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Abstract—A set of low-cost and energy-efficient sensor nodes are designed and implemented using magnetic induction (MI) communications for wireless sensor networks (WSN), which are especially suited for underwater and underground networks where the conventional mode of communication does not perform well. Hardware features of the sensor nodes include a three-dimensional MI coil antenna and its different configurations for transmit and receive operations, low-power circuits for sleep mode, several types of sensors, data storage, and best transmit/receive circuits selected to achieve the maximum communication range with low-power consumption. The material cost of a sensor node is less than $100 USD at the prototyping stage and can be drastically reduced at volume production. Software design utilizes low-power modes of microcontrollers and power supply circuits, state machine implementation of sleep, receive, sensing, and transmit modes, range estimation from received signal strength indicators (RSSIs), and medium access protocols, such as carrier sense multiple access (CSMA). Extensive lab and field tests conducted with the sensor nodes demonstrate promising performance in terms of low-power consumption, communication range, range estimation, and robustness against mismatching of coil orientations, and networking capabilities. The current consumption is as low as 60 μA in sleep mode, 0.49 mA in receive mode, and 253 mA in transmit mode. The sensor node achieves a maximum of 40-m range with 1 kb/s data rate at 125 kHz carrier frequency.

Index Terms—Low power, magneto-inductive communication, underwater communication, wireless sensor networks.

I. INTRODUCTION

WIRELESS sensor networks (WSNs) have been widely applied to environmental monitoring, infrastructure monitoring, smart living, smart manufacturing, etc. In particular, underwater and underground sensor networks play a more important role in ocean exploration, coastal surveillance, infrastructure monitoring, and underground mining, as these environments are hostile to human operators, robots and autonomous vehicles are expected to work with the WSNs in the access-denied environment. Application examples are nondestructive detection of waterfront infrastructure defects [1], levee/river bank monitoring, pipeline monitoring of undersea oil production and transportation, early warning of disastrous flood/storms, ocean observatory, etc. For most of these applications, low-power consumption, long-deployment lifespan, sensing ability, and reliable communication are the key requirements to the sensor network nodes.

Unlike the common wireless sensors that use the radio frequency (RF) propagation for communication in the air, underwater or underground wireless communications have proven to be extremely difficult [2], [3]. The possible means of wireless communication underwater/underground include optics [4], [5], acoustics [6]–[9], magnetic induction (MI) [3], [10]–[21]. In the review papers Akyildiz et al. [22] and Che et al. [23] provided detailed comparisons of the three communication means in the ocean underwater environment. In comparison to acoustic and optical communications, the MI communication has the advantage of being low-cost, low-power consumption, and performing consistently in most communication media: in-air, underwater, and underground. Therefore, the MI is suitable for wireless sensor networks deployed in all environments and with long lifespan requirements.

Recent developments in the MI communication include near-field touchless entry [11], [12], [21], RF identification [15], [16], underground sensing [18], and target localization [13], [14]. A handful of existing MI communication systems are found in the literature for underwater and underground applications. In [19], a high magnetic moment (250 A·m²) at the transmitter was used to achieve 400-m communication range in sea water with a low data rate (40 b/s) and a low carrier frequency (< 3 kHz). In [3], the underwater MI channels were modeled by considering dense networks with closely placed transmitters and receivers. In [12], near-field relaying of closely placed coils was investigated to increase the communication range. In [24], the author reviewed different applications of MI sensor networks such as wireless body area networks, aerial networks for drones, and local area networks in addition to underground and underwater sensor networks. In-body communications was also discussed in [25] with THz applications and significant performance as a WSN for health applications. Moreover, a low-cost design with the network topology modulation providing low-delay, low-cost and low-complexity networking infrastructure was defined in [26] that includes a spatial modulation structure with multiple coils with different frequency modulation methods. In [1] and [20], we presented a low-cost MI sensor node that uses one transmit
coil and one or three receive coils at 125 kHz carrier frequency to achieve a 20-m range at 1 kb/s data rate.

