

Experimental Evaluation of a Near-Field Magnetic Induction Based Communication System

Rajpreet Kaur Gulati, Amitangshu Pal and Krishna Kant

Computer and Information Sciences, Temple University, Philadelphia, PA 19122

E-mail:{tug87941, amitangshu.pal, kkant}@temple.edu

Abstract—Radio frequency (RF) communications, although most popular, are unsuitable for environments involving aqueous and animal/plant tissue media, dense environments (e.g., small regions with many radios), applications requiring extremely low power consumption, etc. For such environments, magnetic induction (MI) communications are an emerging technology that appears to be very attractive. 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. In this paper, we show the feasibility of the proposed MI communications, by developing a small testbed using Freeline boards. We also compare and contrast the existing theoretical claims regarding MI communications with some detailed experimental outcomes, and show how much they differ.

I. INTRODUCTION

Smart sensing and short-range wireless communications is a crucial element for infusing intelligence into a large variety of physical infrastructures. Radio frequency (RF) based communications (e.g., Bluetooth, WiFi) are well established and work exceptionally well in open, uncluttered environments. However, increasingly the communications needs involve environments with characteristics that make RF communications difficult. These include the presence of 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. Also, the power consumption of RF radios is generally quite high. When localization is important, narrowband RF technologies only provide an accuracy of a few meters, which is inadequate. Ultrasound is another well-established technology that works well in aqueous and underground media, but requires larger size radios and higher power consumption, but still cannot operate in a cluttered environment.

Because of these limitations, we are exploring the emerging magnetic induction-based (MI) communication that is reported to be much more effective in challenging environments [1]. MI is based on the principle of resonant inductive coupling (RIC), which involves two matched coils, each forming an LC circuit with the same resonance frequency. MI modulates the magnetic field and forms the basis of near field communications (NFC) between MI devices. Since the electric field plays no role in this communication, the signal is almost purely

magnetic. Such a signal is claimed in the literature do not suffer from usual fading and diffractions associated with the electric field.

Since magnetic induction involves transmit and receive coils, the diameter of the coils and the number of turns are crucial parameters in determining the induced current. Thus, there is a tradeoff between the sizes of MI transceivers and the range (i.e., allowed separation between them) for effective communication. Also, the induced current goes down as $1/r^3$ at a distance r between coils (instead of $1/r$ for NFC RF). This can be considered as both positive (minimal leakage outside of predetermined range) and negative (a rather short span of communication), although a short-range itself can be a virtue in some applications.

Compared to RF, MI-based communication has better penetration performance (i.e., low absorption) as the magnetic permeability of most nonferrous materials commonly in use is very similar to that of air. This includes aqueous media and tissue (e.g., human body, fresh produce, meat, etc.), which are highly absorbent of RF. Even the austenitic stainless steel has a permeability of close to 1 [2], and thus does not affect MI. Recognizing this potential of MI, 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 [3]. RuBee tags are basically coils with associated with a non-volatile tag and a low power transmit circuitry that can be powered by the induced current in the coil.

Although MI communication has been studied for some RF-challenged environments such as underwater [4], underground [5], body area networks [6] and fresh food logistics [7], [8], many of the studies are simulation based with minimal experimentation. Even if some experimental studies are there in the literature [9], [10], 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 [11] and RuBee MI radios [3], 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. In our experiments, we have used Freeline radios without any *shielding* to study the characteristics of typical off-the-shelf MI radios, which results in a combined effect of magnetic and RF signal especially in the far field as observed from our evaluations. Such experimental evaluation coupled with the modeling and simulation is essential to prove the merits of the technology

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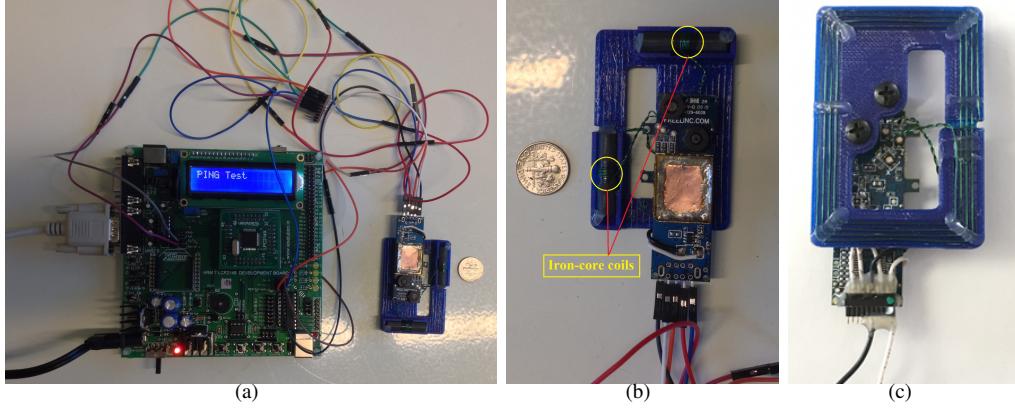


