as follows:

$$\nabla \times \nabla \times \vec{E} = -jw\mu(\nabla \times \vec{H})$$
$$\nabla^2 \vec{E} + B^2 \vec{E} = 0$$

From the above equation, for uniform plane waves propagating along the z direction the wave equation is derived to be the following:

$$\frac{d^2 E_x}{dz^2} + B^2 E_x = 0$$

Note that uniform plane wave implies that Electric field only has one component.
That is $E(x,y,z) = E_x(z)\overrightarrow{a_x}$. The general solution to the above differential equation is:

$$E_x(z,t) = C_1 \cos(wt - Bz) + C_2 \cos(wt + Bz).$$

Considering only the EM wave traveling in the positive z direction the electric field can be defined as follows:

$$E_x(z,t) = C_1 \cos(wt - Bz)$$
$$H_y(z,t) = \frac{1}{\eta} C_1 \cos(wt - Bz)$$

Similarly, for LOSSY medium the wave equation lead to the following magnetic field equation:

$$H_y(z,t) = \frac{C_1}{\eta} e^{-\alpha z} \cos(wt - Bz)$$

2.2.1 Physical Visualization and Interpretation of Waves

Electric and magnetic fields are produced by time-varying currents and charges. If these fields are confined by boundary conditions, as in the case of a waveguide, there is little or no radiation. However, when the fields are not confined, as with an antenna, significant radiation results [8].

The above discussion and derivation of the wave equations and their general solution were restricted to uniform plane waves. Uniform plane wave means that electric field will only consist of x component. That is $E(x,y,z) = E_x(z)\overrightarrow{a_x}$. That is the electric field may vary in the z direction, it is independent of influence from x and y directions. This implies that electric field will be polarized, meaning the electric field points in one direction. Most of our analysis can be reduced to these type waves.

2.3 Infinitesimal dipole fields

2.3.1 Electric dipole

In spherical polar coordinates at a point $P(r,\theta,\phi)$ the non-zero field components of an oscillating small electric dipole of length L carrying a current I and of moment P where $j\omega P = IL$ are

$$E_r = \frac{\beta^2 j\omega P\eta}{4\pi}\left(\frac{2}{(\beta r)^2} - \frac{2j}{(\beta r)^3}\right)e^{-j\beta r}\cos\theta$$

$$E_\theta = \frac{\beta^2 j\omega P\eta}{4\pi}\left(\frac{j}{(\beta r)} + \frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3}\right)e^{-j\beta r}\sin\theta$$

$$H_\phi = \frac{\beta^2 j\omega P}{4\pi}\left(\frac{j}{(\beta r)} + \frac{1}{(\beta r)^2}\right)e^{-j\beta r}\sin\theta$$

2.3.2 Magnetic Dipole

In spherical polar coordinates at a point $P(r,\theta,\phi)$ the non-zero field components of an oscillating small magnetic dipole of moment $M = IA$ are the following:

$$H_r = \frac{\beta^2 j\omega\mu_0 M}{4\pi\eta}\left(\frac{2}{(\beta r)^2} - \frac{2j}{(\beta r)^3}\right)e^{-j\beta r}\cos\theta$$

$$H_\theta = \frac{\beta^2 j\omega\mu_0 M}{4\pi\eta}\left(\frac{j}{(\beta r)} + \frac{1}{(\beta r)^2} - \frac{j}{(\beta r)^3}\right)e^{-j\beta r}\sin\theta$$

$$E_\phi = \frac{\beta^2 j\omega\mu_0 M}{4\pi}\left(\frac{j}{(\beta r)} + \frac{1}{(\beta r)^2}\right)e^{-j\beta r}\sin\theta$$

2.3.3 Characteristics of near and far fields

The above expressions show that the distance $r = 1/\beta = \lambda/(2\pi)$ is of significance in determining the nature of the fields surrounding the dipoles. Within this distance the dominant fields may be recognized as being the same as the energy storage fields with which we are familiar for electrostatic or magnetostatic dipoles. This region is known as the near-field region, and the dominant fields therein are called the near fields, and simply store energy that periodically emerges from, and later disappears back into, the dipole. Outside of this distance, the dominant fields are those associated with energy propagation by electromagnetic waves away from the sources. This region is known as the far-field region, and the dominant fields therein are called the far fields, and transport energy continuously away from the dipoles.

2.4 Antennas: Concepts, Parameters, Types

Antennas are key devices in any RFID system as part of transmitters and receivers. In addition, antennas have wide ranging applications in communications, navigation, instrumentation, radar systems, and radio astronomy. The electromagnetic waves generated by transmitters get propagated by the antennas. When antennas are placed in the electromagnetic field they get induced with alternative current, and an electromotive force between its terminals. In other words, antennas act as coupling or connecting devices between the EM waveguides (transmission lines) and wireless EM waves. In converting from EM waves from transmission cables to radiated EM waves and vice versa the antenna can be said to be a transducer.[7]

How are EM waves transmitted by the antennas? "Electric and magnetic fields are produced by time-varying currents and charges. If these fields are confined by boundary conditions, as in the case of a waveguide, there is little or no radiation. However, when the fields are not confined as with an antenna, significant radiation results [8]". Accordingly, certain conditions need to be met for EM waves to be transmitted by an antenna. Frequency and the type of material used in the antenna are two parameters in determining those conditions. Maxwell equations further establish the theoretical conditions.

How do EM waves propagated by the antennas reach the intended receivers? The answer to this question involves the properties of EM waves described by Maxwell equations, as discussed earlier. In particular, depending on frequency, EM waves can penetrate various materials without being attenuated or being converted to heat [9]. In facing insulating material, the EM waves can propagate around it as water flow would propagate a block.

Antennas are characterized as two port devices. They exhibit the reciprocal property. That is the transmitting and receiving parameters of antennas are same, and they can be used as such.

2.4.1 Antenna Parameters

There are various types of antennas, designed to operate at different frequencies and purposes. There are various parameters that characterize antennas. Among them radiation pattern and impedance are two key parameters. The following lists various parameters involved in antenna analysis and design [10].

1. Physical Setup (type of material, antenna shape, physical dimension relative to wavelength)
2. Radiation Pattern (E Magnitude, Phase pattern, Polarization pattern)
3. Impedance

4. Radiation Resistance
5. Gain (Directive Gain, Directivity, Gain References)
6. Beam Width (major lobes, side lobes)
8. Efficiency
9. Bandwidth
10. Polarization

2.4.2 Basic Antennas

Elemental Dipole Antenna

Hertizian or Elemental Dipole antenna refers to a theoretical short current element I dl. Practically, elemental dipole does not exist, but longer antennas can be analyzed using elemental antennas. The electric field (in the far region), the radiation resistance, and power dissipated can be analytically analyzed.

Half-wave Dipole

A half wave dipole antenna has a length half the wave length of the EM wave that it is designed to radiate. Half-wave dipole is analyzed by considering them as elemental dipole antennas placed end to end.

Quarter-wave Monopole Dipole

A quarter-wave monopole dipole "consists of one-half of half-wave dipole antenna located on a conducting ground plane [6]." Compared to half-wave dipole its radiation resistance is about half, and it radiates half as much power for the same current. The advantage of quarter-wave monopole is that it has more directivity.

Small Loop Antenna

Small loop antennas are loop antennas with about 0.15 wavelength circumference. Small loop antennas are useful when directivity is important, in eliminating unwanted signals and noise, and when limited by physical requirements. It operates for upper high frequency range (TV waves). Loops can take circular, square, rectangular, hexagonal or octagonal shapes.

3 Chapter: RFID Systems

Chapter 3 discusses the system components of typical RFID systems, classifies the systems, and outlines the physical principals upon which RFID systems are based.

3.1 RFID System Overview

A basic RFID System consists of the following three components: RFID Tag, RFID Reader, and the Processing System. Data is embedded in the RFID Tag, and when sensed by the RFID Reader the Tag relays the data to the Reader. Physically, the tag is an electronic circuit chip and an antenna. RFID Reader is a transceiver, which continuously searches for RFID Tag. When the Tag is scanned in or detected, the data is received and relayed to the Processing System. The communication between Tag and the Reader is based on electromagnetic signals. The information received from the Reader is processed and acted upon by the Processing System.

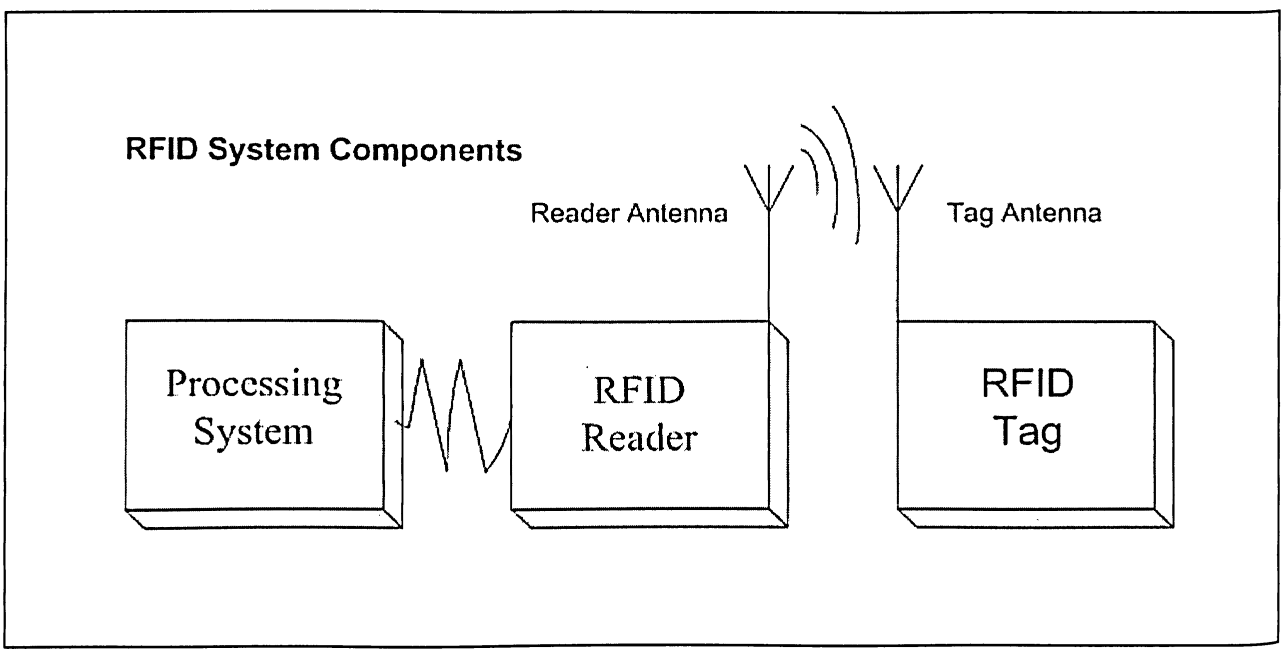


Figure 5: Basic System Components

3.1.1 RFID Tag

A RFID tag consists of an electronic chip and antenna; both of which are mounted on some substrate. Depending on the source of the power supply, the tags are classified as active or passive. Active tags contain their own power source, and passive tags are purely powered by the signals from the reader. Active/passive tags in the high frequency (HF - 13.56 MHz) may have their own power supply, to provide for high data transfer and support additional features. Most passive tags are Read-Only. There are also Write-Once-Read-Many times (WORM), and Read-Write tags.

The tag microchip consists of an AC to DC power converter, modulator, memory, logic unit, and clock extractor. The EM signal power from the Reader is converted to DC power by the converter. The modulator imbeds the digital information into the carrier EM signal.

The tags antenna provides power (by sensing the Reader signal), and relays the EM signals. Depending on the manufacturing and type of the Tag, the microchip and antenna may be printed on the same substrate or be separate. If separate, "attachment technologies" such as 'pick and place' and 'fluidic self assembly' are used to connect them. The Tag's antenna is sensitive to the natural frequency or the resonance frequency of the Tag. The Readers sends its signal at that particular frequency, when the match occurs the communication ensures.

3.1.2 RFID Reader

The main function of an RFID Reader is to recognize the Tags within a defined region. The Reader sends an EM signal at the resonance frequency, and listens to changes in the send signal when Tags are detected. Thus the Reader consists of a transmitting section and a receiving section. The transmitting section has an oscillator (carrier frequency/resonance frequency generator), modulator, an amplifier and an antenna circuit. The receiving section consists of filter/amplifier, demodulator or decoder and the microprocessor. The reader also contains battery to provide for the signal processing [11].

Contemporary design of the Reader uses DSP chip for signal processing (modulation, demodulation, waveform shaping, signal generation), and a general processor for data manipulation, storage, query and networking. Both of these are often integrated into a single chip. An example of RFID Reader is the Texas Instruments TRF7960 IC based Reader.

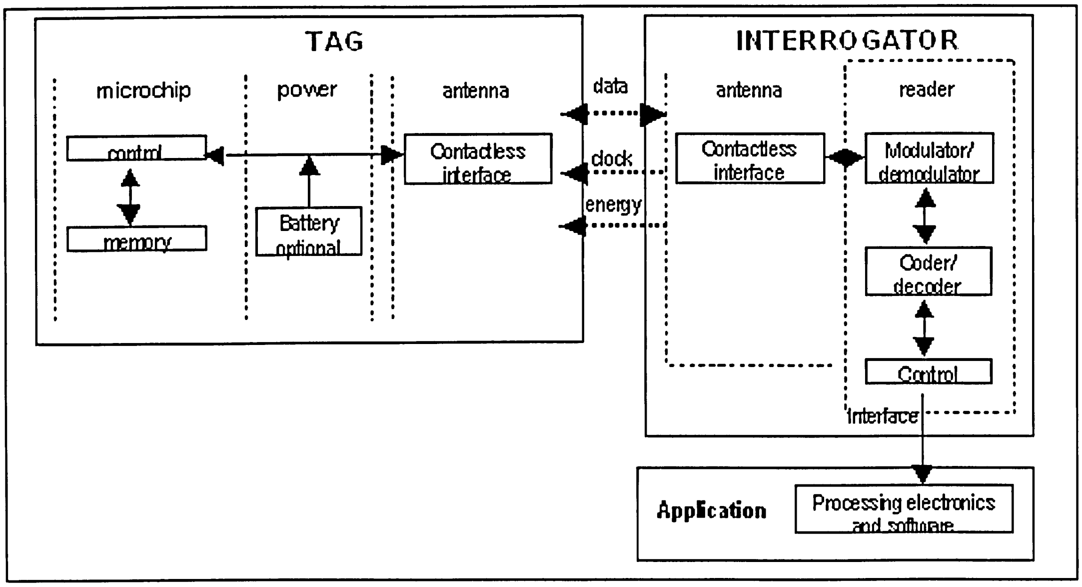


Figure 6: System Overview [12]

3.2 Classification of RFID Systems

RFID Systems can be classified according to their functional characteristics. Frequency, type of wireless communication methods, and power supply are three main defining characteristics of RFID Systems. An application's requirements determine the characteristics of a RFID system. Also, when selecting an RFID system one should take the competing standards and market products into consideration.

3.2.1 Frequency

RFID Systems use the unlicensed radio frequency bands called ISM (Industrial, Scientific, and Medical). The RFID systems operate in four classes of frequencies: Low Frequencies

(LF), High Frequencies (HF), Ultra High Frequencies (UHF), and Microwave Frequencies. The frequencies mainly restrict the range of RFID systems.

Low Frequency

The Low Frequency (LF) range is from 30 kHz to 300 kHz. Typical LF RFID Systems operate at 125 kHz and 134.2 kHz , and 135 kHz. The International Standard Organizations (ISO) has standards for Tags, Readers, and Processing Methods. They are ISO 11785 and ISO 14223 for 134.2 kHz, and ISO 18000-2 for 135 kHz. The LF systems use inductive coupling as the operating principle. A notable feature of LF RFID systems is that they are not affected by metallic items near the Tags, and can penetrate through most materials. However, they are short range and usually handle one tag at a time.

High Frequency

The 13.56 MHz is the globally accepted High Frequency (HF) standard. There are two ISO standards at this frequency, both of which use inductive coupling as the operating principle. They are ISO 14443 and ISO 15683. Compared to LF, the Tags are of low cost, have higher reach, and multiple Tags can be read simultaneously. The HF signals can penetrate most materials; however, it is affected more by metals in the environment.

Ultra High Frequency

The Ultra High Frequency (UHF) range is from 300 MHz to 1GHz. The UHF RFID Systems use wave propagation as the electromagnetic communication method, which is different from the inductive coupling used by LF and HF systems. Usually, UHF systems use active Tags, and can provide high data rate. The Reader can process multiple Tags (up to 200), and work over much greater distance than HF systems.

Microwave Frequency

The microwave frequencies are of the range above 1GHz. The North American standard is 2.45 GHz or 5.8 GHz. Generally, these RFID systems provide longer reach, higher data transfer, and higher number multiple Tag reads compared to other frequencies. However, the cost of these systems is notably higher.