In this paper, we present the design and evaluation of the three-dimensional (3-D) multicoil MI sensor node. We first investigate the three different transmission configurations through the 3-D coils and their effects on communication range and power consumption. One transmit configuration is three coils connected in a series and excited simultaneously with one signal source [see Fig. 1(a)]; the second configuration is three coils connected with three separate signal sources that simultaneously transmit three signals [see Fig. 1(b)]; and the third configuration is three coils connected with one signal source via a switch that transmit three separate signals sequentially in time [see Fig. 1(c)]. Our study shows that the sequential transmission scheme has more advantage over the simultaneous transmission schemes in terms of omnidirectionality and power consumption.

With the third configuration, we also provide an integrated solution to a low-power MI sensor node that achieves robust communication over a 40-m range and 1–5 kb/s data rate. With commercial off-the-shelf (COTS) components, the integrated sensor node has a small form factor, and a low material cost of less than $100 USD. Sensing and data storage capability, range estimation, and medium access protocol are also implemented in the sensors. Laboratory and field tests demonstrate that the sensor nodes achieve good communication range and with very low-power consumption.

II. MI COMMUNICATIONS USING 3-D COILS

MI communications uses well-tuned coils to create an alternating magnetic field. If $\lambda/2\pi >> d$, where $\lambda$ is the wavelength and $d$ is the distance between the transmitter and receiver, then the magnetic field within the radius $R$ is regarded as a quasi-static field. A single MI coil exhibits strong directionality, meaning that the magnetic field along its axis is stronger than that along the other directions. The induced voltage in the receive coil is higher when the receive coil faces the transmit coil than those when two coils are at different orientations. For this reason, a multicoil system is often necessary for MI communication systems to achieve near omnidirectional communication in the 3-D space. Similar to inductive power charging systems [27], three coils are often used together with their center coinciding at one point and their axes orthogonal to each other. This physical configuration helps achieve maximal strength in both transmission and reception, as well as the best omnidirectionality [17], [28], [29]. However, different configurations of the three transmit and receive coils are available, and these configurations have rather different performance.

Three configurations are commonly used in the literature, as shown in Fig. 1. Configuration 1 uses a single signal source to excite the three coils connected in series. Configuration 2 uses three independent signal sources to excite each coil separately or simultaneously. The use of independent sources allows Configuration 2 to transmit either the same or different signals at a given time. Configuration 3 uses a single source to transmit sequentially through the three coils and the magnetic fields generated at different times may be combined differently.

The transmit timing for the three configuration is shown in Fig. 2, where the three coils in Configurations 1 and 2 transmit simultaneously, and the three coils in Configuration 3 transmit sequentially. Note that although the circuit with Tx Configuration 2 may also be controlled to implement the sequential transmission scheme in Configuration 3 or the parallel transmission scheme in Configuration 1, we refer Configuration 2 solely for the option of simultaneous transmission.

The 3-D coils are placed in a Cartesian coordinate system and $\hat{x}$, $\hat{y}$, and $\hat{z}$ are unit vectors that align with the three axes. Coil 1 is on the $xy$ plane and its coil axis is $\hat{z}$, Coil 2 is on the $xz$ plane with coil axis at $\hat{y}$, and Coil 3 is on the $yz$ plane with coil axis at $\hat{x}$. Since all three coils are perfectly centered at the origin and strictly orthogonal to each other, there will be no interference between the closely spaced coils given in [30]. The magnetic field at an arbitrary observing point $(x, y, z)$ produced by the

![Fig. 1. Three configurations of the transmit coils. (a) Single source with coils connected in series. (b) Separate sources connected with coils in parallel. (c) Single source connected with coils in parallel.](image)

![Fig. 2. Time slot representation of magnetic fields in the three configurations. Configurations 1 and 2 use a single time slot whereas Configuration 3 uses three time slots.](image)
transmit coil $i$ is then derived by [13]

$$
\mathbf{B}_i = C_i I_i(t) \left( B_{ix} \hat{x} + B_{iy} \hat{y} + B_{iz} \hat{z} \right) \quad i = 1, 2, 3
$$

$$
\begin{bmatrix}
  B_{1x} & B_{1y} & B_{1z} \\
  B_{2x} & B_{2y} & B_{2z} \\
  B_{3x} & B_{3y} & B_{3z}
\end{bmatrix}
= \begin{bmatrix}
  3z x & 3z y & (3z^2 - d^2) \\
  3y x & (3y^2 - d^2) & 3yz \\
  (3x^2 - d^2) & 3xy & 3xz
\end{bmatrix}
$$

