Low-Cost Magneto-Inductive Communications
Using 3D Spherical Multi-Coils for Wireless Sensor Networks

Niaz Ahmed, Justin Hoyt, Andriy Radchenko, David Pommerenke Fellow, IEEE, Y. Rosa
Zheng Fellow, IEEE

Abstract

This paper presents the design and field tests of a low-cost Magneto-Inductive (MI) communication system for wireless sensor network applications. The proposed MI communication system utilizes three coils in a 3D spherical structure to improve the spatial sensitivity patterns and communication range. The sensor nodes equipped with the 3D multi-coil MI system are designed to communicate at 125 kHz carrier frequency with 1 – 5 kbps data rate. The sensor nodes are implemented by micro-controller, watchdog receiver, RFID transmitter, and digital and analog sensors. Field tests in air and underwater demonstrate that the proposed sensor nodes can achieve reliable communication at a range of 50 – 60 meters with a data rate up to 4 kbps. The power consumption of the nodes is less than 1 mW in sleep mode, 10 mW in active receiving mode, and 200 mW in transmit mode. Therefore, the system is suitable for long-term deployment in underwater and underground WSN.

I. INTRODUCTION

Underwater wireless sensor networks play an important role in environmental monitoring, underwater mining, ocean exploration, and coastal surveillance. Example applications are non-destructive detection of water-front infrastructure defects [1], levee/river bank monitoring, pipe-line monitoring of undersea oil production and transportation, early warning of disastrous flood/storm, and ocean observatory, etc.

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The authors are with the Department of Electrical & Computer Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA. (email: {namn3, jshvy7, zhengyr}@mst.edu)
For most of those applications, low-power consumption, long-deployment lifespan, sensing ability, and reliable communication are the key requirements to the sensor network nodes.

Possible means of wireless communication underwater/underground [2], [3] include optics [4], [5], RF [6], acoustics [7]–[10], and Magneto-Inductive (MI) communications [3], [11]–[22]. Gulbahar et al gives an interesting comparison of the four types of underwater communication systems [3]. Optical systems can achieve huge data rate at the cost of high energy consumption. RF communication underwater is only feasible at very short distances. Acoustic systems have significant advantages in medium and long range communications and data rates of few tens of kilo-bits-per-second (kbps) can be achieved at a reasonable energy cost. In contrast, MI systems are best suited for short range low-data-rate communications with very low power consumption. Another advantage of MI communications is that MI is robust and performs consistently in most communication media: in-air, underwater, and underground. Therefore, MI is suitable for applications in complicated and varying environment.

In recent years, MI communication has attracted great research interests thanks to its wide application to nearfield touchless entry [12], [13], [22], RF identification (RFID) [16], [17], underground sensing [19], and target localization [14], [15]. MI underwater communications [3], [20], [21] usually use low frequency bands from a few kilo-Hertz to a few hundred kilo-Hertz to achieve 50 m – 400 m range at low data rates. Filamentary coil antennas are usually used at both transmitter and receiver sides, which have low radiation resistance. The transmit coils generate a low radiation field, but a high reactive field such that the receive coils induce an electrical current if placed in the nearfield of the reactive field. This property is in contrast to the RF systems where a high radiation power is desired and the reactive power is kept low.

A handful of existing MI underwater communication systems are found in the literature. In [20], a high magnetic moment (250 Am$^2$) at the transmitter was used to achieve 400 m communication range in sea water with a low data rate (40 bps) and a low carrier frequency (< 3 kHz). In [3], the underwater MI channels are modeled by considering dense networks with closely placed transmitters and receivers. In [13], nearfield relaying of closely placed coils were investigated for increasing near-field communication range. In [1], [21], we presented a low-cost MI sensor network node that uses one transmit coil and one or three receive coils at 125 kHz carrier frequency to achieve 20 - 30 m range at 1 kbps.