3.2.1 EM Communication Methods

All RFID systems use electromagnetic signal communication. The two types of electromagnetic signal communications are inductive coupling and wave propagation coupling. The inductive coupling corresponds to near field systems, and wave propagation coupling corresponds to far field systems. These methods are discussed in detail sections 3.4 and 3.5 in the report.

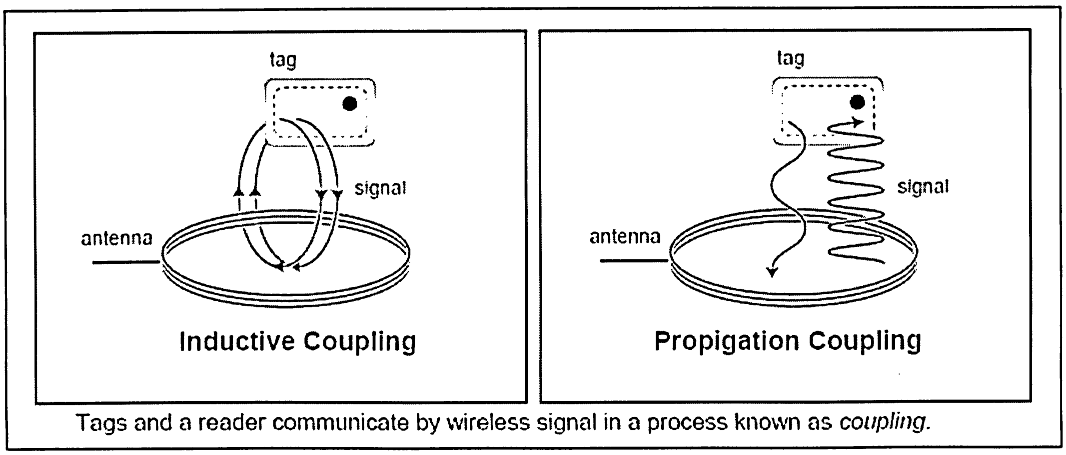


Figure 7: Types of Communication [13]

3.2.2 Power Supply (Tag Types: Active vs. Passive)

Another important classification of RFID Tags is whether they are powered by own power supplies (battery) or use power supplied from the signal. The Tags that rely on signals sent by the Reader to power up the Tag electronics are called passive, and that contain their own power sources are called active. The passive tags use inductive coupling method for communication, while active tags use wave propagation. Active Tags can send and/or power the signals sent to the Readers, thus they have longer reach, and higher data transfer rate. There are also passive/active Tags, which operate using inductive coupling, but can provide high data transfer and enhanced functions powered by their own batteries.

Table 1: RFID Classification

Frequency	Typical Frequencies	Communication Method	Tag Types	Standards	Advantages	Disadvantages	Applications
Low Frequency (LF)	125 kHz, 134.2 kHz, 135 kHz	Mutual inductive coupling	Passive and Active Tags	ISO 11784 ISO 11785 ISO 18000-2	- low cost - mature technology - easy implementation	- low data transfer - low range (<1m) - mostly one tag recognition at a time	- Access Control - Animal ID - Car immobilizer
High Frequency (HF)	13.56 MHz	Mutual inductive coupling	Mostly Passive Tags	ISO 15693 ISO 14443 ISO 18000-3	- multiple tag processing (up to 50!) - low cost - global standards	- medium range - limited data transfer	- Retail - Access Control - Smart Cards
Ultra High Frequency (UHF)	915 MHz (passive); 315 and 433 MHz (active)	Wave propagation (back scattering)	Mostly Active Tags	ISO 18000-6	- longer reach - multiple tag processing (up to 200) - high data transfer	Susceptible to weather conditions, noise interferences, metal and liquid packaging interferes with wave scattering lack of global standards expensive	Tracking Military Toll Collection
Micro Wave Frequency	2.45 or 5.8 GHz	Wave propagation	Mostly Active Tags	ISO/IEC 18000-4	-longer reach - high data transfer	Susceptible to weather conditions Expensive	Military Experimental Satellite

3.3 Wave Equations Governing the Reactive Near Field (Hertzian Dipole Case)

All RFID systems use wireless transmission of electromagnetic waves. Antennas act as the transmitters or the coupling receivers of the EM signals. "Theoretically, if we know the current distribution of an antenna, we can find the retarded magnetic vector potential A, and from it we can find the retarded electromagnetic fields H and E using the following relations" [6].

$$H = \nabla \times \frac{A}{\mu}$$
$$E = \eta H \times a_k$$

From this for the Hertizian Diapole antenna the following near field equations can be arrived at [100]: (in the spherical co-ordinate system)

$$Er = \frac{\eta I_o dl}{4\pi} \sin\theta \left[\frac{1}{r^2} - \frac{j}{\beta r^3} \right] e^{-j\beta r}$$
$$E_\theta = \frac{\eta I_o dl}{4\pi} \sin\theta \left[\frac{j\beta}{r} - \frac{1}{r^2} - \frac{j}{\beta r^3} \right] e^{-j\beta r}$$
$$E\phi = 0$$

where the retarded current is $I = Io \cos(\varpi t - \beta r)$.

Depending on the frequency or the corresponding wavelength the RFID systems can be said to operate in the reactive near field or the far field. Near field is where the "energy is stored in the electric and magnetic fields very close to the source but not radiated from them. Instead, energy is exchanged between the signal source and the fields" [14]. Far field is where the energy radiates from the source. Far field can be defined as the field more than twice the wavelength of the electromagnetic waves.

In terms of wavelength, near field can be defined as "the region located less than one wavelength from the source" [15]. The reactive near field is the region located less than one wavelength over two pie or $\lambda / 2\pi$ or 0.159 of the wavelength. In the near field Maxwell

Faraday Law holds ($\nabla \times \vec{E} = -\frac{d\vec{B}}{d\vec{t}}$) or asserts it self. And the relationship between E and H is complex. In the above equations for hertizian dipole antenna, the $\frac{1}{r^2}$ term is called the inductive field, and it is predictable from the Biot-Savart law. The term is important only at near field, that is, at distances close to the current element [6].

3.4 Coupling and Mutual Inductance

In the near field Maxwell Faraday law is asserted. From this law follows the mutual induction. Theoretically the energy stored in the field is conserved. "Should a device capable of coupling energy from the fields be nearby, a received signal will be developed by that device. This is the mechanism behind near field radio frequency identification (RFID) tag coupling [14]."

Coupling here refers to the mutual inductance. To understand mutual inductance, first consider self inductance. In the near field the Maxwell-Faradays conservative law applies. In the absence of a coupling device or secondary coil, only self induction exists.

Faradays law states that changing current creates changing magnetic field and changing magnetic field creates a voltage (also referred to as electromotive force) or changing current that opposes the original current. This property of inducing an opposite voltage across the coil terminal is referred to as self inductance or inductance in general.

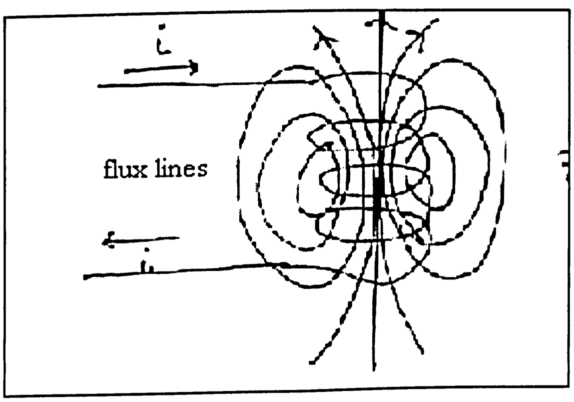


Figure 8: Self Inductance

In other words, the changing magnetic field is proportional to the changing current in the coil. $\frac{d\phi}{dt} \propto \frac{di}{dt}$. Then, the following equation directly equates the induced voltage across the coil terminals and the $\frac{di}{dt}$.

$$V = L\frac{di}{dt}$$

In the above equation, L is the constant called inductance or self inductance and is proportional to the number of turns.

Now consider placing a secondary coil in the core where magnetic flux of field exists as shown in Figure 4R. The flux through the primary coil is the same as in the same secondary coil inducing the same amount of voltage drop across secondary coil, $V_2 = M\frac{di_1}{dt}$, where M is called the mutual inductance.

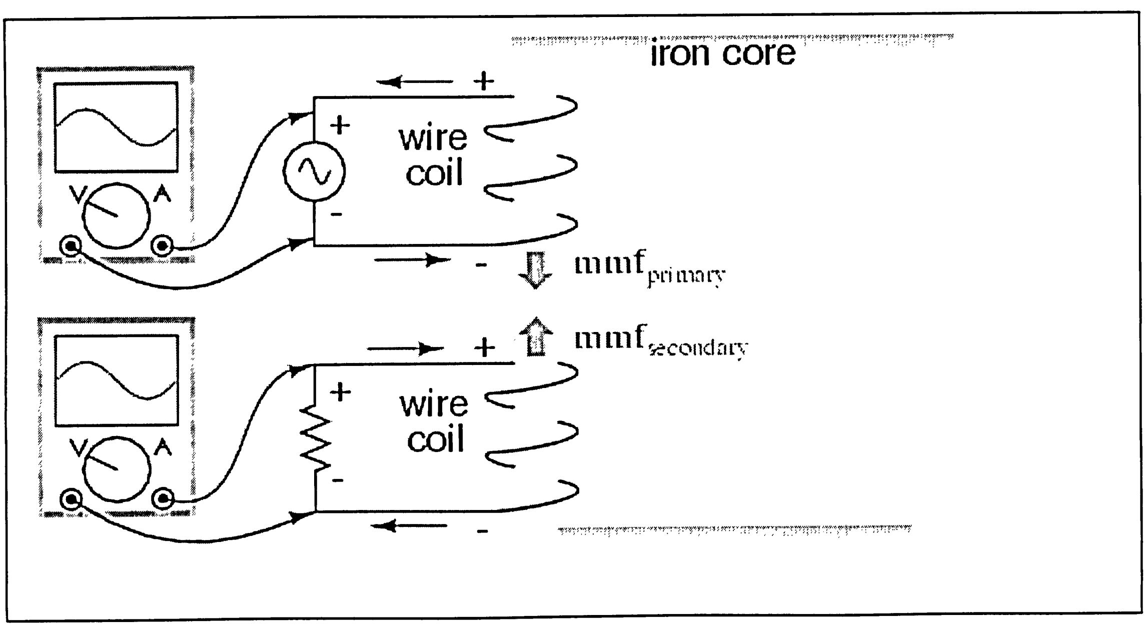


Figure 9: Primary coil and secondary coil [16]

Here, the following facts should be noted. Generally, if a constant voltage is applied at the primary coil the induced voltage must remain constant to balance with the applied voltage. The presence of the secondary coil can alter the Magnetomotive force. "Usually, this mmf is accompanied by magnetic flux, in accordance with the mmf=ΦR "magnetic Ohm's Law" equation [18]." To maintain constant flux in the core, an opposing current is induced in the primary coil. This principle is useful in the RFID System circuits. The coupling device is the Tag. Tag can couple the energy or the signal and Tag electronics can embed information within the signals.

3.3.1 Mutual Inductance

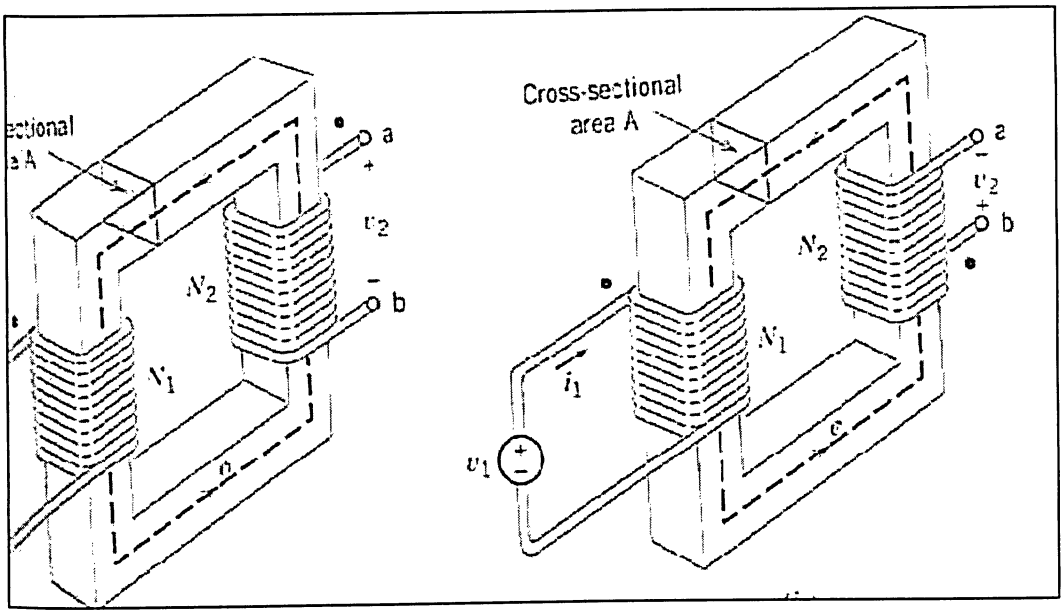


Figure 10: Mutual inductors [17]

Consider the coupled coils above. The change in current in one coil will cause voltage and current flow in the second coil as discussed in the previous page. The voltage and current in the first coil is

$$V_1 = L_1 \frac{di_1}{dt}$$

$$V_2 = M \frac{di_1}{dt}$$

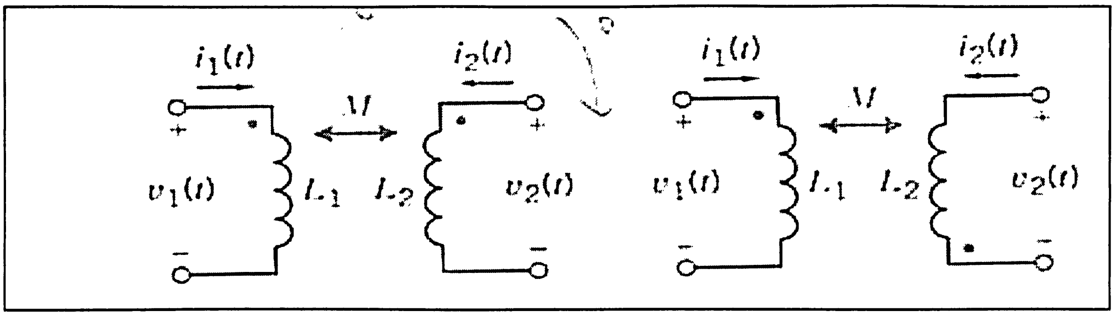


Figure 11: Dot Convention [17]

In the above equation, L is the constant called inductance or self inductance. When both currents from the dotted or non dotted terminals the terminal voltages are the following:

$$V_1 = L_1\frac{di_1}{dt} + M\frac{di_2}{dt}$$

$$V_2 = L_1\frac{di_2}{dt} + M\frac{di_1}{dt}$$

When one current enters the dotted and the other from the un dotted end terminal the terminal voltages are the following :

$$V_1 = L_1\frac{di_1}{dt} - M\frac{di_2}{dt}$$

$$V_2 = L_1\frac{di_2}{dt} - M\frac{di_1}{dt}$$

In sum mutual inductance quantifies how the change in current in primary coil affects the current and voltage in the secondary coil.

3.4 Near Field RFID Operation

In the near field systems, the Reader generates a large alternating current which generates an alternating magnetic field in the near field. When a Tag is placed in the near field, its coupled coil detects the alternating magnetic field, and generates an alternating voltage. In accordance with the Faradays Law it will generate its own current that can be detected at the Reader. The tags electronics applies a load to its own antenna coil and varies it over time. A signal can be encoded as tiny variations in the magnetic field strength representing the tags ID. The reader can then recover this signal by monitoring the change in current through the reader coil.

As noted before, usually near field systems employ passive Tags, which means Tags do not have power supplies and depend on the energy supplied by Reader signal to power its electronics. When the signal is in the range of the Tag, the alternating current is rectified and coupled to a capacitor to provide the power.

In inductive frequency based system the Tag's ability to absorb the energy from the Readers signal is due to the resonance effect. The coupling or antenna element of the tag is really an inductor coil and capacitor connected together and designed to resonate at the 13.56 MHz system operating frequency. The Tags resonant frequency, f_0 is calculated by $f_0 = \frac{1}{2\pi\sqrt{LC}}$, where L is inductance of Tag antenna coil, and C is capacitance of Tags tuning capacitor

Another factor that influences the Tag is the quality factor Q. The Q value of the coupling element defines how well the resonating circuit absorbs power over its narrow resonance band. Both the resonant frequency and Q value are the primary factor determining the operational range of the inductively coupled RFID System.

In sum, the project will limit itself to RFID systems that are near field, passive and inductively coupled, and will consider the operating frequency to be the internationally available 13.56MHZ.