(1)

where $C_i = \mu_0 \mu_r N A / (4\pi d^2)$, $\mu_0 = 4\pi \times 10^{-7}$ H/m is the magnetic permeability constant, $\mu_r$ is the relative permeability of the medium, $N$ is the number of turns, $I_i(t)$ is the current signal flowing through the $i$th coil, $A = \pi r^2$ is the area of each coil, $r$ is the radius of each coil, and $d$ is the distance from the origin to the observing point $s$, respectively.

Assume all configurations are well tuned to an operation frequency $f_c$ and the current source is $I_i(t) = \exp\{j2\pi f_0 t + \phi_i\}$. Then, the combined magnetic field of Configurations 1 and 2 is the vector sum of the fields of the three coils

$$
\mathbf{B}_{\text{sum}} = \mathbf{B}_1 + \mathbf{B}_2 + \mathbf{B}_3.
$$

Substituting the values of $I_i(t)$ and $\mathbf{B}_i$ for $i = 1, 2, 3$, the magnitude of the combined magnetic field is then

$$
B_{\text{sum}} = \sqrt{\left( I_1(t) C_{11} + I_2(t) C_{22} + I_3(t) C_{33} + 2I_1(t) I_2(t) C_{12} \right)^2 + 2I_2(t) I_3(t) C_{23} + 2I_3(t) I_1(t) C_{31}}
$$

(2)

$$
C_{11} = B_{1x}^2 + B_{1y}^2 + B_{1z}^2,
C_{22} = B_{2x}^2 + B_{2y}^2 + B_{2z}^2,
C_{33} = B_{3x}^2 + B_{3y}^2 + B_{3z}^2,
C_{12} = B_{1x}B_{2x} + B_{1y}B_{2y} + B_{1z}B_{2z},
C_{23} = B_{2x}B_{3x} + B_{2y}B_{3y} + B_{2z}B_{3z},
C_{31} = B_{3x}B_{1x} + B_{3y}B_{1y} + B_{3z}B_{1z}.
$$

Configuration 1 uses a single current source, therefore $I_i(t) = I(t) \forall i$, and (2) is simplified as

$$
B_{c1} = I(t) \sqrt{C_4}
$$

(3)

where $C_4 = C_{11} + C_{22} + C_{33} + 2C_{12} + 2C_{23} + 2C_{31}$.

For Configuration 2, similar sources of the three coils can have the same phase or different phases. We studied two options: Option 1 is $\phi_i = 0$ for all $i$. Similar to Configuration 1, the magnitude of the combined field strength is then $B_{c2o1} = B_{c1}$. Option 2 is $\phi_1 = 0$, $\phi_2 = \pi/2$, and $\phi_3 = \pi$. The combined field strength is then determined by (2).

For Configuration 3, the three magnetic fields were generated in series and were received at different times. If the received signals are combined by selecting the maximum strength over time, then the equivalent magnetic field strength can be viewed as

$$
B_{c3} = \max(B_1, B_2, B_3).
$$

(4)

where $B_1$, $B_2$, and $B_3$ are the magnitudes of the three transmit coils, respectively.

To illustrate the three configurations, we simulate the magnetic fields using MATLAB and the results are shown in Fig. 3. The magnetic field is calculated at points around the three coils from $\theta = 0^\circ$ to $\theta = 360^\circ$. Configuration 1 $B_{c1}$ and Configuration 2 Option 1 $B_{c2o1}$ have similar performance, as shown in Fig. 3(a). They both have oval shaped directionality with maximum strength at $45^\circ$ and $225^\circ$, and minimum strength at $135^\circ$ and $-45^\circ$. The maximals and minimals are the results of superimposed fields from different Tx coils adding constructively or destructively at these points. There are also points in space where the superposition of the three fields cancels altogether to have a null. The slight difference in $B_{c1}$ and $B_{c2o1}$ is due to the slight phase delay between the three Tx coils in Configuration 1 while Configuration 2 Option 1 has exact the same phase in all three transmit coils. The directionality in the $xy$ plane is improved in Configuration 2 Option 2 $B_{c2o2}$ by using different current sources with different phases, but can still result in null points in a different plane depending on the superposition of the fields.