This paper improves up on the original prototypes in [1], [21] by theoretically modeling the mutual inductance of the transmit and receive coils, fine tuning transmit and receive coils for better resonance at operating frequency, improving sensing capability, and enhancing hardware and software functionalities. The three coils at the receiver side are arranged in spherical configuration and are centered at the same
point such that the mutual inductances of the three coils are independent, while the three coils in [21] was arranged on three sides of a cubic with different centers which caused interfering fields and detuning at the operating frequency. The new spherical configuration enables the coils to be tuned to the same resonant frequency and the communication range is improved to 50 — 60 meters. Extensive laboratory and field tests of the multi-coil MI communication system have also been conducted, which verify that the field performance matches the theoretical model. Other improved aspects include the reduced receiver directionality which can benefit localization via radio signal strength indicator (RSSI), reduced power consumption for long-term deployment, and enhanced networking and sensing capabilities.

II. 3D MULTI-COIL MAGNETIC FIELD MODEL

Similar to Radio Frequency (RF) electro-magnetic waves, MI communication systems employ alternating Electric (E) and Magnetic (B) fields as the data carrier [2]. The E and B fields generated by alternating electrical current in a transmit antenna coil can be modeled by Maxwell equations, and their field strengths decay with the distance r from the transmit current source. Let the operating frequency of the current source be $\omega = 2\pi f$. Then the wavenumber is $\kappa = \omega / v$ with $v$ being the wave propagation speed in the medium. The region that $r\kappa \ll 1$ is called static field, in which the E and B fields attenuate at a rate of $1/r^3$. If $r\kappa \gg 1$, then the field is called radiation field and the field strength decays at a rate of $1/r$. In between, the field is called quasi-static field and the strength decays at $1/r^2$. Unlike RF communication systems that operate in the radiation field, MI communication systems operate in static or quasi-static fields by using low frequency and/or low power.

To model the MI communication channels, the mutual inductance of the transmit and receive coils is analyzed here. Figure 1 shows the 3D spherical multi-coil MI system model, where a single transmit coil located at the origin and on the $x - y$ plane of the $x - y - z$ coordinate system. On the receive side, the 3D spherical multi-coil is centered at point $(x_0, y_0, z_0)$, with coils 1, 2, and 3 aligned on the $x' - y'$, $x' - z'$, and $y' - z'$ planes, respectively. Denote the normal vectors of the three coils as $\hat{z}'$, $\hat{y}'$, and $\hat{x}'$, respectively, since these vectors align with $z'$, $y'$, and $x'$ axes, respectively. Let $\theta_i$ be the “in-plane tilt angle” of the $i$th normal vector around axis $x$, and $\psi_i$ be the rotation angle of the $i$th normal vector around axis $z$. The parameters $(x_0, y_0, z_0)$ and $(\theta_i, \psi_i)$ describe the lateral and angular displacement between the transmit and receive coils.

Although the Finite Element Method (FEM) and Boundary Element Method (BEM) are commonly used for calculating the mutual inductance of a pair of transmit and receive coils with arbitrary displacement.
Fig. 1. Coordinate system of the transmit coil and multiple receive coils. The multiple receive coils are co-centered and are perpendicular to each other.

parameters, a fast-convergent formulas is given by [23] as

\[
M(R_i, \theta, \psi) = \frac{\mu_0 N_t N_r R_i}{\pi} \int_0^{2\pi} \frac{(p_1 \cos \varphi + p_2 \sin \varphi + p_3)\Psi(m)}{\sqrt{mU_0^2}} d\varphi
\]

(1)

where \(\mu_0\) is the magnetic permeability constant, \(N_t\) and \(N_r\) are the numbers of turns of the transmit and receive coils, respectively, \(R_i\) is the radius of the \(i\)th receive coil, and other definitions are

\[
a = \sin \theta \sin \psi, \quad b = -\sin \theta \cos \psi, \quad c = \cos \theta,
\]

\[
\alpha = \frac{x_0}{R_t}, \quad \beta = \frac{y_0}{R_t}, \quad \gamma = \frac{z_0}{R_t}, \quad \delta_i = \frac{R_i}{R_t},
\]

\[
l = \sqrt{a^2 + c^2}, \quad L = \sqrt{a^2 + b^2 + c^2},
\]