3.5 Far Field Systems

In the far field systems, the Tag captures the Reader signal and the accumulation of power turns the Tag chip electronics on. The antenna at the Tag is designed to receive a particular frequency. If impedance mismatch occurs at this frequency, the antenna will reflect some of the energy towards the Reader. The Tag electronics is designed in such a manner that by changing the antennas impedance over time, the tag can reflect back more or less of the incoming signal in a pattern that encodes the tags ID. For instance, turning a impedance mismatched antenna on or off according to the tags information can relay or reflect back to tags information.

4 Chapter: Applications, Industry and Limitations of RFID

4.1 Applications

As a real-time wireless tracking and data communication and processing technology, RFID has a wide range of applications. This section of the report will note the areas of applications and notable specific examples. The RFID technologies used in particular applications differ by the wireless communication method used. Long range applications use EM radiation based communication, while near range applications use EM inductive coupling communication. Real time identification and location systems are the forefront long range applications, while mass volume product identification is a prime area for near range RFID systems. Please refer to the RFID theory section for detail discussion about the types of RFID technologies.

Most of the RFID applications can be classified into the following areas: identification, tracking, timing, and control. These functionalities alone or in combination allow application development across various industries. Adopting RFID technologies usually reduces labour requirements, automates the processes, saves time, and leads to cost effectiveness.

The RFID technology is similar to Information Technology (IT) in that it can be used in all sectors of the economy including: retail, manufacturing, health care, government, defense, transportation, and communication. The following lists main areas of RFID technologies with specific primary usage examples.

4.1.1 Product or Asset Tracking

One of the most important areas of RFID applications is the retail industry, where products are identified and tracked using RFID. An often cited goal of the industry is "self check out", where the customers purchase the products on the shelf and leave without waiting for a human to check out. RFID tags are used to handle the logistics of the customer transaction. The manufacturing and backend operations of the store also use RFID systems to identify, track, and keep inventory. The largest retailer in the world, Wal-Mart has adopted RFID, but has experienced considerable drawbacks in its implementation.

Electronic Product Coding (EPC)

RFID enabled Electronic Product Code (EPC) is a driving component of RFID technologies. EPC identifies each product uniquely, similar to the current Universal Product Coding (UPC) barcode numbering scheme. The primary difference is the level or range of identification possible. UPC only has 12 digits, while EPC has 96 bits, thus can possibly identify each product uniquely. The 96 bit number is structured as follows: | Header | EPC Manager | Object Class | Serial Number | = | 8 bits | 28 bits | 24 bits | 36 bits | [19]. This is a global standard that has been developed after years of discussion by various companies, organizations, and governments.

Further advantages of an RFID system are listed below.

1) An RFID system can identify multiple objects at the same time while a bar code system usually scan one item at a time;

2) Information can be written into an RFID tag's integrated circuit memory as many times as desired;

3) In capturing the tags, an RFID base station does not need line-of-sight alignment such as that in a bar code system

Library Self Checkout

A good example of asset tracking application is the Library Self Checkout system. Ryerson University Library has implemented this system where each book is assigned a unique RFID Tag. The user scans the Reader to checkout the item. This reduces labour involved in human checkout, allows for automated inventory, and provides security at the library gates. Tracking books is just an example, as any item can be tracked this way.

Manufacturing

The Tag attached to the product is used for identification, to contain process information, to track of the assembly status and for inventory management. An example is the Ford's Essesx plant in Windsor. It uses RFID tags with instructions for assembly of car engines, and the Tags also accumulate test data during manufacturing .

Healthcare

Patients identified with RFID wristband enables data security, automatic and digital data retrieval, treatment matching, and basic vital sign monitoring. Also, patients can be remotely tracked, and monitored. Accurate, digitalized, and integrated record keeping prevents errors, improves safety and efficiency, and reduces costs in the long term.

4.1.2 Real Time Locating Systems

In agriculture, transportation, and defense industries real time location systems are useful. Animal tracking in agriculture, vehicle tracking in transportation, and tracking people and equipments for security are examples of real time location systems. Real time location systems use long range RFID to identify, track and communicate data and/or control the systems.

Automotive

Ignition keys, door/trunk opening, component status, and vehicle condition monitoring can all use RFID. On the road, vehicle locationing, tracking, vehicle to vehicle cooperative driving can be enabled by RFID. A specific case in the transportation industry is where cars get billed as they go through highway tollbooths. This saves time and reduces congestion. An example of this system is the E-ZPass in the Northeaster and Mid Atlantic US states [19].

Animal Tracking

Information about the animal, and where it is can be tracked using RFID. This allows for inventory control and farm field management. Basic health monitoring can also be recorded. This information is becoming more important in the global livestock industry, as quickly identifying the source of any disease outbreak in key to control and quarantine the source population. Also, RFID is useful in monitoring endangered species, and for research.

Mobile and Internet Applications (Online Purchase, Navigation)

Mobile phone can act as a RFID Reader, and read in tagged goods or street posters and obtain product information or purchase the product online. RFID Tag with position information can be scanned in by the Reader to enable handicap people, or tourists to assist in navigation. Potentially, each product and location can be Tagged and networked to allow for network of things and ubiquitous computing.

4.1.3 Access and Control Systems

Authentication, access and control systems are another major area of RFID applications. Smart Cards is a key application in this area. A widely used Smart Card system uses the 13.56 RFID contactless method, and are based on ISO/IEC 14443 RFID standards. Credit and debit cards (ex American Express), U.S. ePassport and GSM (Group Special Mobile) are specific applications that use smart cards.

Airport Security

RFID attached to parcels can be used to select suspicious parcels, implement random security checks, and track baggages through the transport. RFID can also be used to restrict access to particular areas for employees or passengers, and manage the overall security of the airport. This can be applied to sea ports and rail way stations as well.

4.1.4 Timing Systems

A recent development area of RFID technology is timing applications. In sport competitions where thousands compete, tracking the finishing time of the each competitor has been a difficult task. RFID Timing systems are now employed to automatically track the finishing time of each competitor with a high degree of accuracy. Triathlon, running, swimming, and canoeing are sports where RFID Timing systems are used widely.

4.2 RFID Industry

The RFID Industry was worth about $2.5 billion at 2006, and expected to grow to $25 billion by 2015 [20]. The retail, commercial, and healthcare industries are found to be the leading segments for adopting RFID. North America leads in adopting RFID, while Europe, Japan, and the rest of Asia.

The RFID technologies are primarily developed by electronic and software companies. A lot of the initial research was done by universities such as MIT's AutoID Lab, and sponsored by government's defense or security departments. There does not exist a large developer community as there is in Information Technology. However, RFID companies specializing in development, implementation, and testing are establishing themselves. There also exist various standard or application groups. The leading companies that provide RFID Readers, Tags, systems, and development kits are listed below.

Texas Instruments

TI is a leading electronic consumer company and a "leading supplier" of RFID products. Animal Identification, electronic toll collection, challenge response system, and low cost product identification are key products in its lineups.

Philips

Philips has been involved in the RFID industry since 1982. It is known for developing the proposal for standard Global Tag (GTAG). GTAG protocol enabled multi-tag reading.

Intermec

Intermec Technologies was found in 1966, and it is considered one of the oldest in the RFID industry. Current focus of the company is towards portable computing devices, wireless communication and tagging technologies. It generally offers products in the UHF range.
Other firms in the RFID industry are the following: TagSys, Hitachi , Checkpoint Systems, Symbol Technologies, Descartes Systems, Manhattan Associates, Accenture, IBM, Dallas Semiconductor.

4.3 Limitations

The limitations of RFID systems can be classified into technological, business, and governmental areas. The technological limitations include: channel, frequency, power, interference, environmental or physical settings, electronic design, manufacturing, software and implementation limitations. Business limitations include cost considerations, standardizations, and legacy systems. Security, privacy, and regulatory considerations are of concern to governments.

Security

RFID systems transfer data in the shared vicinity, thus a primary concern is that others can probe or snoop the data. Unauthorized snooping, and collection of personal information is vulnerability that restricts the use of RFID in financial governmental sectors. Another issue is if systems are designed to produce harmful effects using RFID. For instance, terrorists can design bombs that sense for vehicles with particular Tags and explode it upon sensing the information.

Privacy Issues

RFID enables identification, tracking of detailed personal information of individuals and groups. Miniaturization of Tags allows for hidden tagging and collection of information. Such information can be exploited. These concerns have caused consumer advocates to demand stricter regulations, which have restricted wide scale adoption of RFID.

Standardization

Standardization of communication systems and RFID components have been one of the obstacles in wide spread applications of RFID systems. Each major companies and even small companies develop their own systems and components. These systems and components can be incompatible with each other, and this creates difficulties for companies to work in a networked environment.

Costs

Although RFID is usually cost effective in the long term the initial cost of implementation may be prohibitive. The technological and implementation challenges have shown to considerable, and even large companies such as Wal-Mart have not meet the financial benefits they initially expected.

System Integration

With multiple standards, vendor or component offers, and multi protocols integrating a RFID system, and inter operating over network of RFID systems becomes challenging. RFID system integration needs special consideration to the physical environment in which they are implemented. Furthermore, as any new system the business or operations need to adapt to the system as well.

RFID Viruses

Recent research has shown that tags can be "infected with a virus and this virus can infect the backend database used by the RFID software. From there it can be easily spread to other RFID tags" [21]. A scenario is scanning in tags written with viruses, infecting the databases and leading to a network or chain reaction or crash. This possibility increases the vulnerability of the RFID enabled applications and impacts public acceptance of RFID technologies.

RFID Channel Limitation

The frequency used by RFID limitation is the physical EM frequency spectrum shared by various other technologies and regulated by local and/or regional governmental bodies. Only a limited spectrum is designated for RFID applications. Various regional bodies control this radio spectrum, and thus it is difficult to agree upon RF spectrum allocation.

Power Limitations

Passive RFID system depends on the Reader's signal for power. Tags absorb sufficient power to turn on and rely back the data. The power that can be transferred can be interrupted by environmental factors, and device limitations. For active RFID systems the power radiated out is regulated by governments for health and safety reasons.

Environmental Limitations

RFID systems operate under various conditions and the typical communication interference challenges are encountered by RFID systems as well. Passive Tag reliability is impacted primarily by the presence of metals or liquids. The focus of this project is the limitation of RFID Tag reliability due to the presence of metals. This limitation is discussed further in the following section.

4.3.1 Degradation in performance of RFID systems near metals

Passive RFID Tags degrade in performance near metals. As many products are packaged using metal layers, or shelved in metal shelves the impact of metals is a major limitation in the retail industry. This often limits the range and universal application of RFID Tags.

The main reason for less reliability near the metals, and "the decrease in read range at perpendicular incidence in close proximity to metals or dielectrics (such as water) is the decrease in electric field near the surface required to meet the boundary conditions" [22]. The near range RFID systems are tuned to or optimized to operate at resonant frequency. The optimization is done by impedance matching. Metals change the impedance of the RFID system. This offsets the resonant frequency or the optimum design frequency.

Metals in the vicinity cause eddy currents, which absorb RFID energy, "thus reducing the overall effectiveness of the RFID field. These eddy currents also create their own magnetic field that is perpendicular to the metal surface. This perpendicular magnetic field "cancels" the reader field" [4].

Four standard solutions for overcoming the problem are noted below.

1. Placing a separator in between Tag and Metal
2. Using special material between Tag and Metal
3. Using different frequency range RFID
4. Considering the physical constrains in the RFID selection and implementation phase.

5 Chapter: RFID System Modeling

Chapter five reviews approaches to RFID modeling found in the literature. It briefly outlines the criteria for an RFID model in relation to the thesis. In attempting to take eddy currents into the model, various methods of calculating eddy currents are discussed.

There are different methods to solve Maxwell equations such as Finite Difference Method (FDM), Finite Element Method (FEM), Boundary Element Method (BEM) and Analytical approaches. The two commonly used methods are discussed in this section.

5.1 Models in the Literature and Analysis

A Model is a representation of a system. Systems are modeled to understand, and predict their behavior. RFID systems can be modeled at different levels and in different ways depending on the application requirements. RFID systems are often modeled to evaluate data transfer rate, tag read rate, coupling level, performance, and environmental tolerances. The following are different types of models used for RFID systems: physical model, mathematical model, electromagnetic model, communication model (BER, Channels), electric circuit model (circuit component), and system level model. In the literature, there are various methods used to model the reactive 13.56 MHz – inductively coupled RFID system, and these are reviewed in the following sections.

5.1.1 Maxwell Software 3D EM Model

Bogdan simulates the 13.56 MHz RFID systems using the Maxwell 3D Field Simulator [23]. The model is to "extract from the 3D field solution the electromagnetic essence which is the inductance and capacitance matrices as well as the resistance of the antenna loops [23]." In other words, use a geometric representation to gather the electromagnetic essence. The Maxwell software must be able to translate the geometry and interpret its electromagnetic behavior within a defined framework. "The main modeling steps for the RFID application is to compute the distributed inductance matrix, capacitance matrix and the resistance of the loops. Additionally the stray capacitance of the reader antenna is also necessary for the calculation of another 60 mm 60 mm 10 mm quantity, the self resonance of the antenna

[23]." Here, much of the modeling power is invested within the simulation software. This type of modeling is suitable for design of the tag reader antennas.

5.1.2 Circuit Model

The paper "Energy scavenging for inductively coupled passive RFID system" [24] models RFID system as a circuit model and seeks to adoptively match the Reader and Tag impedance in order to maximize the reading range. Impedance matching is useful when the load characteristics are fixed, and the source still needs to supply the maximum power possible. The mutual inductance of the coupled 13.56 MHz system is viewed as a "load at the reader".

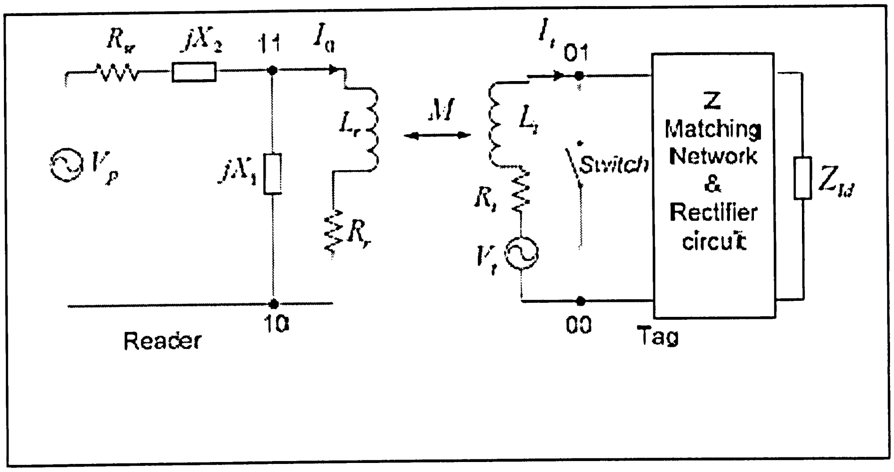


Figure 12: RFID Circuit Model

At the reader side the circuit model is applied (Figure 6), where X1, X2 are reactive elements. The discussion as to how the adoptive impedance matching is done is not the primary focus of this project. The focus rather is how the modeling is done. The inductor or inductive loop is simplified as a serious of small magnetic dipoles. The magnetic field for the small dipoles are calculated, and added to get net magnetic strength at a point. Equation 8 in the paper provided a way to adjust the number of turns and dimension of the loop with Io to calculate the induced voltage at the Tag.

5.2 Criteria for RFID System Modeling

5.2.1 Physical Attributes

Various physical attributes have to be taken into consideration when modeling mutual inductance including "core and coil configuration, self and mutual inductances between coils, leakage fluxes, skin effect and proximity effect in coils, magnetic core saturation, hysteresis and eddy current losses in core, and capacitive effects [26]." In this project the three important physical attributes are the following:

* modeling the Coils (2 loops primary, 1 loop secondary)

* modeling the Core (free air)

* modeling the disc (disc of varying radius and thickness)

The EM energy is conserved, except for the ohmic losses. (A topological approach where the SW deals with the EM details is a possible approach to modeling the RFID SM.)

5.2.2 The Current in the Primary Loop and Magnetic Flux

The current in the primary loop due to applied voltage is directionally proportional to the magnetic flux generated, and the proportional constant is the inductance. This relation needs to be adequately reflected in the model. Either the current or the voltage needs to be specified for a given configuration (configuration fixing the mutual inductance), and the flux needs to be determined at a given point.

5.2.3 Loss Function and RFID System Modeling

The loss function is defined as the ratio of the flux value when material is in over flux value in air. The loss function of a given constant radius disc and thickness is a function of the "distance over the sphere surface".

$$LossFunction = \frac{Flux\_when\_material\_in}{Flux\_in\_air} = \frac{M\_when\_disc\_in}{M\_when\_disc\_out}$$

The function is the focus of the RFID System model as it describes the projects problem. Loss Function behavior over the distance of the product to which Tag is attached is what the model essentially has to help understand.

