MAGNETIC INDUCTION COMMUNICATION IN CHALLENGING ENVIRONMENTS

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ABSTRACT

Radio frequency (RF) communication, although most popular, is unsuitable for environments involving aqueous and animal/plant tissue media, cluttered environments (e.g., small regions with many radios), applications requiring extremely low power consumption, etc. For such environments, magnetic induction (MI) communication appears to be a viable new technology. It has many desirable properties for propagation in challenging environments. In this thesis, we have experimentally explored the use of Magnetic Induction (MI) based communications for communication through the body. Such communication modalities are essential for wireless communication between implanted therapeutic devices. RF is known to work poorly in this environment due to primarily an ionized aqueous propagation media. We have built a custom experimental testbed using magnetic coils and performed simulations of intrabody propagation for MI based communication using the Sim4Life package. Ultrasound (US) communications have been explored extensively for intra-body environments, and we compare MI against US as well. We experimentally showed that ultrasonic coupling (USC) works better than magnetic resonance coupling (MRC) for transmission through the body at 8 MHz frequency, as USC generates more power than MRC. We have also experimentally compared MR coupling against other forms of intra-body communication, such as galvanic and capacitive. We have done a deep in-depth study of in/on body simulation. According to those studies, the simulations work quite well, and yield a percentage error in the power received for USC as 3-4%, while for MRC, as 4-5 %. The orientation of USC and MRC sensors causes only 1-2% error, which doesn't have much impact.

To my Father, Late S. Parminder Singh Gulati.

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LIST OF ABBREVIATIONS

Abbreviation	Explanation
MI	Magnetic Induction
USC	Ultrasonic Communication
MR	Magnetic Resonance
MRC	Magnetic Resonance Communication
BER	Bit Error Rate
GC	Galvanic coupling
CC	Capactive Coupling
PER	Packet Error Rate
SAW	Surface Acoustic Wave

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CHAPTER 1

INTRODUCTION

1.1 Overview

Effective management of emerging medical devices can lead to new insights in healthcare. Thus, Human Body Communication (HBC) is becoming increasingly important. Biomedical systems of implanted miniaturized sensors and actuators interconnected into an intra-body area network could revolutionize treatment options for chronic diseases afflicting internal organs. Considering the well-understood limitations of radio frequency (RF) propagation in the human body, Magnetic Resonance coupling (MRC) has been explored for both communications and energy transfer through the body. MRC acts as a promising method for the intra-body network (IBNet). HBC has also been explored extensively both for small wearable electronic gadgets and for implanted sensors to deliver relevant data to implanted therapeutic devices. For on-body, two promising technologies, ultrasound coupling (USC) and MRC based communications have emerged as the basis for performing communication. Both of these technologies have capability to propagate signals much better through the body than in the air, thereby making them attractive for communications between in-body nodes, in-body to on-body nodes, and on-body nodes where the direct path includes substantial body area. Magnetic Induction (MI) communications have also been emerged as an attractive technology for environments involving aqueous and animal/plant tissue media, dense environments (e.g., small regions with many radios), applications requiring extremely low power consumption. In these instances, Radio Frequency (RF) communications could not work better, as they work for the conventional in-air communication networks in the communication world. MI communication has been studied for some RF-challenged environments such as underwater, underground and body area networks, most of the studies were simulation based with minimal experimentation. With this introductory review, we will describe the detailed review of the related literature as follows.

1.2 Magnetic Resonance Coupling (MRC) Method

Statistical data suggests that in USA approximately 45%, or 133 million people suffer from at least one chronic disease [1] and more than 50% of older adults suffer from $\geq$ 3 chronic conditions [2]. In some chronic diseases or natural function defects of organs, the formation of a therapeutic network of multiple sensors and actuators in the body can achieve unprecedented consequences [3–5].

All these applications require robust and highly energy efficient means of HBC, i.e., communication between intra-body nodes (or on-body nodes entirely through the body media). The limitations of RF communications for HBC are well known [6, 7] and several alternative technologies have been proposed, but their relative merits in terms of data transfer are not very clear. The HBC signal propagation methods can be classified as Galvanic Coupling (GC) [8, 9], Capacitive Coupling (CC) [10, 11], and Magnetic Resonance Coupling (MRC) [12, 13]. GC coupling does not provide a very efficient way of energy transfer or communication across the body. Capacitive coupling is heavily affected by the local electrical environment [11, 14] making it inefficient for wearable and implantable applications, hence not considered. The MRC couple transmitter and receiver through the magnetic flux through identical inductive coil in parallel with an identical capacitor to form a resonant LC circuit that can transfer energy quite efficiently at the resonance frequency. It works much better through the body than GC and CC. MRC has been studied in the past, there are no comprehensive results for packet loss rate as a function of packet size and in-body distance. Proposed work experimentally studies the performance of packet transmission through the body via MRC.