\[
p_1 = \frac{\beta c}{l}, \quad p_2 = \frac{\alpha l^2 + \beta ab}{lL}, \quad p_3 = \frac{\delta_i c}{L},
\]

\[
p_4 = p_6 + \gamma bc/(lL), \quad p_5 = p_7 - \gamma a/l,
\]

\[
p_6 = (\alpha ab - \beta l^2)/(lL), \quad p_7 = \alpha c/l,
\]

\[
A_0 = 1 + \alpha^2 + \beta^2 + \gamma^2 + \delta_i^2 + 2\delta_i(p_4 \cos \varphi + p_5 \sin \varphi),
\]

\[
U_0^2 = \delta_i \left[ \left( \frac{-b^2 c^2}{l^2 L^2} \right) \cos^2 \varphi + \frac{c^2}{l^2} \sin^2 \varphi + \frac{abc}{l^2 L} \sin(2\varphi) \right]
\]

\[
+ \alpha^2 + \beta^2 + 2\delta_i(p_6 \cos \varphi + p_7 \sin \varphi),
\]

\[
m = \frac{4U_0}{A_0 + 2U_0}, \quad \Psi(m) = \left( 1 - \frac{m}{2} \right) K(m) - E(m).
\]

(2)

and where \(R_t\) is the radius of the transmit coil, \(K(m)\) and \(E(m)\) are the complete elliptic integrals of
the first and second kind, respectively, defined as

\[ K(m) = \int_{0}^{\pi/2} \frac{d\alpha}{\sqrt{1 - m \sin^2 \alpha}} \]  

(3)

and

\[ E(m) = \int_{0}^{\pi/2} \sqrt{1 - m \sin^2 \alpha} d\alpha \]  

(4)

For the special case that \( a = 0, c = 0 \) and \( l \to 0 \), some of the parameters in (2) are simplified into

\[ p_1 = 0, \quad p_2 = \mp \beta \text{sgn}(b), \quad p_3 = 0, \]

\[ p_4 = \mp \alpha \text{sgn}(b), \quad p_5 = \pm \gamma, \]

\[ U_0 = \alpha^2 + \beta^2 + \delta^2 \cos^2 \varphi \mp 2 \alpha \delta \text{sgn}(b) \cos \varphi. \]  

(5)

For the special case of \( x_0 = 0, y_0 = 0 \), the transmit and receive coils are parallel, (1) will experience numerical instability. A small offset \( \epsilon \) shall be added to the center coordinates to mitigate the problem.

The equivalent circuit of our transmit and receive system is shown in Fig. 2, where \( R_p \) and \( R_s \) are the resistances of the transmit and receive coils, \( L_p \) and \( L_s \) are the self inductances of the transmit and receive coils, and \( C_p \) and \( C_s \) are the tuning capacitors. The input impedance of the receiver is \( Z_L \) and the mutual inductance \( M \) between the transmit and receive coils is calculated in (1).

Fig. 2. Equivalent circuit of transmit and receive configurations.

Following the analysis used in [3], [19], the induced voltage in the receive coil is then

\[ V_r = -j \omega M \frac{V_t}{Z_L} \]  

(6)
where $V_t$ is the transmit voltage and $Z_t$ is the impedance of the equivalent circuit of the primary loop. The parameters in the equivalent circuit are calculated as is the impedance of the equivalent circuit of the receive loop,

$$Z_r = R_s + j\omega L_s, \quad Z_t = R_p + j\omega L_p + \frac{1}{j\omega C_p},$$

$$Z_L = \frac{Z_{Cs} Z_t}{Z_{Cs} + Z_t},$$

$$Z_{rt} = \frac{\omega^2 M^2}{Z_r + Z_L}, \quad Z_{tr} = \frac{\omega^2 M^2}{Z_r} \quad (7)$$

