Demo Abstract: Prototyping M^{2}I Communication System for Underground and Underwater Networks

Hongzhi Guo and Zhi Sun

State University of New York at Buffalo, Buffalo, NY, USA
{hongzhig, zhisun}@buffalo.edu

***Abstract*—In the past few years, magnetic induction (MI) communication and networking have attracted significant attentions for wireless applications in underground, underwater, and many other complex and extreme environments. Although the technology is becoming more and more mature, there are still many research challenges, which prohibit MI from being widely applied. One of the most challenging task is to extend the limited MI communication range. Metamaterial-enhanced magnetic induction (M^{2}I) has been theoretically proved to be an efficient way to achieve long distance communication without increasing antenna size. In this demo, we for the first time present a prototype for M^{2}I communication and networking. The objective of this demo is to show the communication-range enhancement of M^{2}I and the proposed communication and networking architecture.**

I. Introduction

Wireless communications in complex and extreme environments can enable a large number of important applications, such as intelligent agriculture by using wireless underground sensor network [1], mine rescue by using through-the-earth communication [2], and underwater environment monitoring by utilizing robotic fish swarm [3]. Existing wireless solutions using UHF band (300 MHz-3 GHz) or even higher frequency cannot work well in such environments due to the high absorption and strong multipath fading. Magnetic induction (MI) communication using loop antennas can obtain an efficient and stable wireless channel since it employs the near field and only utilizes magnetic field [4]. The experiments conducted in [5] using MI testbed in underground environments have verified the high efficiency of MI communications. However, due to the physical limitation of small loop antennas [6], MI communication range is very small (around several meters). To enable wireless networking in aforementioned environments, it is crucial to extend the communication range. Motivated by this, in [7] the artificial metamaterial is employed to enhance the radiation efficiency of the magnetic antenna to achieve long communication range. Since metamaterial demonstrates a negative permeability, it can match with the high reactive power in the vicinity of the antenna and radiate more real power into far field [8]. Although the theoretical results in [7] are promising, there is a lack of practical prototype and to date there is no M^{2}I networking implementation.

In [9] we proposed a practical design of M^{2}I and evaluated its performance, which is almost as efficient as the ideal model in [7]. We will demonstrate a real implementation of the M^{2}I antenna by utilizing printed RLC circuit on FR4 substrate. A 3D printed spherical structure is used to support the PCBs. Its performance has been tested and we will show the improvement by comparing with conventional MI. In addition, a M^{2}I-based communication and networking system is designed by utilizing software defined radio, i.e., USPR. We provide the physical layer, data link layer, and network layer solutions by considering the characteristics of M^{2}I communication and the complex and extreme environments.

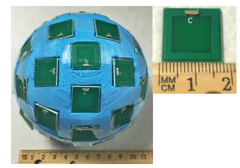


Fig. 1. M^{2}I prototype with 3D printed sphere and coil antennas.

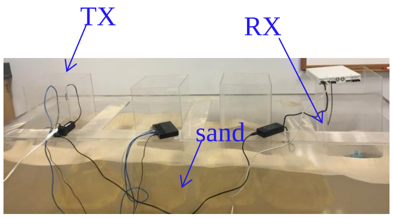
II. Design and Implementation

A. M^{2}I Antenna

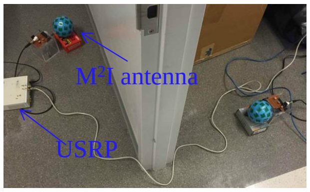
The M^{2}I antenna is shown in Fig. 1. Inside the sphere, there is an active loop antenna whose size is comparable with the sphere (i.e., 5 cm in radius). Moreover, there are 42 small RLC units uniformly distributed on the sphere and the edge of the square PCB is 1.8 cm. The sphere is fabricated using 3D printing. Due to the electrically small size of the active loop antenna, most of the power radiated by it is reactive and constrained in the near region. Therefore, the communication range is limited since the radiated power in the far region is very weak. By using this M^{2}I antenna, those passive RLC units on the sphere can collect the reactive power and transfer it into electric current. The small loop on the unit then becomes a new antenna and it can radiate both reactive power and real power. As a result, part of the reactive power generated by the active loop antenna is converted into real power by the small RLC units and radiated into the far field.

B. M^{2}I Communication and Networking System

The communication and networking protocols are designed mainly based on software defined radio. The M^{2}I antennas are directly connected to USRP boards. The mother board is the USRP N210, which is based on a Xilinx Spartan-3A DSP 3400 FPGA, and the daughter boards are LFTX/LFRX, which can support two independent antennas through connectors



(a) Test of M^{2}I communication in underground environment.



(b) Wall penetration capability test using M^{2}I.

Fig. 2. Experiment environment and setup.

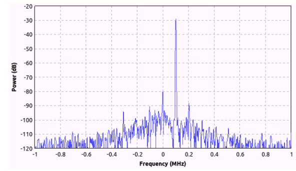
TxA/RxA and TxB/RxB. This daughter board can generate and receive wireless signals from 0 MHz to 30 MHz which is within our interest frequency band, i.e., 18 MHz. Based on these hardware equipments, the signal is generated and analyzed in GNU softwares installed on a computer.

In the physical layer, since the M^{2}I communication has narrow bandwidth, we offer a fully-functional signaling scheme based on continuous-phase modulation (CPM). The CPM has limited out of band power which makes it spectral efficient. For the symbol synchronization, we use a maximum-likelihood algorithm to detect the exact starting point of the symbol. In addition, channel estimation and equalization are performed to optimally decode the signal. We first estimate the channel based on a training approach and then conduct linear adaptive equalization using zero-forcing algorithm. The BCH codes are also utilized to do forward error correction to reduce errors. In the data link layer, we use master-slave network configuration and carrier sensing multiple access (CSMA) for medium access control. In the network layer, we define an adaptation layer that integrates IPv4 protocol.

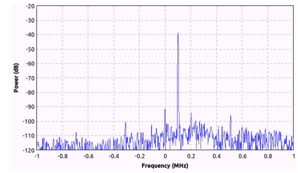
The performance of the proposed M^{2}I communication and networking system has been tested in various complex and extreme environment. As shown in Fig. 2(a), M^{2}I transceivers are deployed in a tank filled with sand to mimic underground environment. The received signal strength and bit error rate outperform conventional MI. As shown in Fig. 3 with and without the metamaterial sphere there is 10 dB difference of the received signal strength. In addition, since M^{2}I has better penetration capability thanks to the relatively low operating frequency, its wall penetration performance is also tested as shown in Fig. 2(b).

III. Demo Description

In this demonstration, we use four M^{2}I transceivers and two computers to mainly show two key points. First, the M^{2}I enhancement compared with conventional MI is shown. We



(a) With metamaterial



(b) Without metamaterial

Fig. 3. Measured received power at 15 in from transmitter.

pay attention to the communication range and data rate. Then, by using multiple devices, we show the capability of M^{2}I communication in a networked environment. Due to the lack of real complex and extreme environments, we provide real demonstration mainly in air and some small obstacles would be utilized to show the penetration capability of M^{2}I.

IV. Conclusion

Metamaterial-enhanced magnetic induction (M^{2}I) communication is an efficient solution to provide wireless connectivity in complex and extreme environments, such as underground and underwater. In this demo, we provide a real prototype of M^{2}I and we designed wireless communication and networking protocol for it. Our demo shows the performance of M^{2}I communication in reality and it fills the gap between theory and practice.

Acknowledgment

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