Configuration 3 results are shown in Fig. 3(b), where only one coil is transmitting at a time, and the $xy$ plane shows $B_1$ and
$B_2$ only. The magnetic field of each Tx coil is also directional and has minimal and maxima; however, the combined field strength $\max(B_1, B_2, B_3)$, shown as black dots, achieves pretty good strength at all directions, with a slightly reduced strength at $\pm 45^\circ$ and $\pm 135^\circ$. This gives an advantage over the simultaneous transmission to have more coverage points and avoid the probability of getting nulls points in space.

Along with more robustness in space, Configuration 3 also outperforms the other configurations in terms of the current consumption. Configuration 2 uses three independent current sources and the current consumption is three times that of Configuration 3. Similarly, Configuration 1 has three coils serially connected, which yields three times the impedance as Configuration 3. Therefore, to produce the same magnetic field, three times as much current is drawn from the source, thus resulting in higher power consumption than Configuration 3.

In the receiver, we assume that the three coils have similar characteristics as their Tx counterpart, with the exception that the tuning capacitors are connected with the coils in parallel to achieve the highest induced voltage. The voltage in the receive coils induced by the magnetic field $B$ at the receive coil is given by

$$V = B2\pi f_c NAQ \cos \alpha$$

where $B$ is the magnitude of the magnetic field $B$, $A$ is the area of the receive coil, $N$ is the number of turns of the receive coil, $Q$ is the quality factor of the tuned coil, and $\alpha$ is the angle between the axis of the receive coil and the magnetic field vector $B$.

We denote the three Rx coils with subscripts $x$, $y$, and $z$, then $\alpha_x$, $\alpha_y$, and $\alpha_z$ are the angles between the sum magnetic field vector and the three receive coils, respectively. In Configuration 1, the receive coil induces a single voltage as all the three coils are connected in series. If we define $C_r = 2\pi f_c NAQ$, the induced voltage is given as

$$V_{c1} = B_{c1} C_r [\cos(\alpha_x) + \cos(\alpha_y) + \cos(\alpha_z)].$$

In Configuration 2, each of the three receive coils induces a separate voltage from $B_{c2}$ which is either $B_{c2,1}$ or $B_{c2,2}$ depending on the current source of the two transmit options. The voltages on the three receive coils are given by

$$V_{c2x} = B_{c2} C_r \cos(\alpha_x)$$
$$V_{c2y} = B_{c2} C_r \cos(\alpha_y)$$
$$V_{c2z} = B_{c2} C_r \cos(\alpha_z).$$

In Configuration 3, the receiver has the advantage to select the maximum of the three individual transmitted fields in $B_{c3}$

$$V_{c3,i} = B_i C_r \max\{\cos(\alpha_{i,x}), \cos(\alpha_{i,y}), \cos(\alpha_{i,z})\}$$
$$V_{c3} = \max_i (V_{c3,i} = 1, 2, 3).$$

The receiver then chooses the strongest of $V_{c3,i}$ for future communication needs unless the sensor node changes location.

Based on the analysis in Section II, we chose Configuration 3 for the design and implementation of our underwater and underground sensor nodes. The design goals were to achieve low power, low cost, sensing capability, good omnidirectionality for localization, and robustness in communication and networking capability. This section describes the hardware and software design and implementation of the sensor nodes.

### A. Hardware Implementation

The multicoil transceiver hardware architecture is shown in Fig. 4, where most of the components are COTS. The main component is the microcontroller unit (MCU) which is the brain of the system. We have selected Texas Instruments MSP430F5529 for its low power, many analog-to-digital converter (ADC) channels, and amber I/O ports. The digital sensor chips include an accelerometer and calendar IC, which are connected to the microcontroller via I2C bus. The analog sensing devices include the pore pressure sensor and inclinometer which are connected to the MCU via the on-chip ADC interfaces. The receiver design uses a watchdog receiver AS3933 which uses the SPI serial bus for control commands and uses the general purpose input/output pins for data communications. The transmitter ATA5276 is controlled by the MCU through universal asynchronous receive and transmit (UART) port.