Figure 1.1. Illustration of intra-body power/data transmission network.

1.3 Performance Evaluation of MRC for Intra-Body Network

The medical community is witnessing significant development of implantable medical devices due to the advancements in integrated circuits, Micro Electro Mechanical Systems (MEMS), wireless systems, and battery technologies, since the arrival of pacemakers [15]. Some chronic diseases or deficiencies in natural function of organs, forming a therapeutic network of multiple sensors and actuators inside the body can enable unprecedented consequences. In view of long-term and continuous monitoring, effective chronic disease management using Implantable Medical Devices (IMD) requires long-term and continuous operation; thus, an Intra-Body Network (IBNet) is becoming increasingly important, further spurred by the advances in ultralow- power electronics and communications [16]. Fig. 1.1 Illustration of intrabody power/data transmission network.

It allows the transfer of data and energy among implantable hubs/sensors, as well as to wearable device nodes (e.g., smartwatch). RF technology suffers from poor transmission through biological tissue. It also needs a relatively large antenna, which limits how small the implantable devices can be and prevents implantation in organs such as the brain, heart, and spinal cord without causing significant damage. To overcome the shortcomings of RF coupling, most probable alternatives are GC, CC, or magnetic induction/resonance coupling (MI/MR). The proposed MRC is more efficient within biological tissue due to lower path loss achieved by employing the resonating behaviour of the coils. It enables transmitting at optimal power to a higher link distance. Three Intra-body Network (IBNet) coupling methods are compared in terms of path loss. MRC emerged as the most suitable technology for the IBNet since the magnetic permeability of the soft tissue is similar to that for the air [17]

1.4 Coupling methods for IBNet

Coupling methods for IBNet: Three standard signal coupling methods for IBNet and HBC, galvanic, capacitive, and magnetic resonance (MR) coupling are illustrated in Fig.1.2.

1.5 Galvanic Coupling

The Galvanic HBC is the coupling of the signal to the human body through a pair of electrodes in contact with the skin to be used as a transmitter (T_x) and receiver (R_x) , as shown in Fig. 1.2(a). When a differential signal is applied, (T_x) couples the signal to the body by producing a primary current flow and induces galvanic currents (secondary flow) to the (R_x). Since only a small fraction of the current goes across the longer path from $T_{x(+)}$ to $R_{x(+)}$ (and back from $R_{x(-)}$ to $T_{x(-)}$), it is generally not an energy efficient coupling method. Furthermore, the relatively low conductivity of the human body may cause rapid signal decays with the distance, resulting in large path loss compared to other approaches [18] On the positive side, this method does

Figure 1.2. Intra-body coupling methods: (a) galvanic coupling, (b) capacitive coupling, and (c) magnetic resonance (MR) coupling and equivalent circuit.

not require an external ground, so it is a reasonably suitable coupling method for wearable and implantable devices.

1.6 Capacitive Coupling

The capacitive coupling (also known as electrostatic coupling) uses a pair of electrodes as T_x and R_x as shown in Fig. 1.2(b). The signal electrodes are attached to the body capacitively while the corresponding ground electrodes are left floating, which creates a capacitance with the environment (earth, air, or other objects in the surrounding). The capacitive coupling mechanism can be modelled as distributed RC circuits [19]. The capacitive coupling from the on-body into the muscle experiences a significant signal loss, but the signal flow inside the body does not experience much loss and is mostly insensitive to the distance travelled [20]. Additionally, due to the weak nature of the received signal and high dependability on the surrounding environment, capacitive coupling in IBNet usually works at short-range making it unusable for use with implantable/wearable devices at a longer distance. [11, 14]

1.7 Magnetic Resonance Coupling (MRC)

The magnetic resonance coupling refers to the signal coupling between the T_x and R_x coils via magnetic flux as shown in Fig. 1.2(c).

The resonance coupling ensures maximum power/signal transfer which also enhances the link distance through the body [13]. The T_x coil generates an oscillating magnetic field that is coupled through the tissue and can be received using a R_x coil placed at other places on the body due to mutual inductance. MRC has two major advantages: (1) magnetic fields travel freely through biological tissues, potentially enabling much lower path loss than both galvanic and capacitive HBC approaches; and (2) there are no requirements about the surrounding environment since magnetic fields can be sensed without a reference. Thus, environmental effects and variance with the human body are minimized. Both advantages serve to reduce the overall power of communication in HBC systems.