The Mutual Inductance will be represented in the model through the loss function. Alternatively, the Loss Function can be said to be represented through mutual inductance.

5.2.4 Eddy Currents and RFID System Model

Eddy currents are the swirling currents in metals or any conducting materials due to changing magnetic field. Assuming magnetic field is in the z direction, and the conductor surface area intersects the magnetic field perpendicularly the current created would be swirling. This is due to Faraday's Law. This has an effect on how the Tag functions.

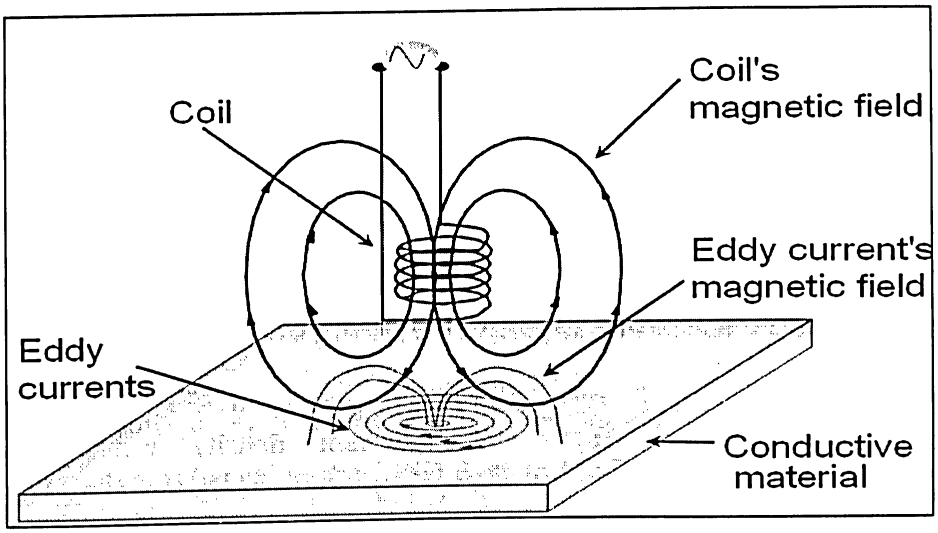


Figure 5.4: Eddy Currents [27]

By Lenz's law the eddy currents in turn create a magnetic field opposing the original magnetic field. This is the magnetic field that directs the energy invested in the original magnetic field away from the Tag. Moreover, that energy is used to cancel or interfere with the original magnetic field, thus reducing or blocking the energy reaching the RFID Tag.

The eddy currents generated by the magnetic field is proportional to the magnetic field caused by the currents generated by the Reader signal. Thus simply adjusting the value of original magnetic field is easily ruled out. Eddy currents are usually flowing on the surface. An important property related to eddy current is how eddy currents behave as depth of the object increases.

Eddy currents concentrate near the surface adjacent to an excitation coil and their strength decreases with distance from the coil. Eddy current density decreases exponentially with depth. This phenomenon is known as the skin effect. The depth that eddy currents penetrate into a material is affected by the frequency of the excitation current and the electrical conductivity and magnetic permeability of the specimen.

5.2.4.1 Calculating Eddy Currents - Power Loss Approach

The eddy currents can be considered to draw the energy from the original source, thus there exist power loss due it. The power loss can be approximated as $p = i^2 R$. This issue is a design concern for transformer designers, and they have devised various methods to reduce the power loss due to eddy currents. The way with which they take the power loss due to eddy currents can be used to express the value of eddy currents for simple geometries.

5.2.4.2 Calculating Eddy Currents - Current Density Approach

Current density approach is related to the above approach. For the stated problem, where $B(z,t) = B_0 \cos(wt - \beta z)$. The current density can be shown to be $B(z,t) = B_0 wr \cos\left(\frac{wt}{2r}\right)$. Then using the Maxwell equation ($\nabla \times \overrightarrow{H} = \overrightarrow{J} + \frac{\overrightarrow{dD}}{dt}$), it is possible to calculate the B at the origin.

5.2.4.3 Calculating Eddy Currents - Magnetization in Materials Approach

What happens to a metallic substance (conductor) with a given geometric structure when magnetic field is applied to a given geometric structure. The problem can be approached from two view points: magnetization theory approach and boundary value problem approach.

All conducting materials can be conceived of consisting of dipole moments. Without an external B field applied to the material, the sum of moments is zero due to random orientation. When an external B field is applied, the magnetic moments of the electrons more or less align themselves with B so that the net magnetic moment is non-zero. Thus, the B becomes $B = \sigma(H + M)$. The magnetization, M (amperes/meter) is the magnetic dipole moment per unit volume. The question now is how M is calculated.

Calculating M would require calculating the bound volume current density (Jb), since Jb is the cross product of M. Calculating Jb would involve calculating the amount of eddy currents.

5.2.4.4 Calculating Eddy Currents - Boundary Condition Approach

The problem can be formulated as how the value of B changes as it goes from first media into the second media. In such a case the relationship at the boundary is defined as follows: $(H1 - H2) \times n = K$ where n is the unit vector normal to the interface, and K is the free current density at the surface. Here the value of K may be a factor of the eddy currents. The question becomes how K can be calculated from eddy currents? Can the current density of the object be calculated from the eddy currents? If so then B at the origin can be calculated as discussed above.

In sum, the above notes about 'Criteria for RFID System Modeling' outlines the factors that need to be adequately reflected in the RFID System Model. Considering eddy currents into the model is important for an adequate description of the RFID System behavior. How this can be done is a complex problem that still lacks a generic solution.

5.2.5 Review of the RFID Compatibility Study

Several authors showed that self inductance cannot be ignored in the RFID system. For instance, the work performed by [25] considers each eddy current as a circular loop (wire) with specific radius (a) and resistance. Thus, the I total = R dl = I due to B field + I due to eddy, where $I, I = A\cos(wt+\psi)$. And assumes the B field from the reader to be: $Br = B_0 \cos(wt - Bz)$ (along z direction).

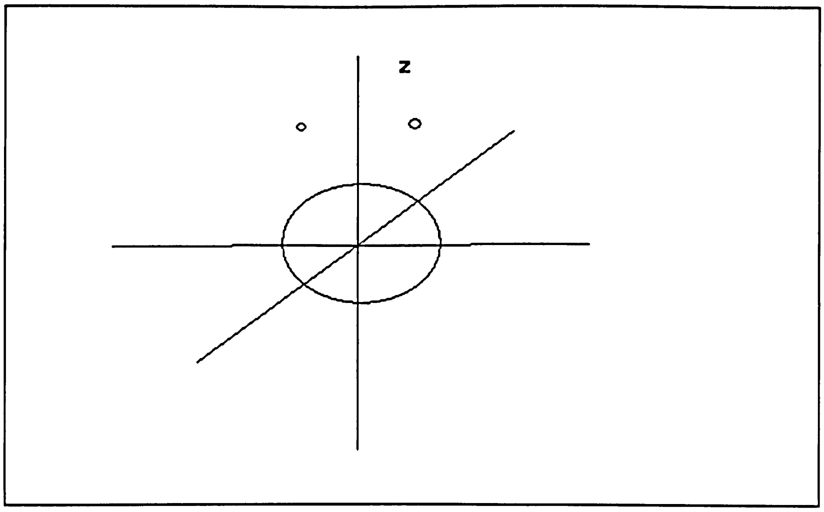


Figure 13: Metal Sphere and reader coil

The study states in order to calculate the total B field due to all eddy currents, loops mutual inductance and self inductance has to be taken into account. Mutual inductance has to be done over the whole surface. This was considered to be an extremely complex problem. Thus, the study focuses its attention on a simpler spherical model of the problem (Figure 7).

The RFID Compatibility study analyzed a sphere model of the problem. There they assumed a superconducting sphere with radius R = a in an external homogenous B field. The total B field at a point _R + R was the external field in addition to the field due to the dipole located at the sphere center. The purpose of the analysis was to determine the flux that flows through an open wire loop or RFID tag, as a function of location on the z axis as illustrated in Figure 7. For this above (Figure 7) simple geometric setup the study showed that an analytical solution can be arrived at. However, it concluded for more complex configurations simulation or numerical methods are required.

5.3 Finite Element Modeling and Maxwell Equations

An equation containing derivatives of a function as one or more variables with respect to one or more independent variables are differential equations. An Ordinary Differential Equation

(ODE) is a type of differential equation where the equation only contains one independent variable. Partial Differential Equation is another type of differential equation where there can be one or more dependent and two or more independent variables. In other words, PDEs are equations involving a function and their partial equations. Maxwell equations are partial differential equations. As noted before, modeling electromagnetic characteristics of the RFID system or operating principles, including the eddy currents, involves solving PDEs. Because of the complexity of the problems as discussed in the previous sections, this involves simulation or numerical analysis.

Solving ODEs involves finding the function described by ODEs. Solving PDEs involves finding the function described by PDEs as well; however, PDEs would involves a function of two or more variables. Analytic solution to high order (more than 2) PDEs are very complex to solve. Some cases can be solved using methods such as Bcklund transformation characteristics, Green's function, integral transform, Lax pair, and separation of variables. Numeric methods are often used to solve PDEs.

In techniques involving continuous sources, the problem is approximated by a geometric model. The sides of the geometric model (elements) and the vertices connecting the various sides are (nodes) identified. Then the entire elements are disconnected by the disconnecting nodes. This process is called disassembly. After the disassembly, a generic element can be defined independently of the original object. Then the target genetic element is calculated by the property called local support. By reconnecting the elements the target property of the object can be calculated reconnecting elements by assembly (adding). For example a circle can be approximated by n-sided polygon, and PI can be approximated. The above described procedure can be described as the Finite Element Analysis, and is used in many computer simulation tools including COSMOL.

5.3.1 Numerical Solutions and COMSOL Meshing and Solvers

In our case there are mathematical models that describe the behavior of geometric objects. The matrix is generated using the mathematical data as well as the geometric description. The solver can employ various techniques available. In general, increasing the elements and nodes can improve the results to some extent, at the cost of computation resources and time.

6 Chapter: Finite Element Modeling and COMSOL Simulation

Although different approaches for analysis of electromagnetic events are available, finite element analyses, which are based on accurate constitutive models, provide the most detailed information on the spatial and temporal distribution of electromagnetic phenomena. The problem under investigation involves studying how the presence of metal disc affects the RFID receiver (refer to problem description). For simple geometry an analytical solution can be found, as discussed in [25]. For complex geometry, analytic method is not feasible. Therefore, COMSOL [5], a finite element analysis tool was selected for our simulation efforts. The detailed modeling steps using COMSOL software are described in Appendix A.

6.1 *Model Overview*

To study the effects of metals in relation to electro magnetic fields, various configurations are possible. For an RFID system (Figure 8) a simple geometric configuration as shown in Figure 9 was selected. This configuration was not simplistic as to yield an analytic solution, but simple as a representative case for the Reader, Tag, and Metal problem.

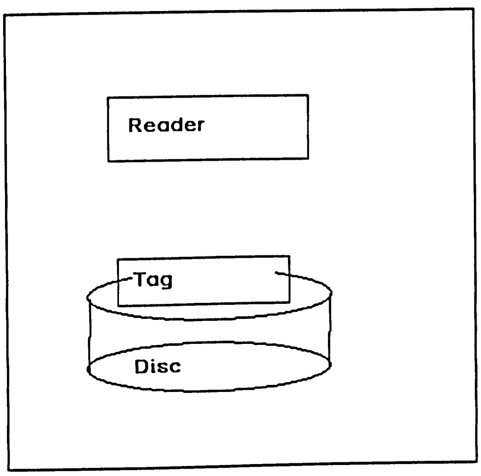


Figure 14: Tag attached to or near metal, and Reader at a distance

The Figure 9 topological model of the RFID System is based on the main operating principal of mutual inductive coupling. The presence of the metal was modeled as a disc, and transceivers of the Reader and Tag are represented as coils. This captured the electromagnetic essence of the RFID System.

6.1.1 Domain Equations

As discussed before, "theoretically, if we know the current distribution of an antenna, we can find the retarded magnetic vector potential A, and from it we can find the retarded electromagnetic fields H and E" (Matthew 2001, 629). COMSOL uses or expresses the vector potential A, and from it H and E values are generated. This relationship can be expressed as below:

From the Maxwell's four equations, the following equations can be noted.

Electric field from magnetic flux density (Faraday's Law):

$$\nabla \times \vec{E} = -\frac{\overrightarrow{dB}}{\overrightarrow{dt}}$$

Magnetic field from electric flux density (Ampere's Law):

$$\nabla \times \vec{H} = \vec{J} + \frac{\overrightarrow{dD}}{dt}$$

The above time domain description can be described in the frequency domain as follows:

$$\nabla \times \vec{E} = -j\omega\mu_0 H$$

$$\nabla \times \vec{H} = \sigma E + J_s$$

where ω is the angular frequency, and μ_0 of the magnetic permeability of free space, and σ is the electrical conductivity. The source current can be specified as $J_s = J_0 e^{j\omega t}$.

$$B = \nabla \times A$$

Magnetic Vector potential substituted into Faradays law gives the following:

$$\nabla \times E = -\frac{d\nabla \times A}{dt}$$

The above equation notes the relation between the magnetic vector potential and the electric field value.

The following notes the domain equation used in COMSOL. The governing equation in this case can be derived from the full Maxwell equations [4]. The COMSOL Software allows for various parameters and or variables to be specified by the user.

$$(j\omega\sigma - \varpi^2\varepsilon)A_\phi + \nabla \times (\frac{1}{\mu}\nabla \times A_\phi) - \sigma v \times (\nabla \times A_\phi) = \frac{\sigma V_{loop}}{2\pi r} + J_\phi^e$$

Where: μ, ε, σ, A_ϕ, J_ϕ^e represent permeability, permittivity, conductivity, magnetic potential and current density, respectively.

6.1.2 Physical Description

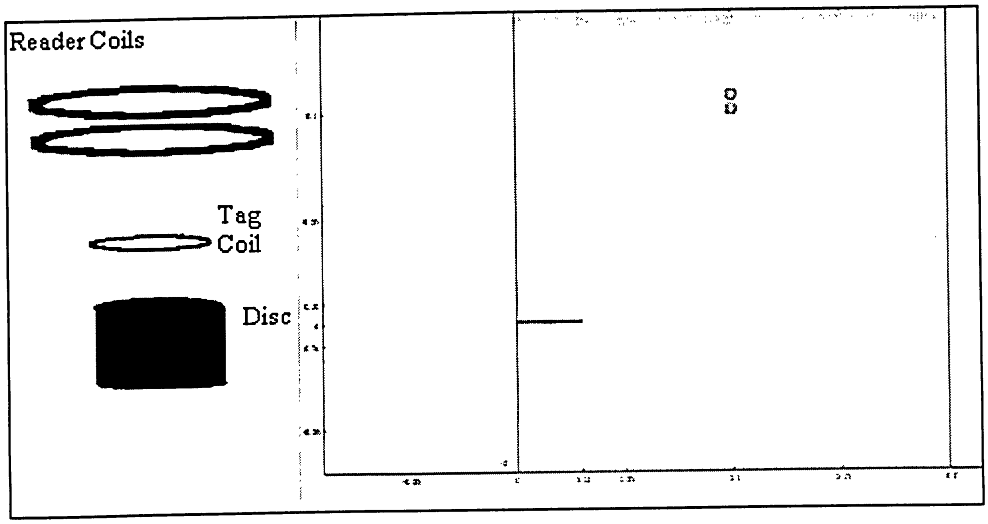


Figure 15: (a) Physical geometric description of the Reader coils, and metal (b) axial symmetry finite element geometry

A physical geometric description of the reader coils and metal is shown in Figure 9.a. The associated finite element model shown in Figure 9.b was developed to simulate the behavior using COMSOL code. The model under consideration consists of two coils representing the Reader, a coil to represent the Tag, and a cylinder. It can easily be described in the cylindrical coordinate system. In COSMOL, describing the geometry using the axial symmetry reduces the mesh elements required to model, thus reducing the solving time. There is no reduction in the information used to describe the model, or in the results that get simulated. The reader coils, tag and the metal were modeled using about 300 solid elements.

The Reader coils were of 0.0025m in diameter. The disc thickness ranged from 6.5mm to 0.001m, and radius from 0.02m to 0.08m. The coils were specified as conducting copper, and the disc was specified as aluminum. The electrical conductivity used for the coils and the disc are 6E7 S/m and 3.8E7 S/m, respectively.

Adjusting and defining parameters here can shape the default domain equations, and the simulation characteristics. .

Quasi-Static leverages the Maxwell law, which states that it takes time for the source current to propagate. The approximation considers stationary currents at every stage. This approximation is valid if the "variations in time are small and that the studied geometries are considerably smaller than the wavelength". In our case, for the frequency of 13.5 MHz , the wavelength is about 22.2 m Under this assumption, only the Amperes law changes, and Faradays law remains unchanged. Another, important assumption to note here is that the Tag coil is left out of the actual modeling as it does not consist of any source currents, thus it will only act as another metal or conductive material, and would not increase the validity of the model.