The three coils in spherical configuration, along with their matched tuning capacitors, are connected to the transmitter or receiver circuitry through relays. All three coils independently receive the transmitted signals which are fed to the three input ports of the AS3933 simultaneously. The AS3933 uses selection combining which chooses the signal with the highest received signal strength (RSS) measure and passes it to the microcontroller. The printed circuit board is shown in Fig. 5, where the two circular boards are joined by connectors and can be debugged separately. The main board contains the MCU, sensors, and the receiver circuitry. The daughter board contains the tuning relays, tuning capacitors, and the transmitter. The diameter of the boards is 7.5 cm, and the thickness of the two fully assembled boards is 2 cm.

The sensor node runs on an external battery power supply of 3.6 V which is the only power source. The MCU and the receiver AS3933 requires 3.3 V, the analog sensors require ±5 V, and the transmitter ATA5276 requires +12 V. The power is...
transceiver circuit is shown in Fig. 7, where the tuning capacitor is connected in series with the coil at the transmitter to achieve a small impedance, which in turn yields a high transmit current on the coil. On the other hand, the receiver requires high impedance to respond to the small changes in magnetic flux passing through the coil, so the tuning capacitor is connected in parallel with the coil. Since the same coil and tuning capacitor are used for both transmit and receive circuitries, the two configurations are switched via a relay which is controlled by the microcontroller. By default, the relay connects the receiver configuration and, when the node needs to transmit data, the microcontroller switches the relay to the transmit configuration and then returns to the parallel configuration after the transmission. The relationship between the operation frequency, capacitance, and inductance for antenna tuning is 

\[ F = \frac{1}{(2\pi \sqrt{LC})} \]

To tune the coils to operate at 125 kHz, we used 1% 4.78 nF capacitors since the measured inductance was 340 μH.

B. Software Implementation

The sensor node is programmed using the code composer studio (CCS v5.5). To lower the power consumption, the sensor node is kept in the idle mode for most of the time. The MCU provides five low-power modes. Each low-power mode consumes current depending on the peripherals enabled and disabled, as given in Table I. We chose the LPM3 mode because the asynchronous clock (ACLK) is used for the timer.

Fig. 8 shows the software implementation of the sensor node. The node starts with the initialization of the clock, variables and peripherals and enters into an idle state. The node remains in the idle state until one of two interrupts occurs: signal received with matching the node’s unique ID or the internal interrupt. The internal interrupt occurs due to a timer which is set to run until a predefined interval \( t_{\text{sense}} \). If the timer reaches \( t_{\text{sense}} \), the sensor node wakes up, acquires data from the interfaced sensors and stores the data in the memory. The node then returns to the idle state.

In the idle state, if a signal is detected, the node will compare the target ID with its own unique ID in the received frame. If the IDs match, the node enters the receive flow graph. The node receives the incoming data, decodes the packet and records the RSSI. For Configuration 3, the receiver node then expects the signals transmitted at the second and third time slots. It is possible that the sensor node is placed in a location where all the three coils of the Tx node cannot reach the Rx node, therefore, a timer is used to avoid waiting for long intervals. Once the data is received through the coils, the Rx node compares the RSSI,
This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

### TABLE I
LOW-POWER MODES OF MICROCONTROLLER

<table>
<thead>
<tr>
<th>Power Mode</th>
<th>Max Current</th>
<th>Peripherals Disabled</th>
<th>Peripherals Enabled</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPM0</td>
<td>95 (μA)</td>
<td>CPU, MCLK</td>
<td>ACLK, SMCLK &amp; PLL loop</td>
</tr>
<tr>
<td>LPM1</td>
<td>85 (μA)</td>
<td>CPU, MCLK &amp; PLL</td>
<td>ACLK, SMCLK</td>
</tr>
<tr>
<td>LPM2</td>
<td>18 (μA)</td>
<td>CPU, MCLK &amp; PLL loop</td>
<td>ACLK</td>
</tr>
<tr>
<td>LPM3</td>
<td>12 (μA)</td>
<td>CPU, MCLK &amp; PLL loop</td>
<td>ACLK</td>
</tr>
<tr>
<td>LPM4</td>
<td>8.5 (μA)</td>
<td>CPU, MCLK, PLL loop &amp; ACLK</td>
<td>None</td>
</tr>
</tbody>
</table>

Fig. 8. Flowchart of sensor node operations.