The signal input to the receiver is then

$$V_L = -j\omega M \frac{Z_L V_r}{Z_t + Z_{tr} + Z_L} \quad (8)$$

Substituting (6) and (7) into (8) and considering the parameters of the three coils, the induced voltages in the three receive channels are

$$V_i = -j\omega M_i \frac{V_t}{Z_t} \left(1 + \frac{Z_{ri}}{Z_{Li}} + \frac{\omega^2 M_i^2}{Z_r Z_{Li}}\right),$$

$$M_i = M(R_i, \theta_i, \psi_i), \quad i = 1, 2, 3. \quad (9)$$

If $\theta_1 = \theta$ and $\psi_1 = \psi$, then the spherical configuration ensures that $\theta_2 = \theta + \pi/2, \psi_2 = \psi$ and $\theta_3 = \theta, \psi_3 = \psi + \pi/2$, since the three coils are perpendicular to each other.

The receiver utilizes a selection combining scheme and the output voltage to the signal detector is

$$V_{recvd} = \max(V_1, V_2, V_3) \quad (10)$$

Figure 3(a) illustrates different curves for different position of the rx coil with respect to tx coil. The tx coil is centered at (0,0,0) and is on the z-axis while the rx coil is centered at different locations to show the effect of mutual inductance at different directions in the plane. It can be seen that the mutual inductance is maximum when both the rx and tx coils are on the same z-axis. The graph also shows placing the rx at (0,2,0), (0,2,2) and (2,2,2). Similarly, the mutual inductance is minimum when the rx coil is placed at (2,2,2).

Since keeping the rx coil on z-axis give the maximum mutual inductance, another illustration is shown in figure 3(b) where the rx-coil is moved away from the tx coil along the z-axis. The curves are plotted with $z = 2$ m, 10 m, 15 m and 30 m. The plots clearly shows decay in the mutual inductance as the rx coil is moved away.
The multi-coil transceiver architecture is shown in Fig. 4, where the sensors and calendar timer are connected to the microcontroller (MSP430F5529 via I2C bus, the pore pressure sensor and inclinometer via ADC interface, the watchdog receiver (AS3933) is connected to the MCU via a SPI bus, and the transmitter (ATA5276) is controlled by the MCU through Universal Asynchronous Receive and Transmit (UART) port. Three coils in spherical configuration, along with their matched tuning capacitors, are connected to the transmitter or receiver via a multiplexer. All three coils independently receive the three signals, which are fed to the three input ports of the AS3933 simultaneously; which then forwards the signal with highest strength to the micro-controller. The transceiver needs a battery power supply of 3.6 V.

The sensor node is designed to work in one of four modes: sleeping, receiving, sensing, and transmitting. Most of the time, the node is in the sleeping mode with the watchdog receiver and the calendar timer powered on. The MCU keeps other parts of the circuit powered off to preserve battery energy. When the watchdog receiver detects the correct carrier and identification code, it will wake up the MCU, which then goes to the receiving mode. Depending on the command received, the node may go to the sensing mode to capture the sensing data and store it, or go to the transmitting mode to transmit either the existing data or the relaying data. When the tasks are finished, the MCU goes back to the sleeping mode.

Alternative to wakeup by the watchdog receiver, the MCU can also be woken up periodically by the calendar timer, which can be reprogrammed via the I2C bus. The detailed hardware implementation and software design are presented next.
A. Hardware Implementation

The sensor node uses a 16-bit MCU (TI MSP430F5529), an ultra low-power watchdog receiver (AS3933), a transmitter (ATA5276), a calendar timer (PCF8523), accelerometer & magnetometer, and analog sensors (pore-pressure sensor and inclinometer) as shown in Fig. 4. The node uses a 125 kHz carrier frequency and OOK modulation to communicate with the neighboring nodes. The finished PCB consists of the main and daughter board and has a diameter of 3 inches. The hardware implementation can be further divided into subparts: MI front end, receiver circuitry and transmit circuitry.

1) MI Front End: The sensor node hardware consists of a MI front-end with three multi-turn coils arranged in a spherical configuration. The outer, middle, and inner coil has a radius: 0.104 m, 0.0965 m and 0.089 m, number of turns: 28, 30 and 32 and inductance of: 328 µH, 338 µH and 340 µH, respectively.