Fig. 1. (a) Freeline board attached to the microcontroller, and (b) its zoomed in view which shows two ferrite-core coils. The rectangular air-core coil is attached to the opposite side of the board as shown in (c).

and its limitations.

The outline of the paper is as follows. Section II introduces the theoretical framework of MI communications. Section III describes a proof-of-concept prototype setup for MI communication and its outcome. The paper is concluded in Section IV with several future directions.

II. THEORY BEHIND MI COMMUNICATION

The magnetic coupling between the two coils depends on their relative orientation, and the energy transfer goes down as the cosine of the relative angle between the coils. Consider a pair of transmit and receiver magnetic coils, with K_t and K_r turns and a radii of ρ_t and ρ_r , respectively separated by a distance r . Suppose that the coils are immersed in a media with the permeability of μ ($\mu = 1$ for air, and close to 1 for most non-ferromagnetic materials including metals). Consider the line segment formed by connecting the centers of the two coils. For a perfect induction, both coils should be perpendicular to this line. If not, the relative angles between them, say, β_t and β_r determine the induced magnetic field between them, denoted as $M_{t \rightarrow r}$. If the transmit coil has current I_t flowing through it, then it can be shown that [12], [13], [14]

$$M_{t \rightarrow r} = \frac{\text{Flux-linkage}}{\text{current}} = \frac{\Phi_{t \rightarrow r}}{I_t} \approx \frac{\mu \pi K_t K_r \rho_t^2 \rho_r^2}{2r^3} \left| \cos \beta_t \cos \beta_r - \frac{1}{2} \sin \beta_t \sin \beta_r \right| \quad (1)$$

$\Phi_{t \rightarrow r}$ is the magnetic flux through the receiving coil.

The induced voltage is proportional to the rate of change of the magnetic flux (Lenz's Law). Therefore, the induced AC current will be proportional to the magnetic field in equation (1) and the frequency of the transmitter current. It is seen that the radius of the coil (ρ_t and ρ_r) have a strong influence on the induced field, and the number of turns (K_t and K_r) also have proportional influence. This coupled with very rapid decay of the induced field with distance r means that (a) the technology is inherently a small range, and (b) to increase range, one must increase the size of coils and/or number of turns, both of which may be undesirable in applications where small size is required. The frequency and the transmit coil

current directly increase the induced current, and hence the overall power consumption and the range.

Since the induced current goes down rapidly with the angles β_t and β_r , it is important to align the coils properly. In cases where such alignment is problematic, one could use 3 orthogonal coils for the transmitter to provide approximately isotropic propagation. Notice that in a tri-directional coil, the orthogonal coils on the same wireless device do not interfere with each other since the magnetic flux generated by one coil becomes zero at the other two coils. The use of 3 orthogonal coils in the MI radio provides a near-isotropic magnetic field and simplifies communication. In particular, it is no longer necessary to ensure that the coil planes of all nodes are identical.

Previous studies in magnetic induction (MI) based communications suggest that the impact of media such as water or soils is entirely captured by the relative permeability and conductivity of the medium. They also indicate that 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. 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. The conductivity σ is measured by the skin depth, which is the depth in the medium at which the electromagnetic field becomes attenuated to $1/e$ of its original strength. The skin depth is given by [15]

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} \quad (2)$$

where ω is the operating frequency. For example, sea water is much more conductive than tap water due to the high concentration of Na^+ and Cl^- ions. The conductivity reduces the skin depth. The skin depth is also inversely proportional to the square root of the signal frequency, thus higher frequency signals experience lower attenuation and vice versa. The MI channels are also more determined as the MI signals are not reflected or scattered by the surrounding environments, and