Fig. 9. Transmitted data frame.

identifies the index of the strongest Tx coil, and retrieves its own sensing data from the memory. The data is packetized into a transmitted frame and the node enters the transmit state.

Fig. 9 shows the transmitted frame which starts with 1-B carrier and 1-B preamble followed by the 4-B destination/target ID. The receive sensor node is looking for this 4-B target ID and upon matching this ID, the receive sensor node wakes up the MCU and start decoding the rest of the packet. The rest of the frame consists of the sender node and coil information along with a command or sensors data followed by 1-B EOF to indicate the end of the frame.

Once the transmit packet is ready, the sensor node uses the CSMA protocol to avoid collision. The sensor node senses the channel and waits if a transmission is detected. After a transmit packet interval time, the sensor node senses the channel again and if no transmission is detected, the sensor node transmits the data out using the three coils sequentially. When finishing the transmission, it goes back to the idle state.

### IV. PERFORMANCE EVALUATION

To evaluate the MI sensor node performance, we calculated the current consumption of the sensor nodes in different working modes, obtained the directivity pattern and performed range experiments to determine the maximum distance with our sensor node. We next explain the following tests.

#### A. Power and Energy Consumption

Fig. 10 shows the current consumption of the MCU and the sensor node in the various available low-power modes. The results show that the sensor node consumes an average of 45 μA other than the MCU current consumption. We then computed the current consumption in the three main operating modes: idle/sleep mode, receive mode, and transmit mode, as given in Table II. We performed the same measurements with five different sets of sensor nodes to verify the robustness and consistency of the sensor nodes.

<table>
<thead>
<tr>
<th>Node</th>
<th>Sleep Mode</th>
<th>Receive Mode</th>
<th>Transmit Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Node 1</td>
<td>74 μA</td>
<td>0.53 mA</td>
<td>277 mA</td>
</tr>
<tr>
<td>Node 2</td>
<td>67 μA</td>
<td>0.30 mA</td>
<td>277 mA</td>
</tr>
<tr>
<td>Node 3</td>
<td>43 μA</td>
<td>0.49 mA</td>
<td>225 mA</td>
</tr>
<tr>
<td>Node 4</td>
<td>44 μA</td>
<td>0.42 mA</td>
<td>230 mA</td>
</tr>
<tr>
<td>Node 5</td>
<td>73 μA</td>
<td>0.52 mA</td>
<td>260 mA</td>
</tr>
</tbody>
</table>
The sensor node uses LPM3 for the sleep mode operation. To measure the current in idle/sleep mode the node was programmed to remain in the idle mode and the average current consumption was recorded as 60 μA. To measure the current in receive mode, another sensor node was set to transmit data to let our measuring sensor node receive data. A total of 200-B frames (1.6 s long) were transmitted from the other sensor node to make sure the current was measured over a fair amount of time for receive mode. The average current in the receive mode was recorded as 0.49 mA. For the transmit mode, the sensor node was programmed to keep transmitting long bytes of data. Since the data was Manchester encoded, any sequence of data would be represented by an equal amount of zeros and ones resulting in transmitting half of the time. After repetitive measurements on different sensor nodes the transmit mode current was recorded as 253 mA.

Based on the current consumption in different modes, we calculated the lifetime the sensor node can achieve in a given wireless sensor network application by

$$I_{avg} = \sum I_{mode} \times t_{mode}$$

$$T_{life} = \frac{C_{battery}}{I_{avg}}$$

where $C_{battery}$ is the battery capacity, $I_{avg}$ is the average current per hour, $I_{mode}$ is the current consumed in the mode, and $t_{mode}$ is the time it remains in the mode in a given hour. The modes are sleep, receive, and transmit. With the given battery of 19 Ah capacity, the calculations are shown in Fig. 11, where the lifetime was calculated with a network size of 10, 50, and 100 nodes, respectively. The number of transmissions in a given hour was also considered. The calculation shows that the sensor node can survive about five years for a high traffic and dense network of 100 nodes. For a low traffic and a less dense network, the sensor node can survive for 28 years.