The coil acts as an inductance and the circuit formed is a combination of R, L and C components. Figure 2 shows the two configurations of the tuning capacitor: series and parallel configuration with the coil with inductance, L, and resistance, R. Since the transmitter needs to transmit a strong signal, the impedance needs to be small; this is why the tuning capacitor is used in series with the coil. On the other hand, the transceiver requires high impedance to respond to the slight change produced by magnetic flux passing through it, so the tuning capacitor is used in parallel with the coil. Since the same coil is used to transmit and receive, the two configurations are switched via a relay which is controlled by the micro-controller. By default, the relay connects the receiver configuration and, when the node needs to transmit data, the micro-controller first switches the relay to the series configuration and then transmits data.

The relationship between frequency, capacitance and inductance for antenna tuning is \( F = \frac{1}{2\pi \sqrt{LC}} \). The resonant frequency has to be accurately tuned using low-loss Mica capacitors. To tune all three coils to 125 kHz, we used 4.95 nF, 4.80 nF, and 4.78 nF capacitors, respectively.
2) Receiver Circuitry: The watchdog receiver (AS3933) features three LC input ports with 80 $\mu$Vrms wakeup sensitivity and 5-bit RSSI output. In the 3-channel listening mode, the channel with the highest RSSI is selected automatically for demodulation and decoding. With three receiving channels, the AS3933 receiver can be configured into different listening modes: standard listening mode, scanning mode and On-Off mode. In the standard listening mode, all three channels are active simultaneously and the one with the highest RSSI is selected. The scanning mode, on the other hand, uses time multiplexing to keep one channel active for a given time slot. The On-Off mode allows all three channels to be active for a given time slot and then go to an inactive state to reduce the power consumption.

When the three channels are tuned to the same carrier frequency, the AS3933 uses the standard mode to improve the robustness of the communication. Since the orientation of the Tx and Rx coils greatly affect the RSSI and the communication range, the three receive coils are mounted in different angles to increase received signal strength. When the three channels are tuned to different frequencies for media access, the AS3933 is configured to the scanning mode to scan different carriers. Once it finds one channel that has a matching identification code, it will wake up the MCU to start communication.

3) Transmit circuitry: The ATA5276 is a transmitter IC which can operate between 100 – 150 kHz frequencies. The IC drives the LC antenna tank to the desired frequency. The transmitter IC is controlled by the micro-controller through UART interface. The IC also helps to provide OOK modulation for transmission. The transmitter IC requires in between 8-24 V power supply to operate. Since our sensor node runs on a 3.6 V battery, a booster circuit has been used to power the transmitter IC. The booster circuit boosts the 3 V regulated power supply to 12 V. To keep the power consumption minimal, the
micro-controller shuts the booster circuitry off unless data needs to be transmitted.

B. Software Implementation

To download the code used to program the MSP430F5529, we use the Code Composer Studio (CCS) platform. A simple sleep - wake-up - sense - transmit cycle is implemented where after initialization at reset, the program enters in a super loop of four states: Idle, Receive, Data Acquire and Transmit. The initialization sets the parameters, declares the input/output & digital/analog ports, clears the interrupt flag bits, and enables the global and peripheral interrupts.

On entering the super loop, the antenna is configured as receiver and the program enters the Idle mode with AS3933 in watchdog receiving mode and calendar timer running. Other parts of the system are in sleep and the current draw is as low as 50 uA, yielding less than 1 mW power consumption.

Upon detecting the carrier and correct ID code, the MCU is woken up and enters the Receiver state, where the payload data from the AS3933 are sent to the MCU via dedicated I/O ports. The RSSI values of the selected Rx channel are also recorded by the MCU. In the Data Acquire state, the MCU reads the battery level, accelerometer, magnetometer and gyroscope, etc., and packages the sensing data into payload frames. The Transmit state will turn on the booster power supply, enable the transmitter, and switch the coil(s) to the transmit configuration. The transmit power is constrained at 1 A maximal driving current.