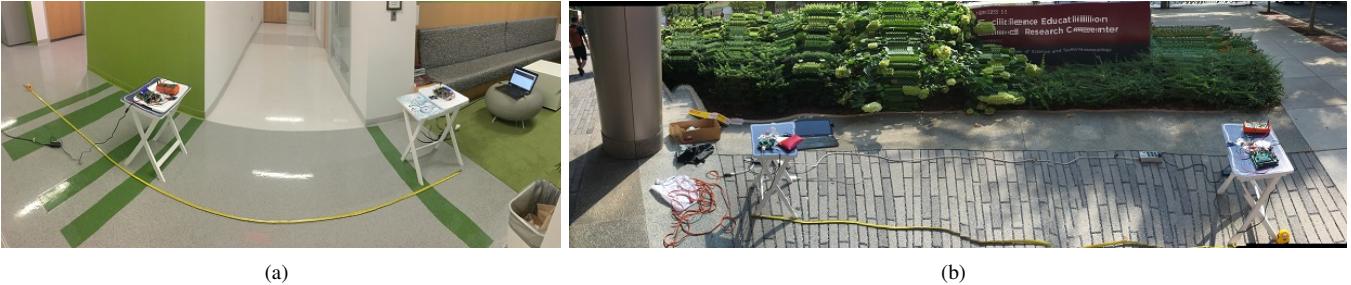


Fig. 2. Experimental locations (a) hallway, and (b) outdoor environments.



Fig. 3. (a) Experimental location in laboratory, and (b) Packet delivery percentage with distance in different environments.

thus suffer from smaller signal fluctuations and multi-path effects. Our experiments with Freelinc radios, however, show much more complex behavior as described in the following section.

III. EXPERIMENTAL RESULTS

In this section, 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 [16] package that provides extensive capabilities for simulating magnetic and electromagnetic phenomena.

A. 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 (www.amazon.in/EMBware-2148-Development-Board-Green/dp/B07785VF7K) as shown in Fig. 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 [17]. The Freelinc radios operate on 13.56MHz, with a current consumption of approximately 18mA. Fig. 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 \times 66 mm rectangular coil as shown in Fig. 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.

B. Effects of Spatial Variation

As the Freelinc board does not provide any facility for RSSI calculation, we solely focus on packet delivery percentage (PDP) to assess the effectiveness of MI communication. We first measure the PDP by varying the distance in between the transmitter and receiver. To examine the effects of spatial variations we conduct this experiment in three different environments (both in indoor and outdoor environments) as shown in Fig. 2 and 3. The hallway we used is normal sized, about 5ft wide, and located inside of the large building. In contrast, the laboratory is quite spacious and has large glass windows to the outside of the building on the 8th floor. The outdoor environment is around the entrance of our building.

The measured PDP is shown in Fig. 3(b). From this figure, we can observe that in hallways the PDP is more than 90% when the distance in between the transmitter and receiver is less than 1.5 meters, and then drops very rapidly. Thus the measured transmission range is $\sim 1.5\text{-}2$ meters in hallways. However, we found that the transmission range is much more in outdoor and laboratory environments. In fact, for laboratory environments, the range is beyond 12 meters.

The observation is contrary to the popular belief that *the MI transceivers show consistent PDP characteristics due to lack of multi-path effects and fading*. This is because for MI communication with 13.56 MHz (i.e., a wavelength of $\lambda = 22.1$ meters) the crossover point between the near-field ends and far-field occurs at $\frac{\lambda}{2\pi} \approx 3.5$ meters. Thus beyond 3.5 meters, the signal carries the RF component which decays at a rate of 20 dB/decade and thus the transmission range is extended to 12 meters in some case. Also, the RF signals experience