In general, increasing the elements and nodes can improve the results to some extent, at the cost of computation resources and time. However during the simulation effort it was observed that the reduction in the numbers of elements would not impact the results significantly.

7 Chapter: Simulation Results and Analysis

7.1 Qualitative Observations

The magnetic field lines are altered in the presence of the metal. They do not vanish, rather the magnetic field lines take an altered path. Metals conduct magnetic field lines better than air; creating a “path of least resistance”. One can note how the path can be altered by referring to Figure 16. In this figure the metal channels the magnetic field lines. How the paths are altered can depend on the orientation of the source material, as well as the geometric configuration of the metal. In considering Figure 16 keep note that the model is a 3-D orientation, modeled in 2-D using the axial and geometric symmetry.

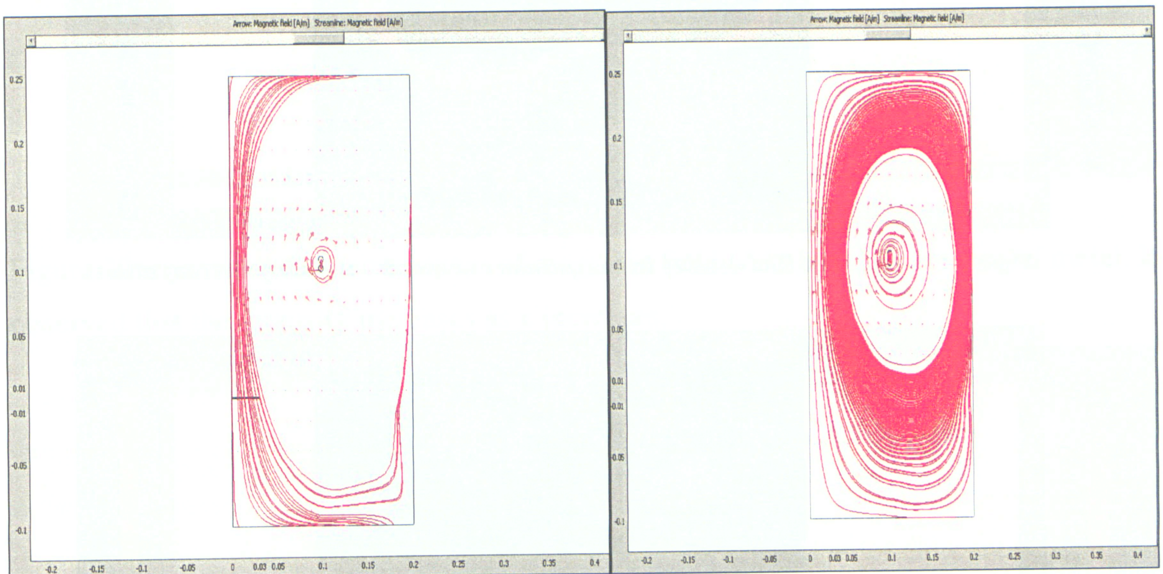


Figure 16: Magnetic field path; the presence of metal affects the magnetic field path

7.1.1 Magnetic field and eddy current effects

The presence of metals induces eddy currents and that influence the magnetic field lines of the source. This is evident in Figure 17 and Figure 18. Figure 17 represents the magnetic flux density in the presence of metal, and Figure 18 represents the magnetic flux density in the absence of metal.

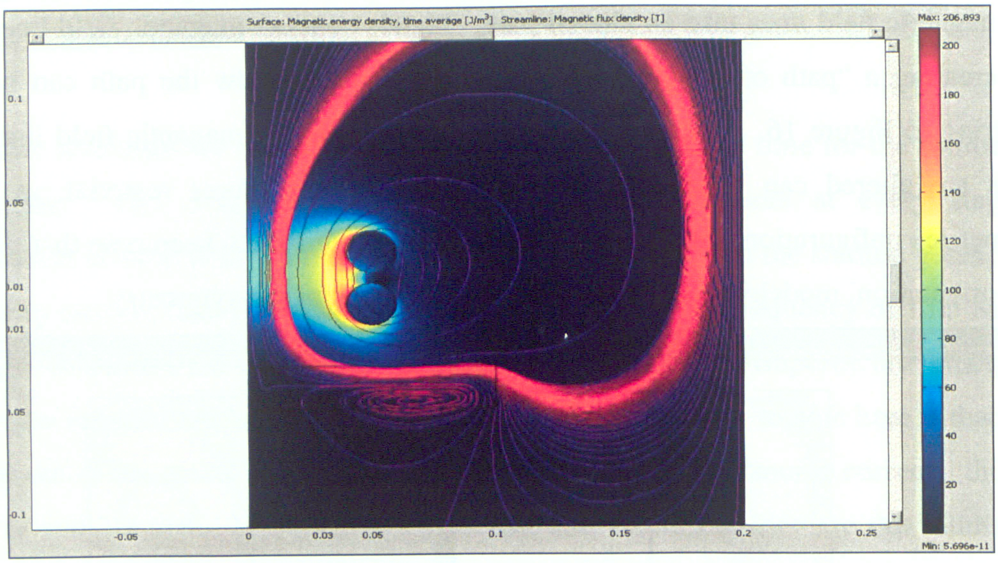


Figure 17: Magnetic flux density in the presence of metal – the eddy current effects

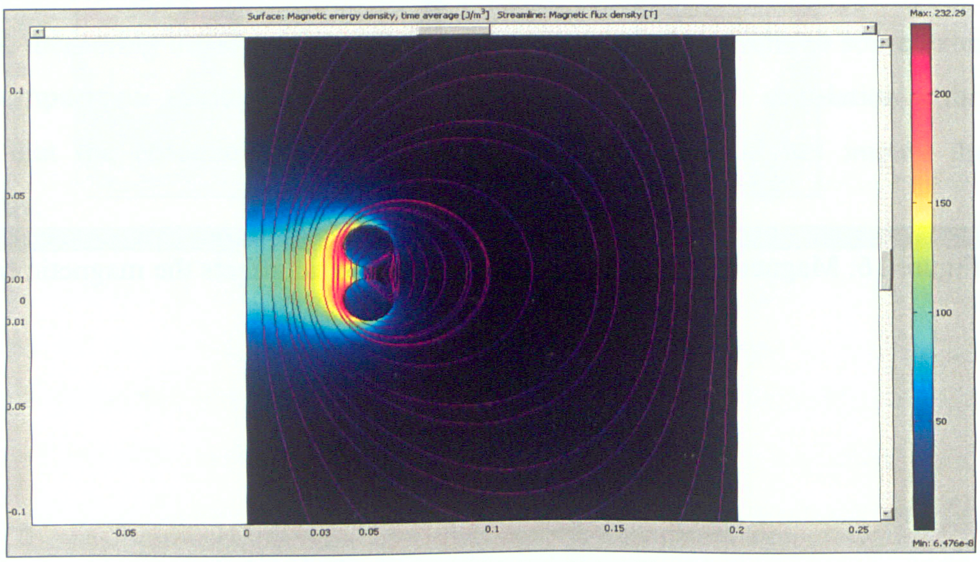


Figure 18: Magnetic flux density in the absence of the metal

7.1.2 Magnetic field z & r components

Figure 19 represents the z component of magnetic field (A/m) in the presence of metal. It can be seen that the intensity decreases as r increases away from the axis.

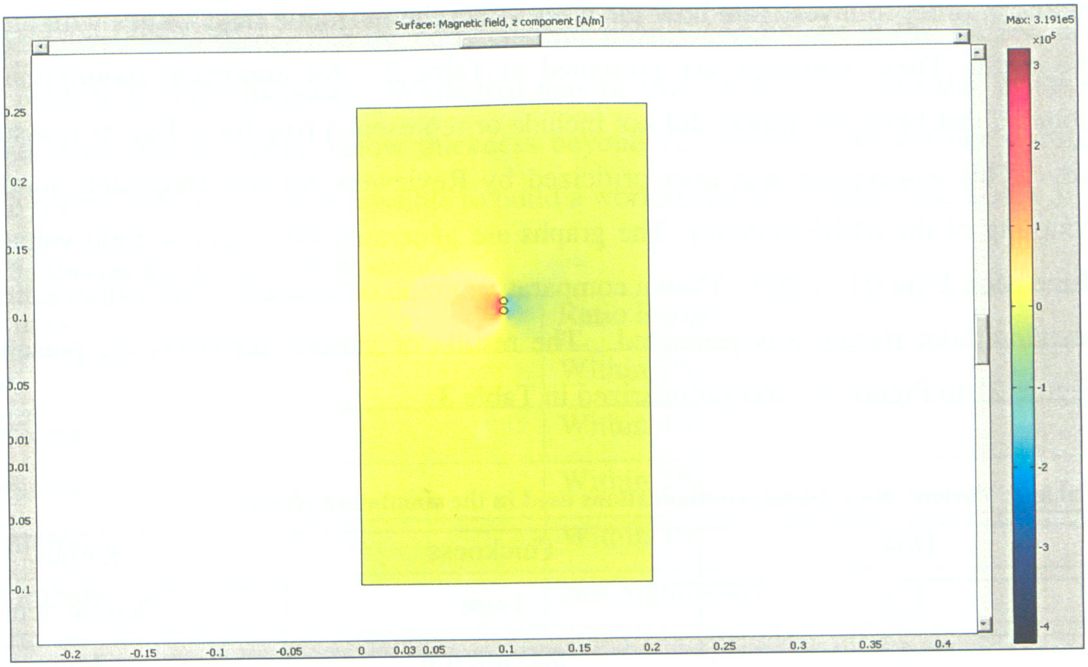


Figure 19: Magnetic field, z component

Figure 20 represents the r component of magnetic field (A/m) in the presence of metal. It is observed that the intensity increases as z increases.

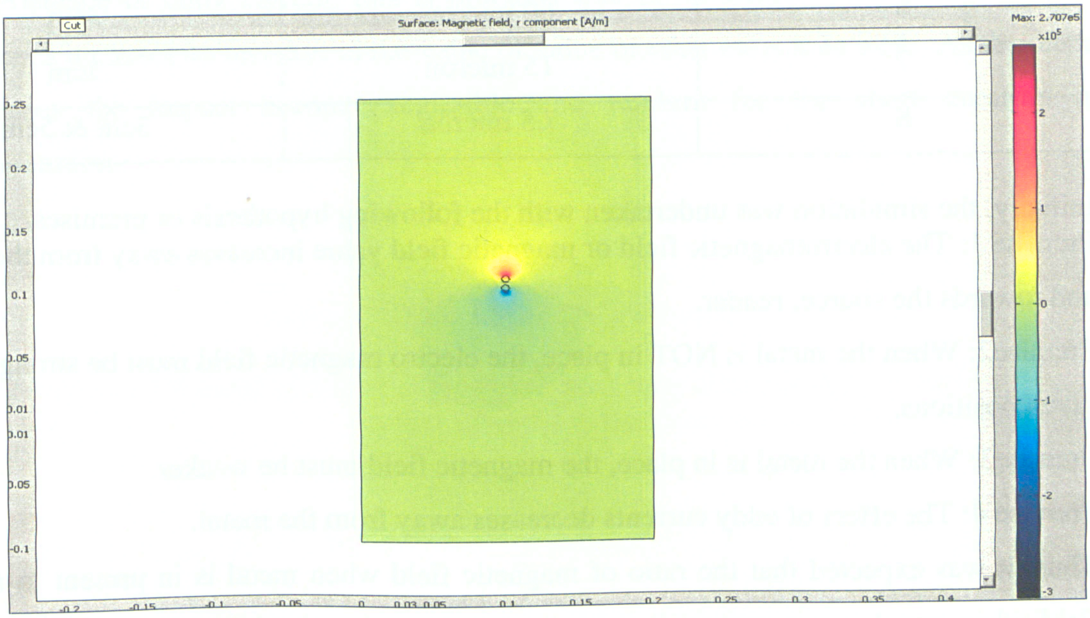


Figure 20: Magnetic field, r component

7.2 Altering the thickness of the metal

The simulation efforts were concentrated for different sizes of discs of varying thickness and radius in order to investigate how the sizes affect the magnetic field values with and without the metal. These scenarios are presented in Table 2. An important assumption must be notated, that being the model did not include or represent a ring for a Tag, as it assumed free air. (This assumption was later criticized by Reviewers for not adequately modeling the coupling of the RFID system.) The graphs are generated for magnetic field values along z dimension from 0 to 0.005. Then a comparative graph of magnetic field values ratios of with metal/without metals was generated. The results of various scenarios are presented from Figure 21 to Figure 27, and summarized in Table 3

Table 2: Various discs (metal) configurations used in the simulation efforts.

Disk	Thickness	Radius
1,2	1mm	3cm & 5cm
3	500 micron	3cm
4	250 micron	3cm
5	125 micron	3cm
6	60 micron	3cm
7	15 micron	3cm
8	7.5 micron	3cm & 5cm

Initially, the simulation was undertaken with the following hypothesis or premises.
Premise 1: The electromagnetic field or magnetic field value increases away from the metal and towards the source, reader.

Premise2: When the metal is NOT in place, the electro magnetic field must be stronger at given positions.

Premise3: When the metal is in place, the magnetic field must be weaker.

Premise 4: The effect of eddy currents decreases away from the metal.

Thus, it was expected that the ratio of magnetic field when metal is in present to magnetic field when metal is not present increases away from the metal because the effect of eddy current away from the metal decreases.

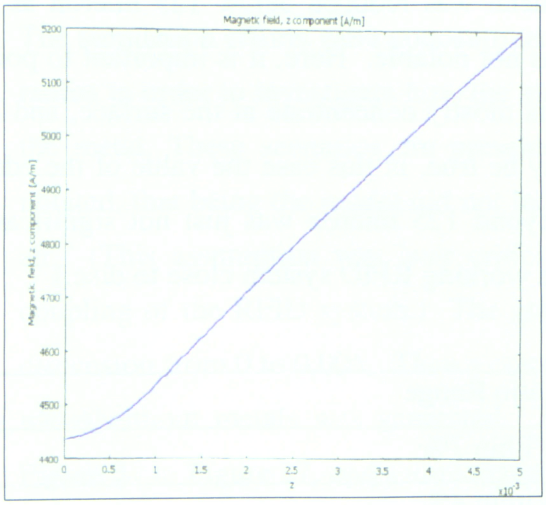
Simulations results showed that the above premises were true when the thickness was significant. However, as the thickness of the metal was reduced below 125 micron as in Figures 26 a-c and Figures 27 a-c, the impact was not notable. Here, it is important to point out the conventional theory that the eddy currents mostly concentrate at the surface, and its value reduces as depth increases. While that may be true, in this case the value of the eddy currents generated for metal below thickness beyond 125 micron was just not significant. (These results indicate that it is possible to build a working RFID system close to disc.)

Table 3: Altering the thickness of the metal

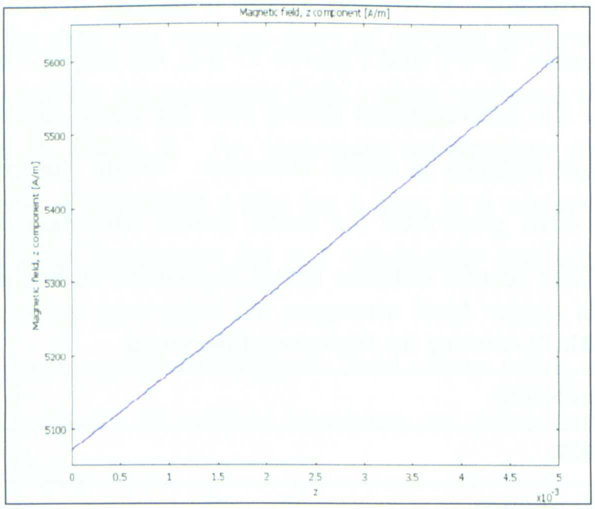
Thickness	Ratio Range
1 mm	Within 7%
500 micron	Within 4%
250 micron	Within 2%
125 micron	Within 1%
<125 micron	Not Significant

Thus, the overall conclusion that can be reached from the first set of simulations is that as the thickness increases the impact on the magnetic field near the metal surface increases. Noting the existence of eddy current, this is probably due to its effect. That is as the thickness increases it causes an increase in the value of value of eddy current as well. As the thickness decreases the impact become negligible and random for the short duration under consideration.