IV. EXPERIMENTAL RESULTS

A. Simulations

Simulations of various coil orientations were performed in EMCoS EMC Studio (V7) software. The main focus of these simulations was to determine which coil orientation would provide the most stable, robust communication. Two different three-coil topologies were tested on both the receiver and transmitter side to determine detuning characteristics and then compared against a single coil. These topologies can be seen in Fig. 6.

For this simulation, the induced voltage was measured on the co-axial coil for each topology and then compared to that of a single receiver coil. A transmitter coil was set to be approximately 3 meters away with an impressed current transmission of 1 A for each scenario. Fig. 7 shows the detuning comparison for the induced voltage of both the interlocked spherical and XYZ receivers against that of a single receiver. It can be seen from this figure that the interlocked spherical topology appears to tune precisely to 125 kHz, while allowing for improved robustness over a single coil.
Additionally, the interlocked spherical topology was also tested on the transmitter side to ensure that no detuning would occur with this coil setup during transmission. Again, the transmitter was approximately 3 meters away with the co-axial coil set to transmit with a 1 A impressed current. Two additional coils were then added to form the interlocked spherical setup. Similar results when looking at the induced voltage in the co-axial receiver coil were witnessed with very little apparent detuning occurring.

Finally, the EMC Studio software was used to create a contoured visualization of the magnetic field from a transmitter coil to a three-coil interlocked spherical receiver. This visualization allows for a better idea as to the interaction of the magnetic field in the receiver, as well as the radiation pattern of the transmitter. A similar setup was used for this simulation and the resulting contour visualization is in Fig. 8.
B. Laboratory Test

1) Helmholtz Testing: The Helmholtz testing was performed in an anechoic chamber with the experimental setup as shown in Figure 9 where the sensor node was placed in the center of the Helmholtz coil. The sensor node was tested with both one coil and three dimensional coil. A base station transmitter was used to send an OOK-modulated signal through the Helmholtz coil, and an F-70 AC current probe was used with a spectrum analyzer to measure the transmit current through the Helmholtz coil. It was verified that the Helmholtz coil provided a uniform magnetic enclosed field and the anechoic chamber provided a noise free environment.

Attenuators were added to the transmitter cable connecting to the Helmholtz coil such that the signal strength was reduced until the sensor node stopped responding to the transmit signal. The measured current at this point was $I = 1.62 \times 10^{-7}$ A. The corresponding magnetic field inside the Helmholtz coil is derived from the Biot-Savart Law as

$$B = \left(\frac{4}{5}\right)^{\frac{1}{2}} \frac{\mu_0 n I}{R}$$

where $\mu_0 = 4\pi \times 10^{-7} H m^{-1}$, is the magnetic permeability constant in free space, $R$ and $n$ are the radius and number of turns of the Helmholtz coil. With our experiment, we had $n = 5, R = 0.33$ m yielding $B_{\text{min}} = 2.21 \times 10^{-12}$ Tesla.

2) Magnetic Moment of Transmitter: To quantify the magnetic moment of the transmitter, we measured the current of the transmit coil. The magnetic moment is defined as $m = N \times I \times A$, where $N$ is the number of turns of the tx coil, $A$ is the area of the coil, and $I$ is the current flowing through the coil.

Fig. 8. Magnetic field contour visualization using EMCoS EMC Studio (receiver on left, transmitter on right)
The Grundig AN200 coil had a radius of 0.11 m and consisted of 28 turns. To measure the current flowing through the transmitter coil, we used the F-70 AC current probe connected to a spectrum analyzer. The transmitter coil current was determined to be 0.89 A root mean square (rms), which yielded a magnetic moment of 1.01 Am$^2$.

This magnetic moment produced a range of more than 60 m with a raw data rate of 512 bps (bits-per-second). In comparison to the published results in [20] that 250 Am$^2$ yielded 400 m with 40 bps data rate, our design performed similarly because the magnetic field decays with range ($r$) at a rate of $1/r^3$, and the field strength required for receiver detection is roughly proportional to data rate. Therefore, magnetic moment of 1.01 Am$^2$ at 512 bps and $r = 34$ m is equivalent to 250 Am$^2$ at 40 bps and $34 \times (250/1.01 \times 512/40)^{1/3} = 499$ m.