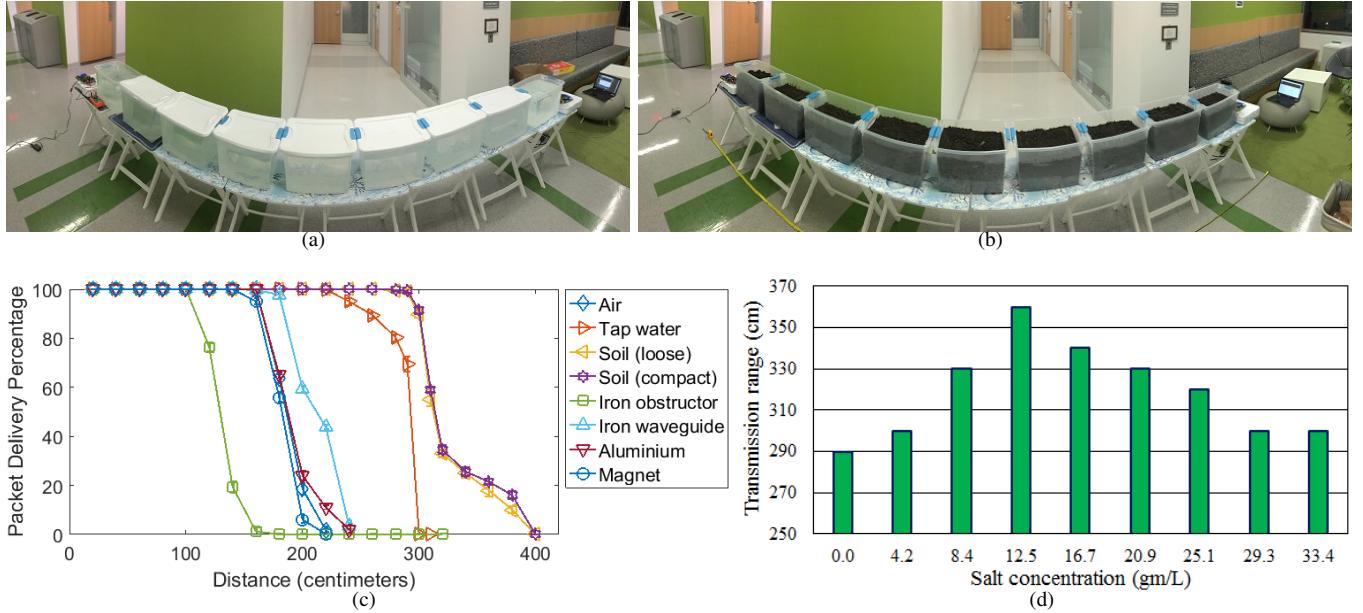


Fig. 4. The experimental setup for (a) underwater and (b) underground medium. (c) The variation of PDP in different media. (d) Transmission range with different salt concentrations.

spatial variation, the transmission ranges vary significantly in different environments.

We surmise that the RF component is arising because of the air-core coils which receive electrical signals at the far-field. We are currently replacing the air-core coils with the ferrite-core coils to dampen the RF component. Also, the Freelinec radios use a high carrier frequency used (13.56MHz) which carries a significant electric field component. We are building our boards for MI communications where we can vary the carrier frequencies to observe up to what extent we can minimize the effect of the RF component by lowering the frequency.

C. Effects of Different Media

We repeat this experiment in different media including water and soil and the results are shown by the measured PDP of the transmitted packets against transceiver distances in different media. All the experiments are done in a hallway environment, where the transmission range through the air is \sim 1.5-2 meters. Some of these results are non-intuitive as reported below.

To observe the propagation characteristics in an underwater environment, we fill up a few boxes with tap water as shown in Fig. 4(a) and with soil as shown in Fig. 4(b), and measure the PDP at different transceiver distances. (The pictures look curved due to wide-angle shot; all boxes are indeed in a straight line.)

From Fig. 4(c) we can observe that increases the transmission range to \sim 3 meters for tap water. This is contrary to the conventional wisdom that the water – having the same permittivity as air – will not affect MI communication; however, the results suggest a somewhat longer range. We next made the water saline by putting measured amounts of salt in each box and dissolving it entirely before experimentation.

Fig. 4(d) shows the effects of salinity on MI communication at different concentration. The maximum salinity level is made to be 33.4 gm/L which is similar to that of a sea water [18]. From this figure we can observe that the transmission range varies between 2.9-3.6 meters depending on the salinity levels; the range actually increases with salinity at first and then decreases. The outcome is extremely non-intuitive. The reported channel modeling suggests that just like RF, magnetic communications will also suffer significantly from salinity because of increasing conductivity [7].

For soil, we experience an increase in the transmission range to \sim 3.5 meters. This too seems counter-intuitive, although the complex composition of soil could have a range of impacts on the signal propagation, which is not well understood.

One potential reason for the above anomalous results is that the interface of media of two different types alters the propagation characteristics. In particular, it has been observed that when RF communications experiments are conducted in an environment where two different media meet, the waves have two different paths that can increase the communication range. For example, an antenna that is submerged in shallow water allows RF to travel in both air and water. Similarly, an antenna close to the bottom of a pond allows waves to travel through the water and along the pond bottom thus resulting in higher signal strength [19]. A similar phenomenon seems to occur with MI communications, and could well be a factor in our experiments. Experiments without such dissimilar material interfaces are not only difficult to logistically but also perhaps unrealistic in most environments where short-range MI communications will be useful (e.g., soil monitoring by shallow buried sensors, on-body communications, monitoring of food packages, etc.) Also, note that this phenomenon alone cannot explain the increasing range with salinity unless the saline-