B. Communication Distance

We now present the range testing of our sensor nodes. We present the theoretical range with our designed system parameters and verify with our experimental range experiments. We performed the range tests both in air and water to compare the air and water performance of the MI sensor node. The in-air tests were conducted at a drive way and parking lot near HyPoint Industrial Park, Rolla, MO, USA, while the underwater tests were conducted in a swimming pool of the university.

To perform the range experiment, we used two sensor nodes. Each sensor node was interfaced with the 3-D coil that acted as both the transmit and receive node. For the range experiments, we programmed one node as Tx and the other node as Rx. The Tx node transmitted a wake-up command to the Rx node. The Rx node started with the sleep mode and upon receiving the wake-up command, woke up and recorded the RSSI. The Rx and Tx nodes were placed on the same axis aligned to each other and after recording the RSSI value, the distance was increased between them until the Rx node stopped waking up. For the underwater range experiment, we used plastic buckets with weights inside to house the sensor boards and coils for easy placement while performing experiments in water.

Fig. 12 shows the theoretical and experimental received voltage where the x-axis is distance in meters and y-axis is the received voltage in decibels. Similar RSSI values can be seen for both the in-air and underwater results. The RSSI values for the water were only recorded for the length of the swimming pool, that is 30 m. The maximum range for the current version of the MI sensor node is recorded as 38 m. To compare with the field experiments, we found the analytical range of the sensor node using the transmit magnetic field and received voltage (1) and (5) where $N = 29, I = 0.8$ A, $r = 0.104$ m, and $f = 125$ kHz.

Effect of Tuning/Detuning on Performance: Fig. 13 compares the range results by using a tuned and detuned sensor nodes. The purpose of the experiment was to show the effect of detuning on the performance of the sensor node communication. When the coil is detuned the performance degrades significantly and limits the communication distance. Thus, the tight tuning of the sensor node to the desired frequency is very important.

C. Directivity Pattern

The primary purpose of the three coil design is to improve the directivity pattern and increase the robustness of the sensor
node when deployed in a practical application. To verify the importance of using the multicoil design, we performed the measurements using both one coil and three coils, and then compared the results.

The experiment was performed using two sets of coils: one node was programmed to transmit a 20-B sequence and the other node was placed in the vicinity to receive the signal. The receive node was connected to the oscilloscope to record the strength of the signal. The signal voltage was recorded after each rotation of 15° until 180° as the measurements repeat after that. The test was repeated for the four possible combinations of one coil and three coils: one-coil Tx versus one-coil Rx, one-coil Tx versus three-coil Rx, three-coil Tx versus one-coil Rx, and three-coil Tx versus three-coil Rx, as shown in Fig. 14.

Fig. 14 shows the directional nature using single coils at Tx and Rx. One coil Tx versus one coil Rx performed the worst with orientation. Using one coil Tx versus one coil Rx performs almost yielded no communication at 90°. On the other hand, using three coils at either Tx or Rx, improved the communication robustness as one of the three coils gets aligned after 90° of rotation. Using three coils at both Tx and Rx further improved the communication robustness and performance. Deployed in a practical application, one cannot guarantee a sensor node to maintain a specific rotation, thus the use of three coil sensor nodes is important.
To further illustrate the advantage of using three coils for omnidirectionality, we used an EMC studio [31] to create a 3-D model for simulations. The Tx and Rx nodes were separated by a distance of 1–50 m. Both the Tx and Rx nodes were randomly rotated (x-axis) and the received strength (y-axis) on each coil is shown in Fig. 15(a). While individual readings from the three Rx-coils vary wildly and the difference can be as large as 50 dB, the maximum value of the three Rx coils stays rather constant [see Fig. 15(b)]. This simulation validated the near omnidirectional receiving properties of using three coils and the results confirmed with the field experiments.

V. CONCLUSION

A low-cost and low-power multicoil MI communication system was presented for underground and underwater wireless sensor network applications. Three different transmission configurations were investigated to choose the optimal configuration. The hardware and software implementations were explained in detail and field tests were performed to demonstrate the promising communication range and robust performance of the sensor nodes.

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