Disc 1 – thickness = 1mm, radius = 3cm



(a) Disc1 with metal



(b) Disc 1 without metal (free)

Figure 21: Magnetic field values along z

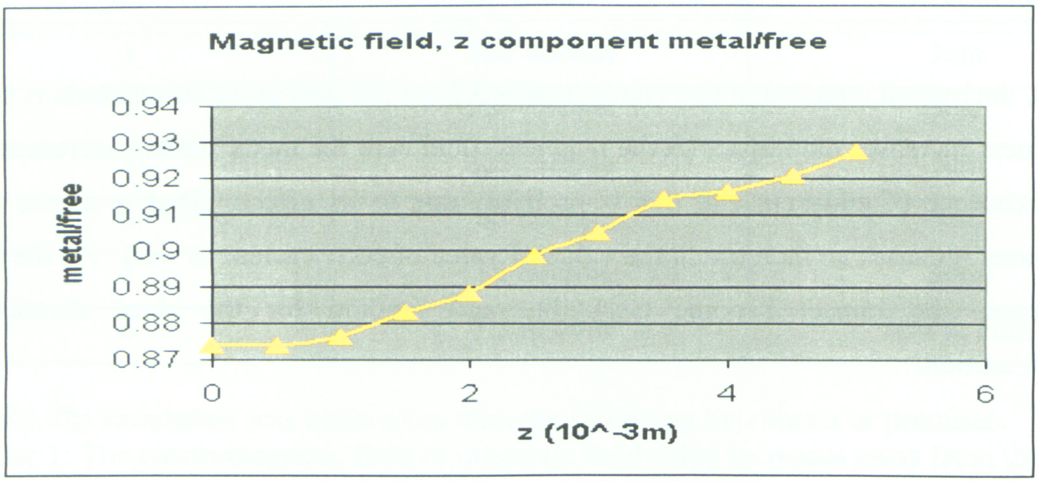
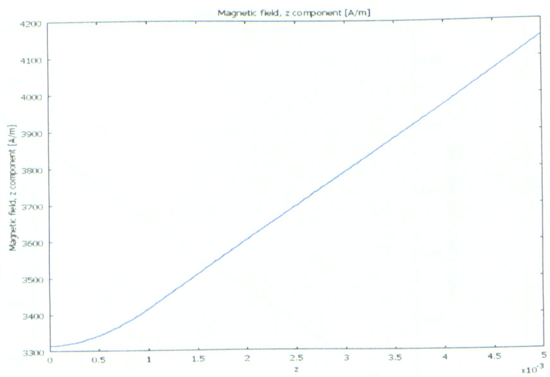


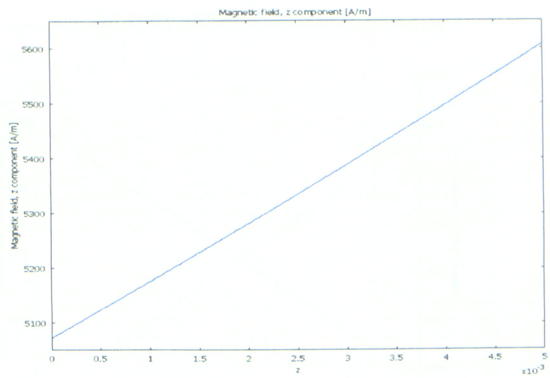
Figure 21 – c: Disc 1 metal/free Ratio

It can be observed that the ratio goes from 0.87 to 0.97 which is about 6% change. Very near the impact is notable and decreases away from the metal.

Disc 2 – thickness = 1mm, radius = 5cm



(a) Disc 2 with metal



(b) Disc 2 without metal

Figure 22: Magnetic field values along z

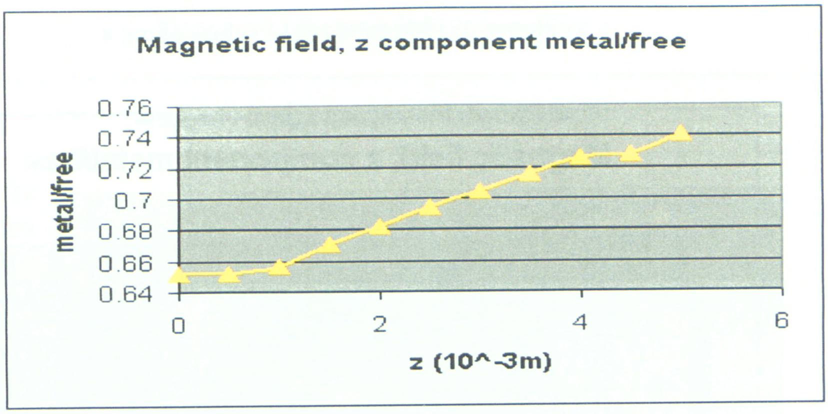
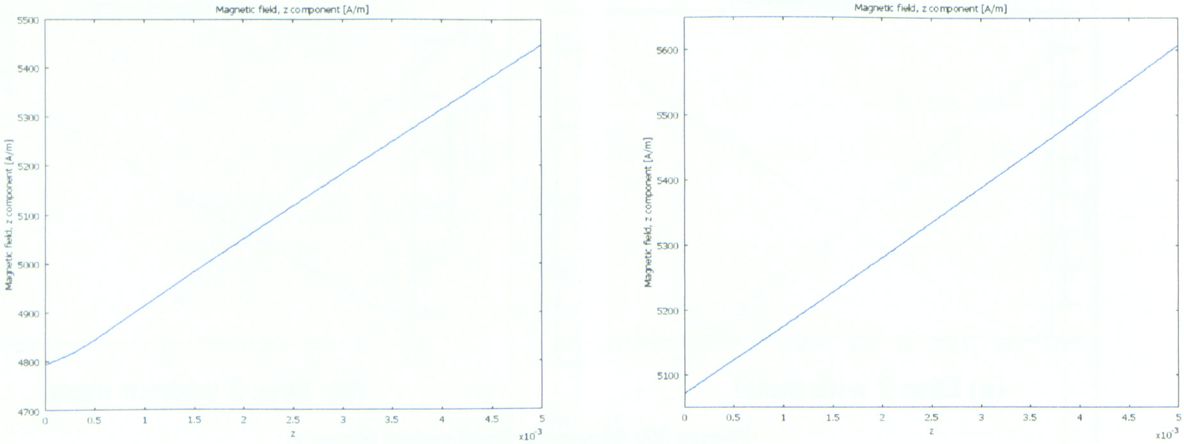


Figure 22 – c: Disc 2 metal/free Ratio

Note here that disc 2 thickness is same, but the radius is different. The impact is significantly higher when the surface area is increased for the same thickness. This is further investigated in Case 2.

Disc 3 – thickness = 500micron, radius=3cm



(a) Disc 3 with metal (b)Disc 3 without metal (free)

Figure 23: Magnetic field values along z

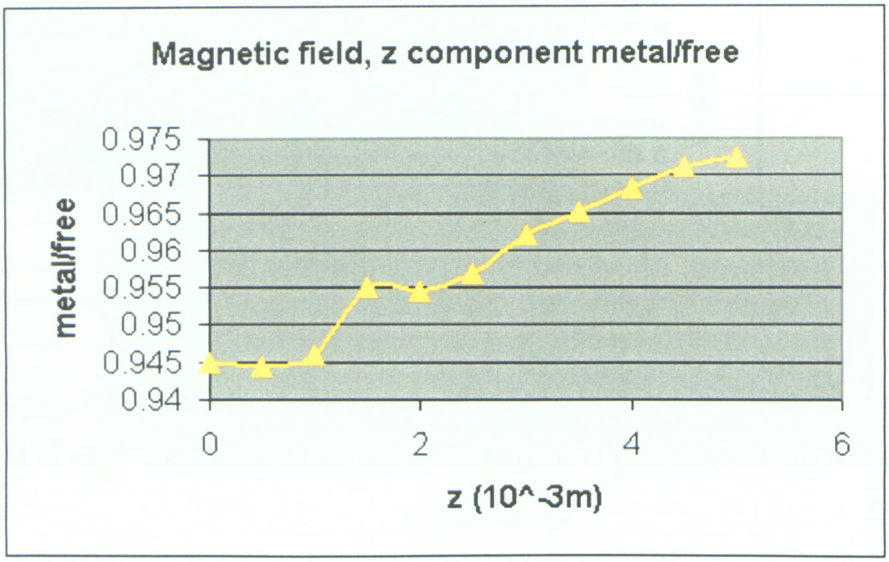
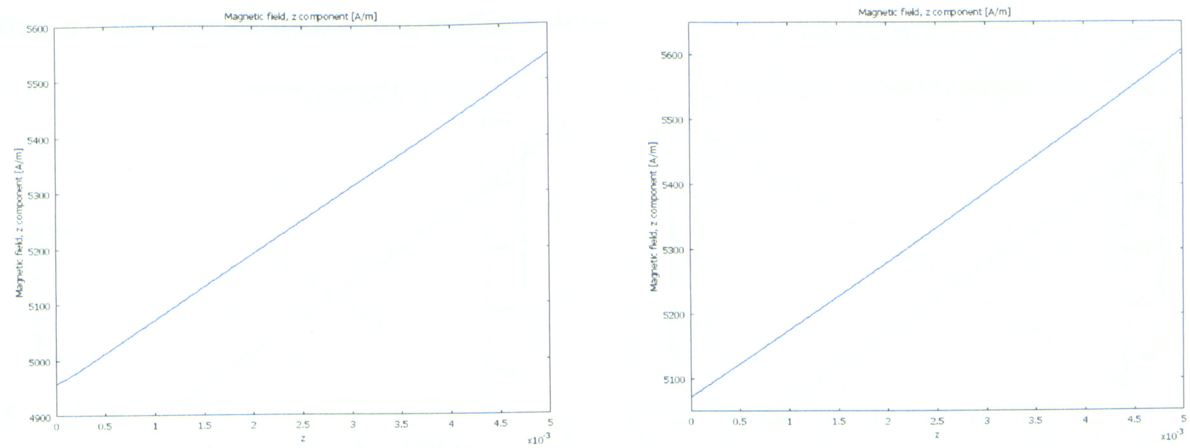


Figure 23 – c: Disc 3 metal/free Ratio

In comparing thickness 1mm and 500 micron, the ratio decreases.

Disc 4 – thickness = 250 micron, radius = 3cm



(a) Disc 4 with metal (b) Disc 4 without metal (free)

Figure 24: Magnetic field values along z

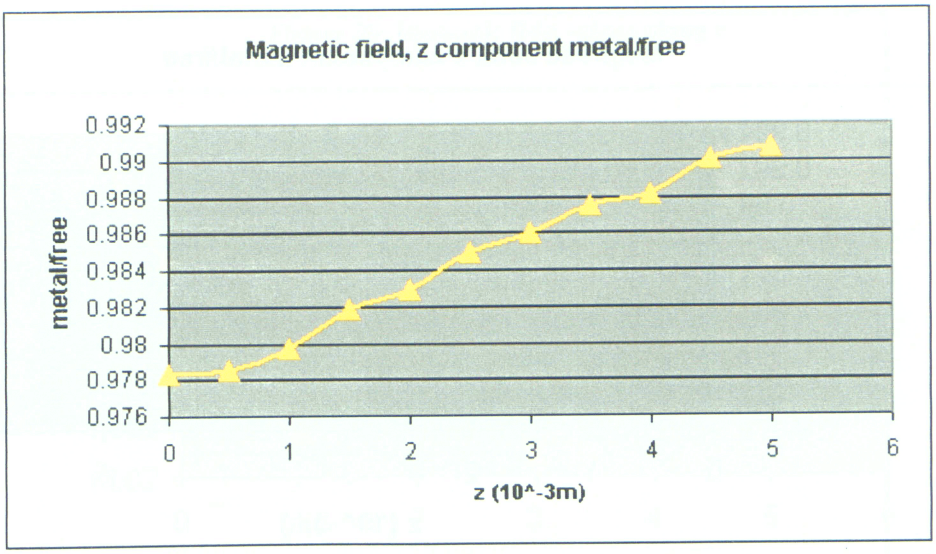
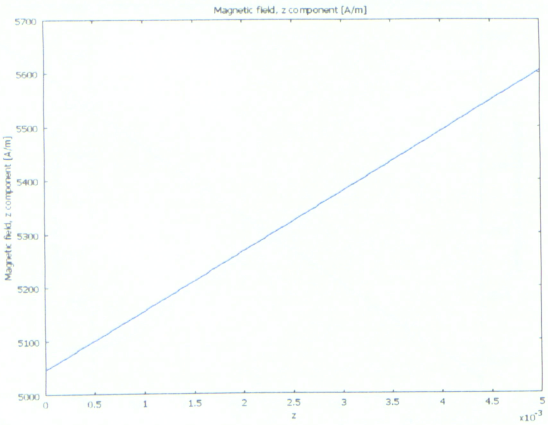
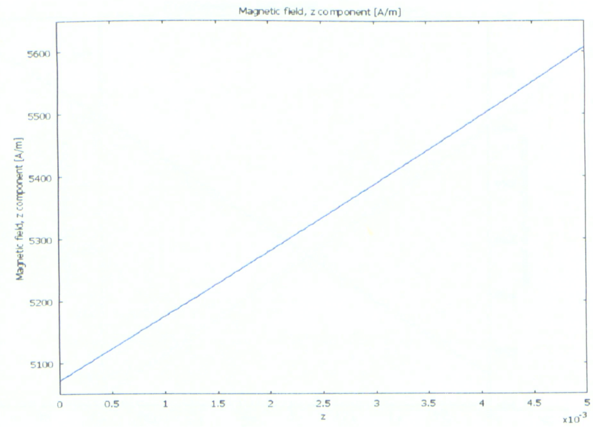


Figure 16 – c: Disc 4 metal/free Ratio

In comparing thickness 1mm and 500 micron, and 250 micron, the ratio range decreases or goes toward 1.

Disc 5 – thickness = 125 micron, radius = 3cm

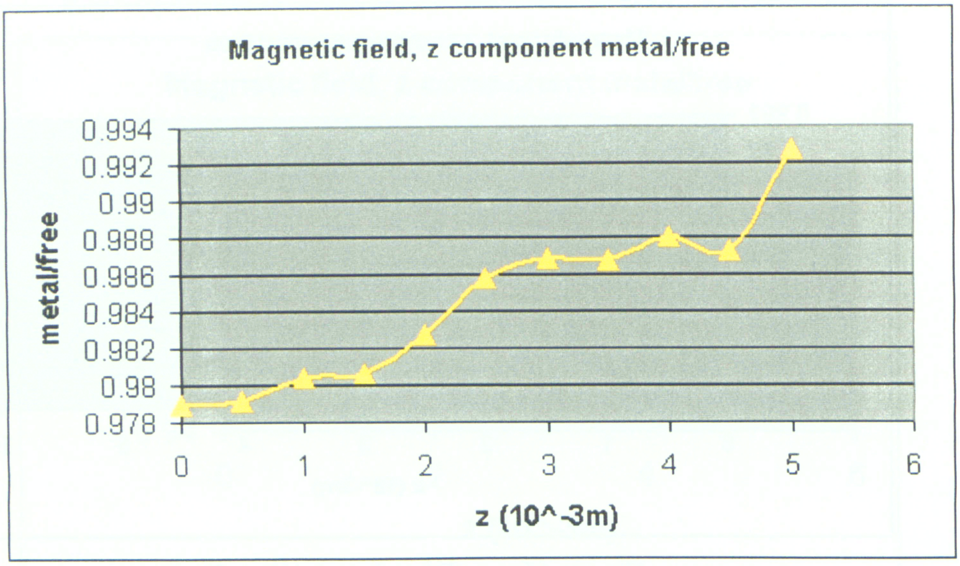




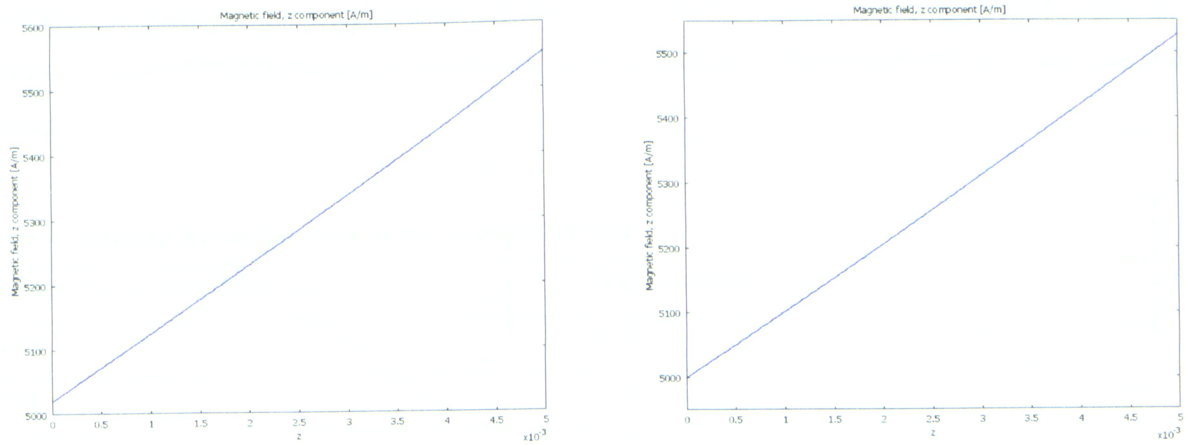
(b)Disc 5 with metal

(a) Disc 5 without metal (free)