1.8 Near-Field Magnetic Induction based Communication System:)

Smart sensing and short-range wireless communications are a crucial element for infusing intelligence into a large variety of physical infrastructures. The conventional RF communication does not suffice the need for the following environments: aqueous or plant/animal tissue media which cause high signal absorption, metallic clutter that creates diffraction or shielding of the signals, or underground operation that results in an extremely complex communications channel. Reducing absorption by choosing lower frequencies helps in attenuation, but needs bigger antennas, which introduces the problem of undesirable size and potentially severe interference with nearby radios.

To suit the communication requirements in aqueous and underground media, Ultrasound communication (USC) serves a better option, however due to limitations of larger size radios and higher power consumption, it cannot operate in a cluttered environment.

To circumvent the aforementioned limitation, MI communication, works on the principle of Resonant Inductive Coupling (RIC), is explored for indicated challenging environments. MI modulates the magnetic field and forms the basis of near field communications (NFC) between MI devices.

When compared with RF, the impact of media such as water or soil is entirely captured by the relative permeability and conductivity of the medium, in MI based communications. Also, MI based techniques have better penetration performance (i.e., low absorption) in the soil, water, rocks as the \magnetic permeability" of them are very similar to that of air, and have predictable channel conditions as MI communications are less susceptible to surrounding environments. RF gets absorbed to a greater extent in these media. IEEE finalized the 1902.1 standards in 2009 that specifies a near-field MI protocol called RuBee operating at low-frequency range of 30-900 KHz [21]. On the other hand, the conductivity of the medium affects the eddy current produced by the time-varying field, and thus influences the MI communication.

Although MI communication has been studied for some RF-challenged environments such as underwater [22], underground [23], body area networks [24] and fresh food logistics [25, 26], many of the studies are simulation based with minimal experimentation. Even if some experimental studies are there in the literature [27,28], the extensive studies of various surrounding factors, mediums and objects on MI communication is still very limited. Some MI based communication products are available, such as audio headphones by NXP [29] and RuBee MI radios [21], but these are commercial products, and thus the comprehensive experimental evaluations of these technologies are sparse. It is thus crucial to build both MI radios and test systems and thoroughly study the channel characteristics in different media. The proposed work shows the experimentation with Freelinc radios, which shows much more complex behaviour.

1.9 Ultrasonic Vs. Magnetic Resonance Communication For Mixed Wearable And Implanted devices

Wearable computing devices [30] which inculcates smart sensing and communications continue to proliferate both for on-body and in-body use. These are used for the functions that contact the body and measure some physiological parameters (e.g., temperature, blood pressure, etc.). The devices may also help augment or enhance human sensing capabilities (e.g., smart glasses or smart hearing aids). They may also be more intrusive and provide stimulus or medication in response to the sensed conditions. Implanted devices often perform all of these functions for dealing with chronic illnesses that continue to increase in an aging population in the USA and elsewhere [1]

Although some of these devices can be self-contained, there is a compelling reason for networking these devices together, so that each can do its local function of sensing/actuation in the most energy-efficient manner, and the complexities of combining multiple signals and decision-making can be left to a more capable device. There are already several examples of such a need, such as bladder control and others [3, 31] parts around the bladder must be collected and analysed to determine the electrical stimulation or drug release amounts. A wearable device such as a smart-watch (or a similar form-factor device attached at a suitable point on the body) can be used as a centralized hub for decision making based on signals from both on-body and in-body devices. The key advantages of an on-body device are high energy capacity (due to easily changed batteries), connection to external devices, and the possibility of supplying energy to other in-body nodes that cannot harvest enough energy on their own.

1.10 Human Body Communications And Possible Technologies

The communication ability (whether for information or energy transfer) is crucial for all such nodes. Although RF can be used by on-body nodes, RF does have some security issues, e.g., the possibility of eavesdropping, intrusion, or jamming by adversaries. Security vulnerabilities of IoT devices in general and in healthcare cases specifically as well, as noted in the recent report (https://cps-vo.org/node/72664), which states that 82% of healthcare organizations' IoT devices have been targeted with a cyberattack within the last year (compared with 80% of organizations overall) and only 7% of attacks had no financial impact. Through the body communications, popularly known as Human Body Communications (HBC) can lessen this concern since the attacker would need to be in close proximity to the person to conduct an attack. Unfortunately, RF itself does not travel well through the body [6], and other mechanisms are needed.Several HBC mechanisms have been explored in the literature. They require various forms of coupling of electrodes into the body such as GC, CC, and MRC, which have been explained earlier in this chapter. The most prominent mechanism Ultra Sound Coupling (USC) is explained as follows:

Ultrasound coupling (USC) [32] is a very well-researched technology and has been widely used in various clinical applications [33], and specifically explored for both communications [34] and power transfer [35, 36]. USC is very popular for imaging in the human body, with typical frequencies in 3–6 MHz range. The USC velocity in human tissue varies in the range 1500–2000 m/s, which is quite slow but adequate for medical applications. However, this results in wavelengths of only 0.3–0.7 mm and has implications for penetration depth. Small USC devices have been used extensively in implants without any reported side effects, and provide a range of 5-10 cm communication range. USC can work quite well in on-body settings, particularly due to the phenomenon of Rayleigh surface acoustic waves (SAW) [37]. Surface acoustic waves travel along smooth surfaces and can cover significant distance without much attenuation; however, undulations in the surfaces of the order of a few wavelengths can disrupt them. The proposed work performs a detailed experimental comparison of two promising technologies for on-body communication devices, i.e. MRC and USC.

1.11 Research Objective

Radio frequency (RF) communication, although most popular, is unsuitable for environments involving aqueous and animal/plant tissue media, cluttered environments (e.g., small regions with many radios), applications requiring extremely low power consumption, etc. For such environments, magnetic induction (MI) communication appears to be a viable new development technology. Although MI communication has been studied in RF-challenged environments such as underwater, underground, and on and in-body networks, most research has relied on modeling with limited experimentation. We investigate the proposed MR communications by building a testbed using magnetic coils. We also plan to compare and contrast earlier theoretical claims about MRC communications with extensive experimental evidence to show how they vary.

In particular, the outline of goal and objective of my Ph.D. research is to explore the following:

- MR propagation characteristics : The propagation of MR across various media, particularly interfaces, is still unknown. There is evidence that magnetic induction occurs at the interface of media with varying electrical conductivity (and hence permittivity).This raises the problem how MR communication varies with different media.

- MR Coupling Method : MR requires a coil as antenna and the transmission is perpendicular to the coil. Coils can be easily placed on the surface of interest. This can be infeasible or challenging depending on the device and its deployment in terms of coupling methods. Thus, we would have devices with different limitations in terms of number of coils, and their orientations. This raises the problem of how antennas should be placed for a set of devices to provide the best coverage considering the movement of body parts, antenna size and orientation restrictions, and positions of devices.

- Performance Evaluation Of MR Coupling (MRC) Method For Intra-body Network : Effective management of emerging medical devices can lead to new insights in healthcare. As a result, human body communication (HBC) is gaining importance. We have discussed MR as a potentially useful technique for the intra-body network (IBNet). This raises the problem how magnetic coupling and its characterisation capable of transmitting and receiving signals in biological tissue. We have also addressed the comparison study of MRC in terms of path loss (dB) with other coupling methods.

- Packet Delivery Performance Of MRC for Intra-body network (IBNet) : Intra-body area networks of implanted tiny sensors and actuators could revolutionize treatment possibilities for chronic disorders affecting internal organs. Given the known constraints of RF propagation in the human body, we have investigated MRC for both communications and energy transfer. We have addressed designing and building a software-defined prototype utilizing USRP boards. Experimental data on packet error rates at various places and packet sizes is documented and analyzed. We have found that MR signals transmit better through the body than other coupling method, and can be used for intra-body energy transfer and communication.

- Ultrasonic Vs. MR Communication For Mixed Wearable And Implanted Devices : Embedded sensors and small wearable electronic devices have lately been investigated for human body communication. We compare two promising on-body communication technologies, ultrasonic coupling (USC) and magnetic induction coupling (MRC), We have investigated here, both of these propagate significantly better through the body than other coupling methods, making them suitable for intra body communication. We have compared experimental results with the simulation study of MRC versus USC

1.12 Organisation Of The Thesis

This thesis is organised into seven chapters. Chapter 1 introduces the relevant topic of research. In the following chapters, we will discuss these research directions in detail. Mathematical analysis and simulation results are provided to illustrate the performance of the proposed techniques. Chapter 2-6 presents proposed research works undertaken. Chapter 2 describes experimental evaluation of a near-field magnetic induction based communication system. Chapter 3 deals with characterization of magnetic communication through human body. Chapter 4 illustrates performance evaluation of MRC for intra-body network. Chapter Chapter 5 compares and contrast ultrasonic and magnetic resonance communication for mixed wearable and implanted devices. Chapter 6 compares the simulation versus measurement study of ultrasonic and magnetic resonance. Chapter 7 concludes the research and depicts the scope for the future work.