3) Tuning the Coil: As mentioned in section III-A, tuning the coil to the desired frequency is required. After using the matching capacitors in series and parallel combinations, the coil must be verified to see if they are tuned to the operating frequency. To verify the tuning of the coil, we used a VNA and measured the S21 parameter. Small test coils were used on both ports of the VNA and were placed on both sides of the desired coil (Figure 10). The S21 parameter was then measured so that the coil resonant frequency could be verified. Figure 11 shows the resonant frequency of the three dimensional coil, which is 124.8 kHz with 1 kHz bandwidth.
Fig. 10. VNA setup to measure s21 parameter

Fig. 11. Resonant frequency of coil
C. Field Tests

We performed field tests for the MI transceivers with one or three coils mounted on the receiver. In the experiments, a sensor node with one coil was used as a transmitter and the spherical three coils were used as the receiver. We used the plastic buckets to house the sensor boards and coils for easy placement. We programmed the Tx node to transmit every ten seconds. If the Rx node received the transmitted signal, then it would wake up and record the RSSI value. With multi-coil as Rx, the Tx used one coil and the Rx had three coils in spherical configuration housed in a plastic bin.

We present and compare tests performed with version 1 and version 2. The results with version 1 of the sensor node are obtained in May 2014 while the results with version 2 are obtained in January 2015. The in-air tests were conducted at a drive way and parking lot near HyPoint Industrial Park, Rolla, MO while the underwater tests were conducted in a pond in the Lions Club Park, Rolla, MO. The underwater results for version 2 could not be performed due to frozen lakes in the winter season.

Fig. 13, shows the RSSI readings along the zero degree for both the versions. The Rx was fixed while the Tx was moving at different angles to record the maximum range achieved. The Tx coil was always facing the Rx node, while one Rx coil was always aligned with $y - z$ plane. The maximum range achieved...
Fig. 13. Results of range tests with version 1 and version 2 sensor nodes.

Fig. 14. Directivity patterns for in-air and underwater communications. The 3-coil config yielded an omni-directional pattern, while the 1-coil config was directional. Range is in meter.

By one and three coil has been increased from 50 m to more than 60 m. The reason for this increase is the increase in magnetic moment of the tx coil in version 2. The version 2 the sensor node can output more current as compared to version 1 which helps to increase the magnetic moment and eventually the range. Version 2 achieve the maximum limit of the current that can be output by the transmitter IC.

Another observation in the 13 is that three coils with version 1 achieve lesser range and the three coils with version 2 gets consistent maximum range as with the single coil. The reason three coils in version 1 achieved less range is their placement in XYZ direction. The coils when placed in XYZ (three sides of the cube), are detuned by one another(Fig. 7).
The maximum ranges at different angles were recorded at which the receiver stopped waking up, and results are shown in Fig. 14. It can be clearly seen that the three-coil configuration achieved an omni-directional pattern, reaching similar range at 90 degrees and 0 degrees. The one-coil configuration had a sharp drop in range at 90°, and the achievable range was very sensitive to the relative orientations of the Rx-Tx coils. It can be seen that using version 2 the sensor node with three coil uses spherical interlocked configurations which helps to achieve the maximum range in omni-direction. The lowest range with the three coils is recorded when all the three coils make 45°.

The fact that MI performs consistent in both air and underwater has been shown in Figure 13. The test was performed with the version 1. For underwater tests, the buckets and bin were closed with waterproof lids.

V. CONCLUSION

A short-range low-cost MI communication system has been presented for wireless sensor network applications. Analytical modeling of three coils in three dimensions has also been shown. The hardware implementation and software design have incorporated three coils for multi-channel receiving and transmission. Experiments with simulations, laboratory tests and field tests have been conducted to show and verify the three coil model. Increased communication range and robust performance have been demonstrated for sensor network applications.

REFERENCES