Figure 25: Magnetic field values along z

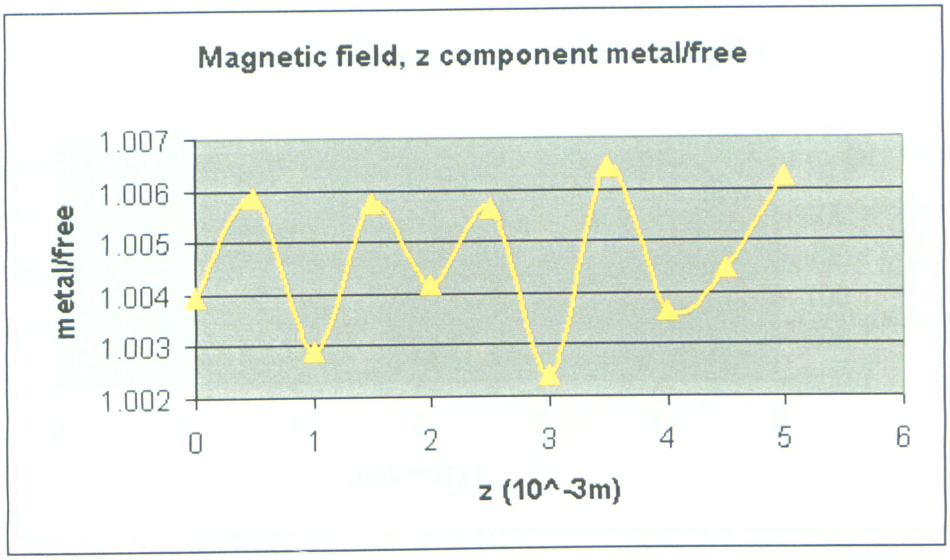


Disc 6 – thickness = 60 micron, radius = 3cm



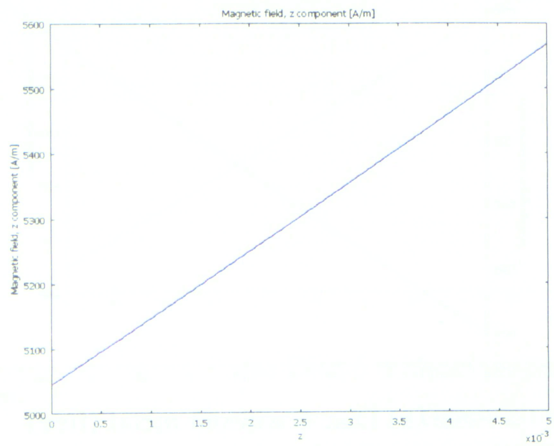
(a) Disc 6 with metal (b) Disc 6 without metal (free)

Figure 26: Magnetic field values along z



Disc 7 – thickness = 15 micron, radius = 3cm

(a) Disc 7 with metal



(b) Disc 7 without metal

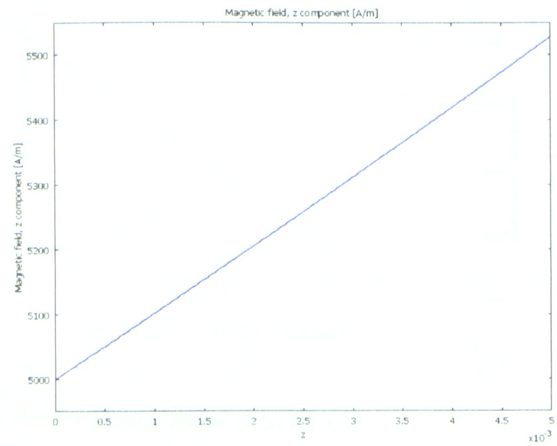


Figure 27: Magnetic field values along z

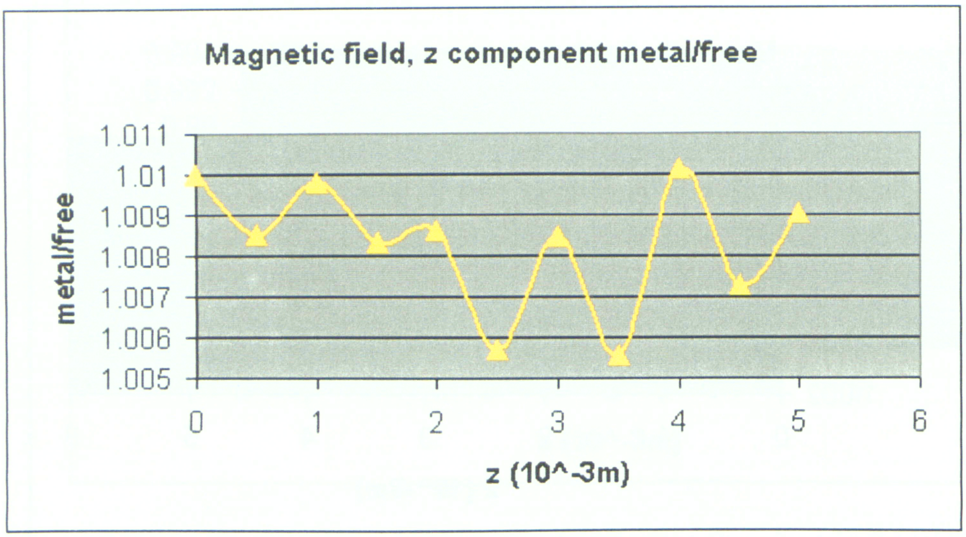


Figure 27 – c: Disc 7 metal/free Ratio

7.3 Altering the surface area or the radius of the disc

The second case investigated was how the radius impacted the magnetic field and eddy currents. The graphs are generated for magnetic field values for the specified topology (Figure 15) at r=0.02 m, along z dimension from 0 to 0.005. The results clearly indicate the impact.

Table 4: Altering the surface area or the radius of the disc

Radius (for 1 mm thick disc)	Ratio (metal/free)
3 cm	0.87
5 cm	0.64
7 cm	0.5
9 cm	0.3
11 cm	0.25

The Figure 29, 30, and 31 are graphs of magnetic field values when metals were in place for radius 0.07 m, 0.09m, and 0.11m. The range for magnetic field values when metal was not in place is between about 5100 [A/m] to 5400 [A/m]. When radius is 0.03 m, and 0.05 m the values range from 4400 to 5100 [A/m] and 3300 to 4100 [A/m], comparable to disc 1 and disc 2.

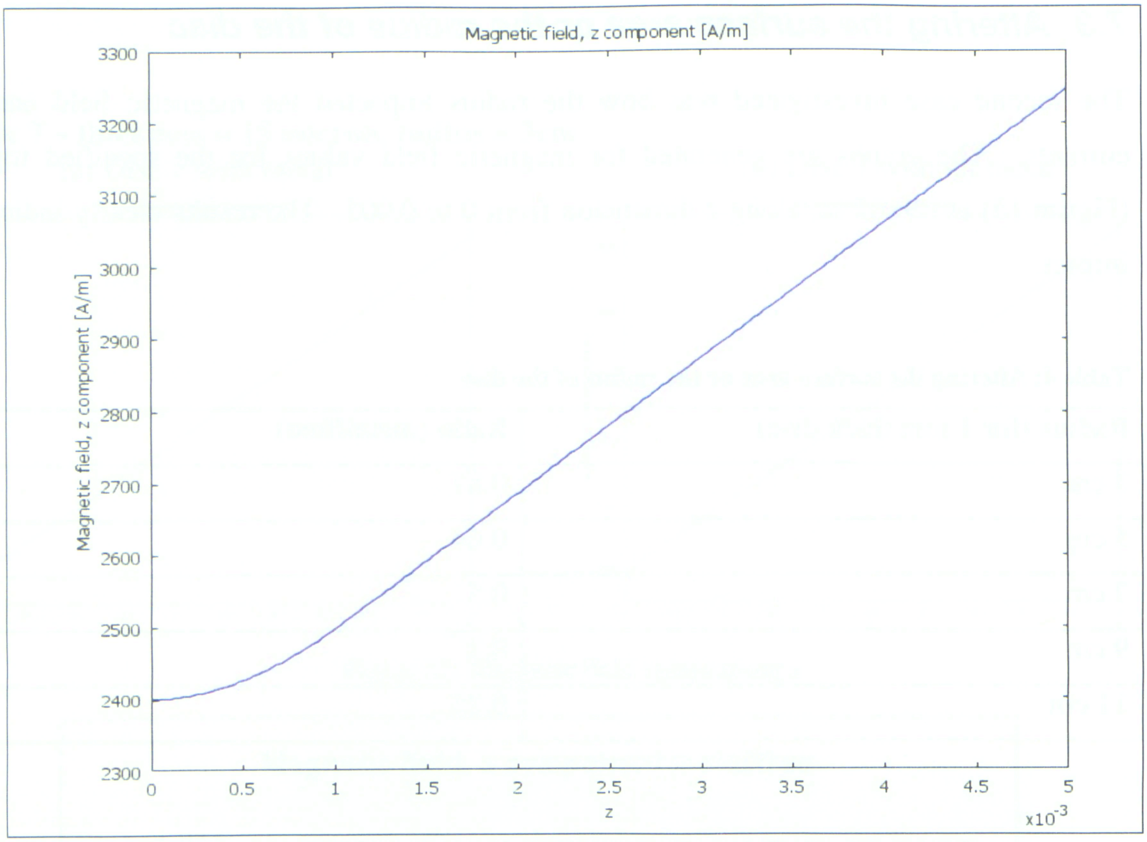


Figure 28: Altering Surface area; r=0.07m, values go from 2400 to 3300 [A/m] (at r=0.02); 1mm thickness

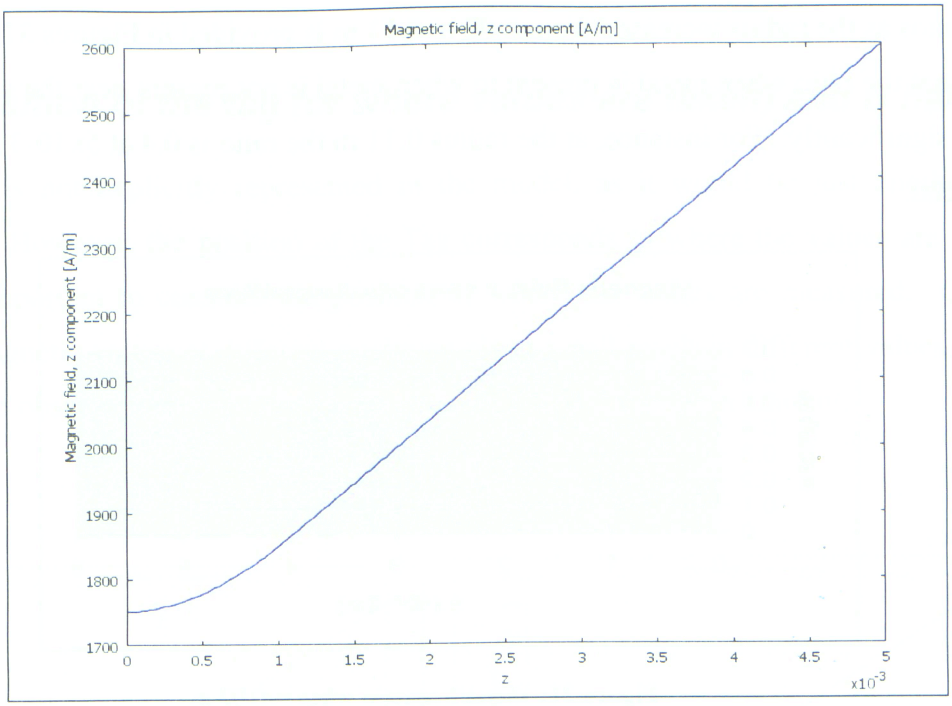


Figure 29: Altering surface area; r=0.09m, values go from 1700 to 2600 [A/m] (at r=0.02); 1mm thickness

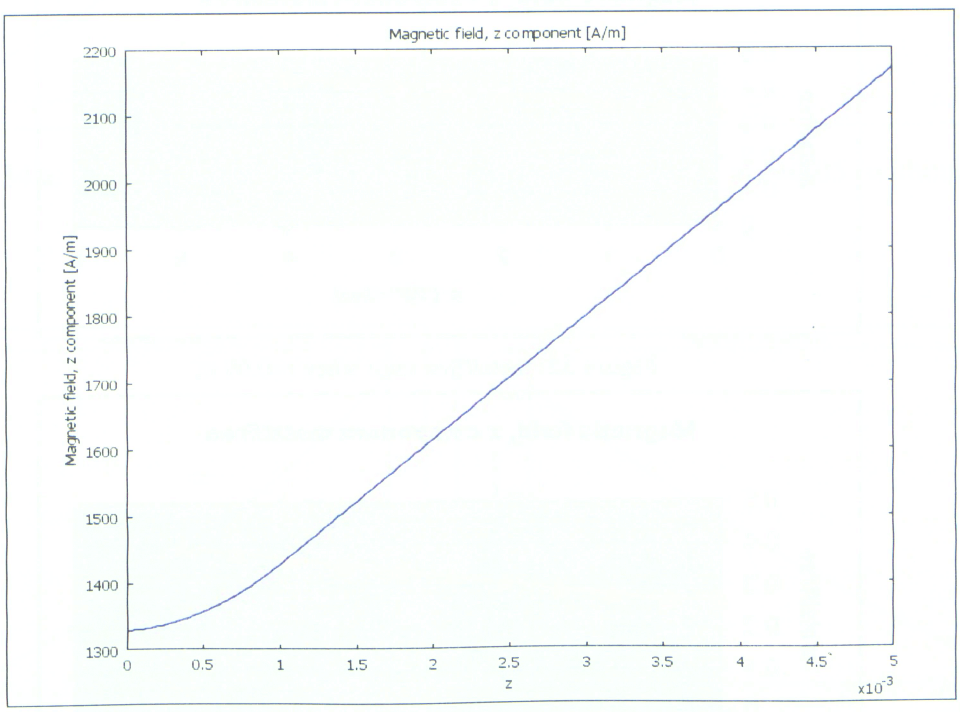


Figure 30: Altering surface area; r=0.11m, values go from 1300 to 2200 [A/m] (at r=0.02); 1mm thickness

The ratios as the radius increased from 0.07 to 0.11 m is provided in Figures 31, 32, and 33. Note that the ratio when metal is present to when metal is not present near the surface goes down significantly. For instance, at the radius 0.11 m the ratio is 0.4 at 5x10-3 m away from the metal.

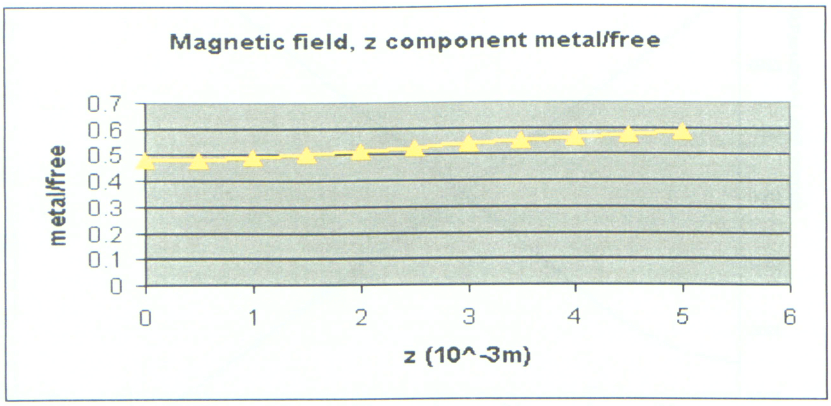


Figure 31: metal/free ratio when r=0.07 m

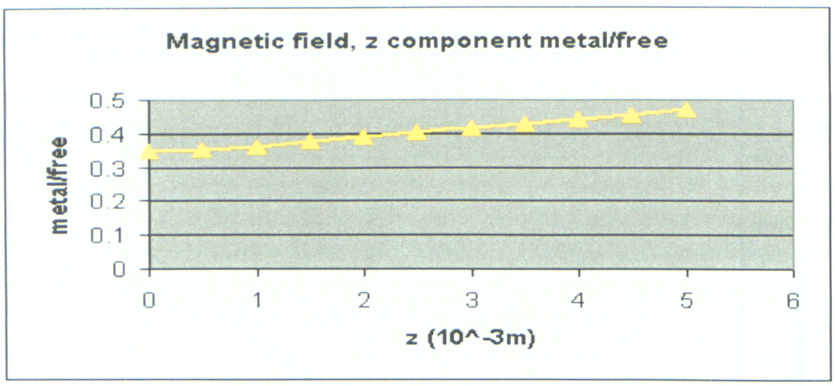


Figure 32: metal/free ratio when r=0.09 m

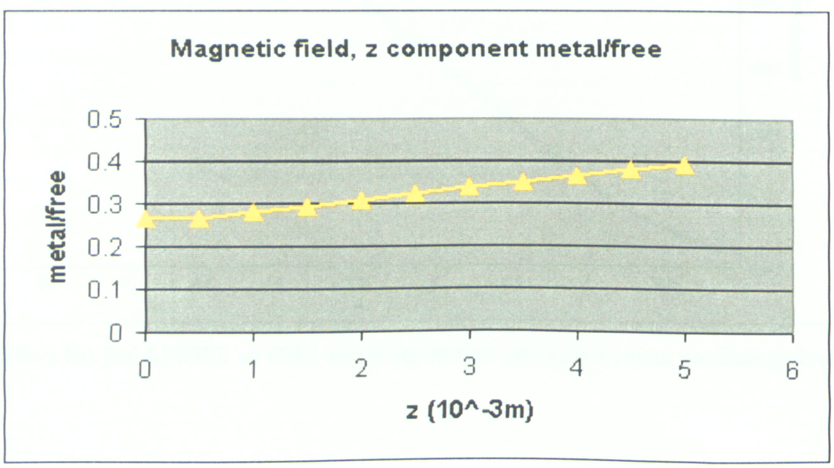


Figure 33: metal/free ratio when r=0.11 m

7.4 Position of the tag (or where values are taken) and B field

The Tag is not explicitly represented in the model, as it would be just another passive material. However, the position of the Tag corresponds to where the values are measured. This is important to consider the position of where the values are measured. Obviously, taking magnetic values at different positions along r will result in different values, and from qualitative observations for z component that would be decrease in amount.