1.13 Publications

During the dissertation research, the author has worked on two projects: (a) Magnetic Induction Communication in Challenging Environments, (b) Comparatively study of Magnetic induction communication versus Ultrasonic communication in challenging environment.

Following is the comprehensive set of publications resulting from the Ph.D. research.

Journal Publications

1. Sayemul Islam, Rajpreet Kaur Gulati Michael Domic, Amitangshu Pal, Krishna Kant, Albert Kim, " Performance Evaluation of Magnetic Resonance Coupling Method for Intra-Body Network (IBNet)". IEEE Transactions on Biomedical Engineering, 2021 (Published). The research work has been highlighted as a featured article on June, 2022.

Conference Publications

1. Rajpreet Kaur Gulati Walia , Krishna Kant, Amitangshu Pal, \Ultrasonic vs. Magnetic resonance communication for Mixed Wearable and Implanted Devices," IEEE ICCC, Jan 2022 (Published).
2. Rajpreet Kaur Gulati Walia , Sayemul Islam, Krishna Kant, Amitangshu Paul, Albert Kim, \Characterization of magnetic communication through human body," IEEE Consumer Communications and Networking Conference (CCNC), Jan 2022(Published).
3. Amitangshu Pal, Rajpreet Kaur Gulati and Krishna Kant, "Towards Building Low Power Magnetic Communication Protocols for Challenging " , ICCCN 2019 Valencia, Spain.
4. Rajpreet Kaur Gulati , Amitangshu Pal, and Krishna Kant, Experimental Evaluation of a Near-Field Magnetic Induction Based Communication System, [Paper], In Proc. IEEE WCNC 2019, Marrakech, Morocco. (Published)

CHAPTER 2

EXPERIMENTAL EVALUATION OF A NEAR-FIELD MAGNETIC INDUCTION BASED COMMUNICATION SYSTEM

2.1 Overview

Chapter 1 describes experimental evaluation of a near-field magnetic induction based communication system. Although MI communication has been studied for some RF-challenged environments such as underwater, underground and body area networks, most of the studies so far are simulation based with minimal experimentation. we show the feasibility of the proposed MI communications, by developing a small testbed using Freelinc boards. We also compare and contrast the existing theoretical claims regarding MI communications with some detailed experimental outcomes, and show how much they differ. This chapter illustrates about a detailed experimentation involving MI signals transferred across MI transceivers.

The chapter is organised as follows. It starts with the description of experimental set up used for performing the experiments, results of experimentation, a set up displaying prototype, effects of spatial variation, effects of different media, effects of different transmission rates. It is than followed by the simulation results representing the observations of the experiments diagrammatically and tabularly. Later than that, we describe experimental outcomes,highlighting key findings and observations. The chapter ends with the conclusive outcomes of the experimentation demonstrating to build an experimental infrastructure, including complete MI-based transceiver boards, that can be used for exploring applications in many emerging applications, particularly those in the IoT based smart environment context.

2.2 Experiment Results

The MI channels are also more determined as the MI signals are not reflected or scattered by the surrounding environments, and thus suffer from smaller signal fluctuations and multi-path effects. Our experiments with Freelinc radios, however, show much more complex behavior described as follows. we build the setup for two MI transceivers and use them for some basic tests of path loss and transmission range for different media. We also conduct a simulation setup in COMSOL L [38] package that provides extensive capabilities for simulating magnetic and electromagnetic phenomena.

2.2.1 A Prototype Setup

Unlike RF communications devices, the MI communication devices are not commonly available in the market. We thus build a small prototype setup as a proof-of-concept for MI communication using the FlexMI/Freelinc boards plus EMBware development boards [39] as shown in Fig. 2.1. EMBware development boards are based on Philips LPC2148 ARM7TDMI microcontroller, with 40 kB of on-chip static RAM and 512 kB of on-chip flash memory. We have integrated this with the Freelinc Near Field Magnetic Induction based radios [40]. The Freelinc radios operate on 13.56MHz, with a current consumption of approximately 18mA. Fig. 2.1(b)-(c) show the Freelinc transmitter board with 3-axis magnetic coils that provide near-isotropic communication environment. Two of these three coils are wrapped around a ferrite-core whereas the third one is an air-core coil. The ferrite-core coils have a diameter of < 5 mm with 9 turns, whereas the air-core one is an 46 mm × 66 mm rectangular coil as shown in Fig. 2.1(b)-(c). The Freelinc receiver board is only equipped with an air-core rectangular coil. This small form factor makes it suitable to be integrated in small spaces such as inside food packages