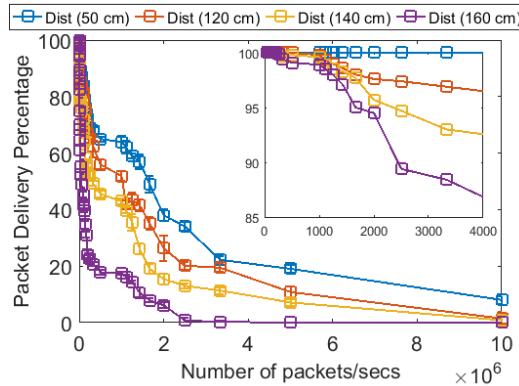


Fig. 5. Variation of PDP with packet transmission rate.

air interface has some special properties that are currently not understood. Incidentally, empty boxes do not seem to affect the propagation and give the same range as for the air.

We next place an iron plate in between the transceivers. The plate blocks the MI signals and thus results in a reduced transmission range of $\sim 1\text{-}1.5$ meters. We next use the iron plate as a waveguide which leads in a somewhat higher transmission range compared to air. This is because using iron plates as waveguides essentially act like a mirror which reflects the transmission signals towards the receiver which boosts the propagation characteristics. Reference [20] uses the *image theory* to conclude that the ferromagnetic plates effectively “reflect” the magnetic flux and strengthen the signal. Our experiments corroborate this.

We next cover the transmitter with an aluminum foil. As expected the aluminum foil does not perturb the MI signals, and thus the range remains similar to that of air. We also place a strong magnet (advertised as 50lb lift capability) just next to the transceivers to observe its effect. However, the MI communications remain unperturbed even in the presence of the strong magnet as well. This is because a permanent magnet only produces a DC magnetic field which does not cause a time-varying change in magnetic flux and hence cannot be detected by a receiving coil (Faraday’s Law).

TABLE I
COMSOL PARAMETERS

Parameter	Values	Parameter	Values
Core radius	2.5 mm	Core length	20 mm
Ferrite-core coil radius	3.5 mm	Air-core coil dimension	20 mm \times 20 mm
Num. of turns for ferrite/air core coil	9/4	Coil wire thickness	1 mm

D. Effects of Different Transmission Rates

We next vary the packet rate of the transmitter to observe its effect on the PDP. The results are shown in Fig. 5. From this figure, we can observe that within the transmission range the PDP is above 90% for a packet transmission rate of ~ 2000 packets/sec. As in our experiments, the packet size is set to 11 bytes and this provides a data rate of ~ 22 Kbps which is a sufficient transmission rate for the typical sensing operation.

As expected the PDP drops significantly with the increase in packet transmission rate.

E. Simulation Results

To compare the experimental results with the simulations, we imitate the Freeline board in the COMSOL simulator. Fig. 6 shows the simulation environment. The lower coils are for the transmitter which consists of two ferrite-core and one air-core coils, whereas the receiver (the upper one) has air-core. We keep the dimensions identical to that of the Freeline board as reported in Table I for accurate emulation. In particular, the twisted wire segments protruding from the ferrite core coils are exactly as used in Freeline board and provide additional inductance and capacitance. COMSOL does simulate the impact these fine features due to its ability to use finite element models for simulation.

Fig. 7 shows the magnetic field around the transmitter coil.

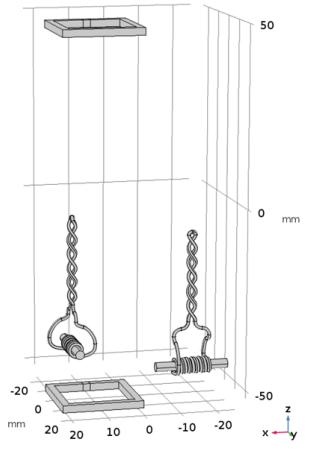


Fig. 6. COMSOL Simulation of Freeline board coils.

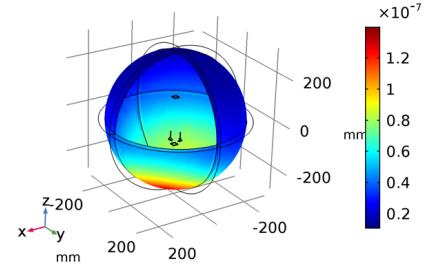


Fig. 7. Magnetic field (in Tesla) around the transmitter.