Figure 34

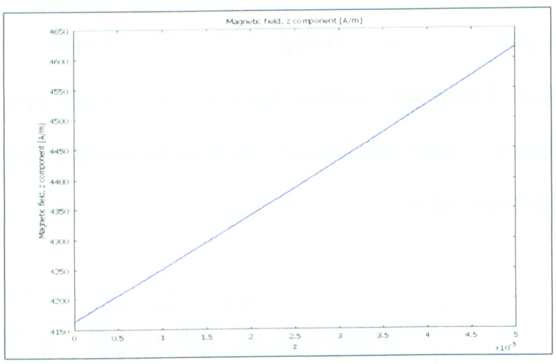


Figure 34 a: disc5 at r=0.05 (with metal)

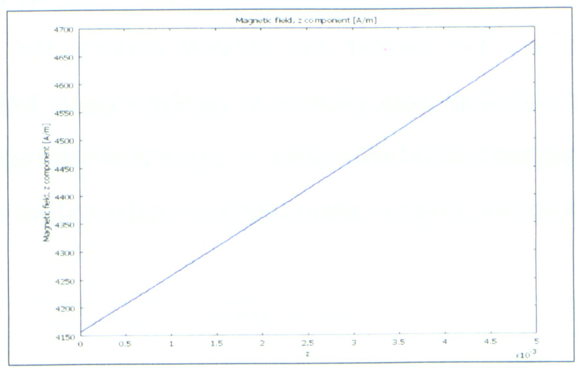


Figure 34 b: disc5 at r=0.05 (without metal)

Figure 35:

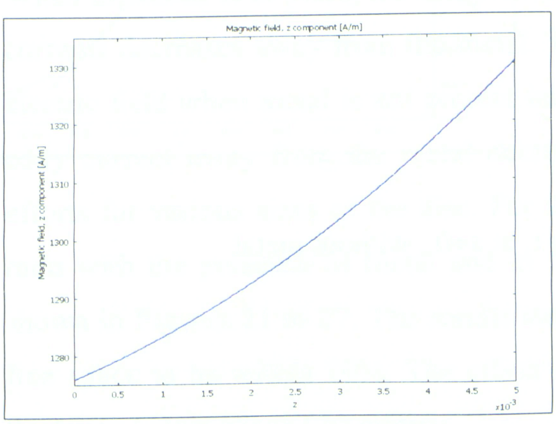


Figure 34a: disc5 at r=0.1 (with metal)

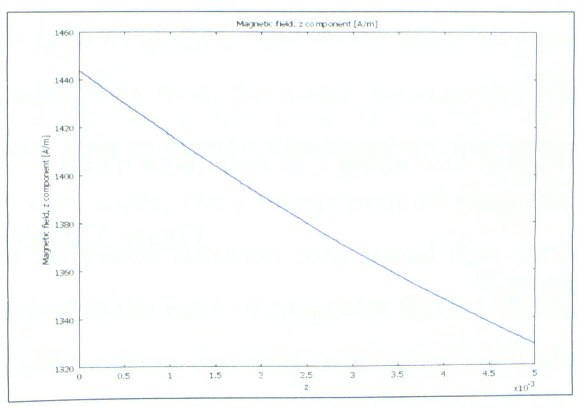


Figure 34b: disc5 at r=0.1 (without metal)

Comparing Figures 34 and Figure 35 show that taking the values at different position along r has notable impact on the overall result.

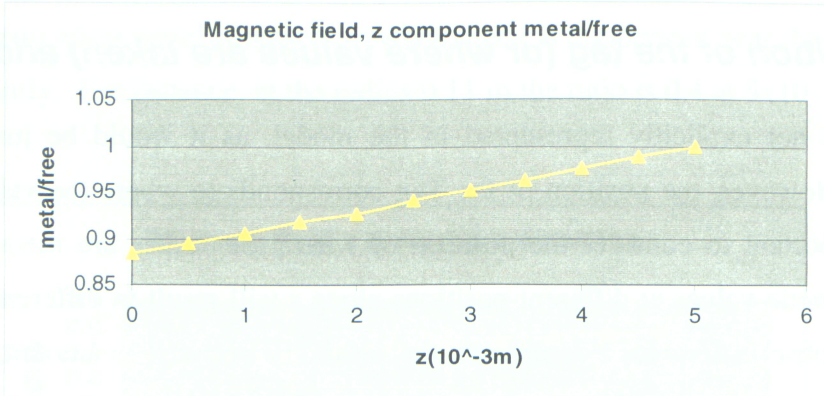


Figure 36: Altering the position; disc 5 at position at r= 0.1

In the above observations, the data was only recorded for a given radius over smaller range of z. To observe the general pattern, the magnetic values along r, for the range of r at z=0.012 m was plotted as in the figures below. The disc radius was 3 cm. It shows that magnetic field decreases in general when metal is not present, but when the metal is present a constant value is maintained over the radius of the metal.

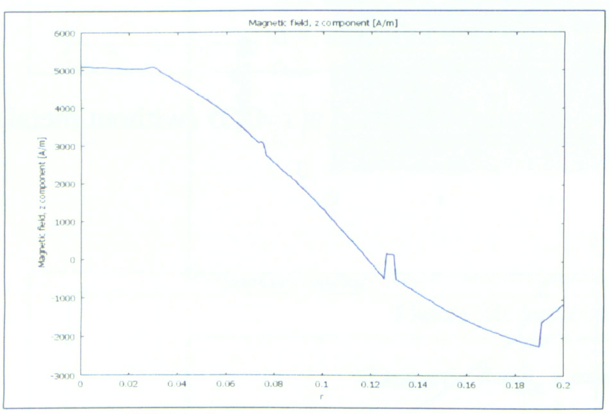


Figure 37a: along r, at z=0 , with metal

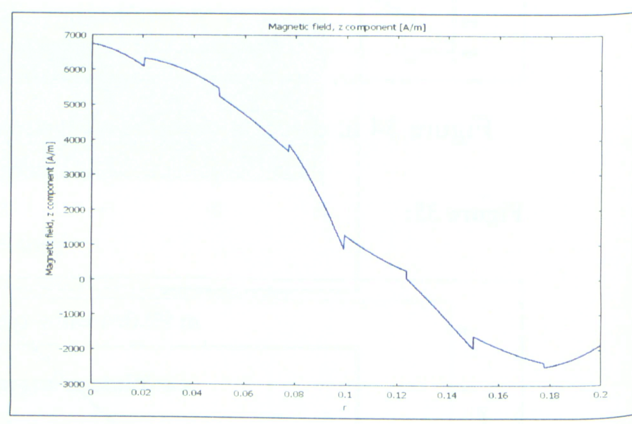


Figure 37b: along r, at z=0 , without metal

Figure 37

7.5 Factors that can impact the simulation magnetic field values

There are various other factors and simulation conditions that can impact the value of the magnetic field. For instance, altering the field size can impact the magnetic field values. Increasing the field size increased the magnetic values taken near the metal surface. The field size needs to be consistent in comparing a set of results.

Another consideration is how the boundary conditions get specified and its impact upon the magnetic field values. The source current can be specified either as surface area current density (A/m2) or an edge current density (A/m); otherwise, continuity boundary condition is suitable.

Altering the loop potential between the coil, and altering the frequency are two other considerations that were not fully explored in this study. Also, the permeability and saturation induction of the material itself can have notable impact on the magnetic field.

7.6 Results Summary

Magnetic field value increased away from the metal and towards the source or the RFID Reader. When the metal is not in place, the magnetic field was stronger at any given position. When the metal is in place, the magnetic field was weaker near the metal. The effect of eddy currents decreases away from the metal. The ratio of electric field when metal is present to electric field when metal is not present increases away from the metal, because the effect of eddy current away from the metal decreases. This is clearly illustrated in the simulation efforts for various sizes of the disc. For this case study, the z component of magnetic field ratio with the presence of metal and in free air versus distance over metal disc surface is shown in Figures 21 to 27. The results indicate that the ratio of magnetic field with metal to free space to be within 10%. The effect of eddy current can said to become negligible for thickness below about 125 micron.

In addition, the radiuses of the disc, and the position of the tag or the position where the values are taken impact the eddy currents and the magnetic values. The greater the radius, the greater the impact upon the magnetic field and eddy currents that are generated. The current in the primary loop is directionally proportional to the magnetic field generated, and the proportional constant is the inductance. This relation was adequately reflected in the model, as increasing the source current proportionally increased the value of the magnetic field.

8 Conclusion

The fundamental principal governing electromagnetic coupling between a tag and its reader in an RFID system have been simulated using COMSOL finite element analysis software. Electromagnetic compatibility in the presence of metal was investigated, and some of the interesting consequences for RFID operation have been identified. The aim was to calculate the electromagnetic field values in the presence of the metallic disc and in free air. The field at different positions over the disc was compared to the flux at the same positions when the disc is not present. The simulation efforts have been performed for different radius and thickness of the disc.

The simulation results obtained established that the ratio of magnetic field values when metal is present /free goes to 1 as the z increases or away from the metal. The thickness of the metal impacts the metal/free ratio. When the t is large the ratio is high, and after minimum thickness the ratio is not significant. For proportional alteration in radius, the impact is significantly higher. That is higher metal/free magnetic values near the surface. This can be explained in terms of eddy currents theory, where eddy currents exist mainly at the surface and decrease exponentially along depth. The exact relative importance can be verified by further parametric studies using the developed models and simulation. Moreover, the position of the tag obviously alters the ratio. Along r (as r increases), the ratio tends to become notable. But this must be taken into consideration with the overall magnetic field behavior.

Reviewers of this paper noted that the modeling and simulation was not adequate in capturing the coupling of the inductors. In particular the absence of Tag, and explicit coupling was not captured. Thus it did not capture how the metals impacted electromagnetic behavior or values of the entire RFID system. Although, this work highlighted how the physical attributes of the metal impacted the electromagnetic values generated by the RFID Readers, the criticism that it did not explicitly model the coupling is valid. This can be investigated further, and adjusted to in future work.

In general, this work emphasizes the importance of considering the physical parameters of the metals in packaging or in other RFID applications. It has been shown that RFID systems compatibility issues in proximity to metals are critical and must be considered during their early design phase.

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10 Appendix

10.1 COMSOL

10.1.1 Why COMSOL? – The General Case

The problem definition, the theoretical description of the RFID System model, and the literature review lead to COMSOL as an appropriate software to capture the electromagnetic essence. COMSOL or FEMLAB (Finite Element Modeling Laboratory) application software allows for in integrated finite element, and equation based mathematical modeling, simulation, analysis, and visualization of physical phenomena that involve solving PDEs. Finite element method (FEM) is a way to solve partial differential equation (PDE) using numerical methods, or by converting to ordinary differential equations (ODE) which have analytical solutions. Finite Difference Method (FDM) can be thought of as a subset of FEM. COMSOL employs FEM to solve problems involving PDEs,

COMSOL is designed to handle multiphysics modeling. Multiphysics modeling is where problems from different physical fields are coupled together to solve a problem. The power of COMSOL is that it does not require extensive mathematical analysis in order to model the problem and to solve it. "By using the built in physical modes it is possible to build models by defining the relevant physical quantities such as material properties, loads, constraints, sources, and fluxes rather than by defining the underlying equations."

10.1.2 COMSOL Problem Definition and Platform

Before the physics problem can be simulated and analyzed, it needs to be clearly understood. This may involve identifying PDE or simpler equations relevant to the problem, the geometry governing the problem, and the parameters which you want to solve for and graph.

FEMLAB is designed to facilitate computation involving mainly modern physics and chemistry problems. At Ryerson University the FEMLAB is located at ee network

Engineering Tools folder. The user interface is GUI based, but can also be program driven (code based). Also, it can work with the popular MATLAB. The model file extension is .mph. The old version also used .fl. Various MATLAB data file extensions are recognized well. Also, the graphical results can be saved into different files as well.

10.1.3 COMSOL Modeling Process

Step1: Selecting the Application Domain and Modes

From the theoretical requirements the user would know whether the simulation need to be *2D* or *3D*, and also which *Applications Modes* are necessary. FEMLAB facilitates multiple *Application Modes*.

Starting FEMLAB Application takes to the screen with Tab options New, Model Library, User Models, and Setting. The user must select the appropriate physics module or modules in the New tab. For any given module the default dependent variable, application mode name, and element are given. The user can change the dependent variable. The element is the particular FEM used.

Step2: Setting up the Work Settings

Units

FEMLAB allows you to select various standards. SI units is the default setting; and one can verify that by Options -> Units.

Constants

Constants can be defined and used in expressions. The constant menu is under the Options menu.

Grid and Axis

Set the grid and axis to suit model requirements in the *Options* menu. In particular, the maximum, minimum values of x, y, z gird, and steps can be adjusted.

Step3: Drawing the Geometrical Model

From the *Draw* in the Menu or by drag and draw from the tool box, the physical setup of the problem can be defined. If in other modes one can switch to Draw Mode by selecting it from the Draw Menu. There you can also Specify Objects and also change object properties. FEMLAB allows for various operations to be performed with the objects of the objects to facilitate complex geometric modeling.

Step4: Defining the Physical Settings
There are primarily two ways to define the physical characteristics of the model. The two ways Subdomain Settings and Boundary Conditions. They are also referred to as the Subdomain Mode and Boundary Mode. In the Subdomain Settings one mainly sets the material properties of the model. Boundary conditions define the interactive settings between as well as other behavior.

Step5: Mesh Initiation, Creation, and Solving
Various mesh parameters can be set from the Mesh menu. Also, there exist various solvers that can be selected from Solver Parameters. Selecting appropriate solvers, and mesh parameters would need to be carefully considered for complex geometries and physical phenomena; however, for relatively simple problems defaults should perform well.

Step6: Post-Processing
Allows you to automatically graph various relevant information. Using the Postprocessing mode quick buttons it is possible to graph separately, and certain graphs superimposed on each other up to seven types of graphs, including streamline, contour, vector, and 3D. In the Postprocessing mode you can also analysis how values of certain variables and have changed in a given position. Also, various integration and other operation can be done with available data.

10.2 Technical Terms and Details

Transducer
"A transducer is an electronic device that converts energy from one form to another. Common examples include microphones, loudspeakers, thermometers, position and pressure sensors, and antenna."

Transmitter
"A transmitter is an electronic device which with the aid of an antenna propagates an EM wave such as radio. A transmitter usually has a power supply, an oscillator, a modulator, and amplifiers."

Electric Dipole
It is well established that an electric dipole antenna can be formed by exciting complementary currents in two thin wires; whereas, the magnetic dipole antenna can be constructed by a wire loop with current flowing in or by a radiating slot.

Decibels
Gain in dB = 10 * log(Gain factor)

Gain Factor	Bel	dB
1000	3	30
100	2	20
10	1	10
2	.3	3
1	0	0
0.5	0.3	-3
0.1	-1	-10
0.01	-2	-20
0.001	-3	-30

Electromagnetic Spectrum
Wavelength = Speed of the wave / Frequency
We are working within the range of 125 kHz to 13.5 MHz. That is about 2400 m to 22m.
(The communication between Tag and the Reader is based on electromagnetic signals of 125 kHz (, 13.5 MHz.)

Two types of Antennas
Electric Dipole Antennas (couples E field) – length wire
Magnetic Coupling Antenna (couples B field) – coil

Azimuthal Current
Azimuthal current refers to the current along the phi component or the azimuthal angle. Azimuthal angle is measured from the x-axis in the horizontal plane (xy plan). It is usually measured counter clockwise.