We vary the distance in between the transceivers and record the path loss and received signal strength at the receiver. Fig. 8 shows the path loss at different distances. From this figure, we can observe that the path loss is around 70 dB when the transceiver separation is 2 meters. This result matches pretty well with our experimental outcomes at the hallway, where the transmission range is $\sim 1.5\text{-}2$ meters. We also vary the orientation of the receiver to show the effect of tri-directional coil transmitter. In Fig. 8, θ denotes the relative angle in between the air-core coils of the transmitter and receiver. From this figure, we can also observe that the path loss at the receiver is almost identical irrespective of the value of θ . This ensures reliable communication between the transceivers, irrespective of their relative orientations.

Fig. 9 shows the induced current at the receiver at different distances. From this figure, we can observe that the induced current goes down at a rate inversely proportional to the distance cube (in a log-log scale), which matches the theoretical counterpart. The induced current is also identical irrespective of the receiver coil orientations.

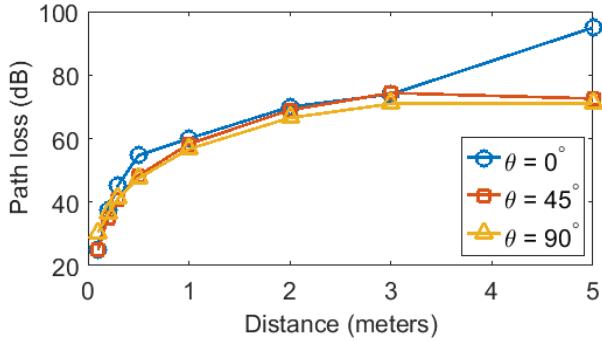


Fig. 8. Path loss at receiver with different orientations.

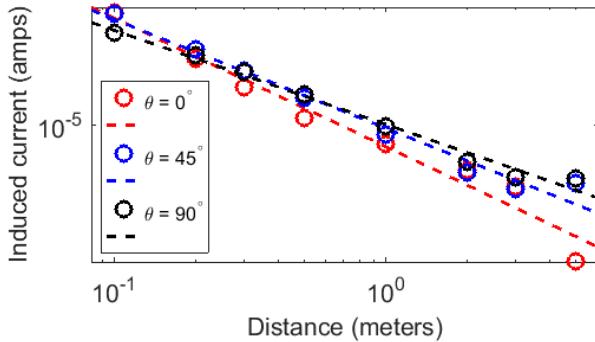


Fig. 9. Induced current at receiver with different orientations (the dotted lines are the best fit straight lines).

F. Experimental Outcomes: Key findings and observations

As observed, many of our experimental outcomes are expected from the theoretical claims addressed in the literature [4], [5], [6], whereas some of them are non-intuitive. These are summarized as follows:

- We have observed that the signal propagation using the off-the-shelf Freelinc devices without sufficient shielding experience a significant amount of spatial variations, due to the RF component present in the far-field. In particular, narrow hallways can reduce the transmission range to as low as 2 meters, whereas the entirely open outdoor area or laboratory environment yields 5-12 meters.
- A permanent magnet does not perturb the MI communication significantly, thus MI communication is immune to any permanent magnetic field.
- An iron plate in between the transceivers blocks the MI signal, whereas using the plate as a waveguide enhances the magnetic field.
- Aluminum foils do not perturb the MI communications, thus such foils can be used for shielding purposes.
- The conventional wisdom is that the water and soil — having the same permittivity as air — will not affect MI communication; the results suggest a somewhat longer range!
- The impact of salinity on transmission range is also found to be non-intuitive. As derived from the expression of skin effect, increasing salinity will increase the conductivity of the medium which should reduce the transmission range; however, our experiments show an entirely different picture: the range actually increases with salinity at first and then decreases, but the impact is rather muted.

IV. CONCLUSIONS AND FUTURE WORK

The paper makes a case for MI-based communication that promises several advantages over the traditional radio frequency (RF) communication including extremely low energy use, ability to work reliably in a variety of difficult propagation media (e.g., water, non-ferromagnetic metals, underground, tissue media of fresh produce & meats, etc.), and low leakage possibility because of fast decay. The primary purpose of this work was 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.

We are currently building some boards equipped with magnetic coils that can provide more flexibility than the Freelinc devices which include: (a) ability to make coil antennas with different number of turns and diameters, (b) easily insert the antenna into or remove from the board, (c) alter the frequency of operation of MI over a suitable range, and (d) alter the MI transmission power (i.e., the changeable current through the the antennas). This will help us to characterize the channel flexibility through more comprehensive measurements.

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