

Design and Implementation of Medium Access Control Protocol for Magneto-Inductive Wireless Sensor Networks Using Low Power Sensor Nodes

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Abstract—Magneto-inductive (MI) wireless sensor networks (MIWSNs) are rapidly emerging networks that offer a wide variety of applications due to their similar performance in air, underground, and underwater mediums. With the increasing demand of using MIWSNs for different applications, the need for an efficient medium access control (MAC) protocol to better utilize the available channels also increases. This article thus realizes the need for a MAC protocol for MIWSNs and presents the design and implementation of a simple and an energy-efficient MI-MAC protocol. This article first presents the design decisions and the proposed algorithm of the MI-MAC protocol. It then discusses the implementation of the MI-MAC protocol for the two possible (sequential and simultaneous) transmit configurations available with a 3-D MI transceiver. MI-MAC implementation for both sequential and simultaneous transmit configurations are evaluated for energy consumption and throughput performance. The results show that the sequential configuration outperforms the simultaneous configuration in energy efficiency by three times, whereas simultaneous configuration outperforms the sequential configuration in terms of throughput by three times. This article, therefore, presents MI-MAC implementation for a hybrid configuration to achieve optimal performance in terms of both energy efficiency and throughput.

Index Terms—Low power, medium access control (MAC) protocol, magneto-inductive wireless sensor networks (MIWSNs).

NOMENCLATURE

Parameters	Definitions
$\mu_o = 4\pi \times 10^{-7}$	Magnetic permeability constant.
μ_r	Relative permeability of the medium.
N_t	Number of turns of Tx coil.
$I(t)$	Varying current flowing through the coil.
A	Area of the coil.
d	Distance from the origin to the observing point.

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μ_d	Permeability of magnetically permeable material.
$w = 2\pi f$	Angular frequency.
B	Magnitude of magnetic field $\mathbf{B}$.
Q	Quality factor.
α	Angle between the magnetic field vector $\mathbf{B}$ and the axis of the receive coil.
P_{Rx} and P_{Tx}	Receive and transmit power.
Q_{Tx} and Q_{Rx}	Q factors of the transmit and receive coil.
r_{Tx} and r_{Rx}	Radius of the transmit and receive coils, respectively.

I. INTRODUCTION

THE common communication techniques for wireless sensor networks in air, water, and underground mediums are electromagnetic (EM) communications, optical communications, acoustic communications, and magneto inductive (MI) communications. Table I shows the favorable mediums for each communication technique. The most commonly used medium for terrestrial communication is EM communications which offers long distance communication with propagation speed of 3×10^8 m/s and high data rates. Similarly, optical communications is used for short range, reliable, and high data rates and is being actively used in applications [1]. Unlike EM communications, where frequency reuse is restricted, the optical carrier does not require any spectrum licensing and therefore, is an attractive prospect for high bandwidth and capacity applications. Both EM and optical wireless communications are good for terrestrial application but are a poor choice when it comes to underwater and underground communication. EM waves highly suffer from attenuation in underwater and underground communication because of low penetration into these mediums. Similarly, optical communications is not able to achieve good performance when it comes to underground and underwater communication. Acoustic, on the other hand, is widely used for underwater communication with both military and civil applications despite the slow speed of propagation (1500 m/s) and extreme physical layer challenges.

In recent years, magneto-inductive (MI) communications has emerged as a real alternate communication technique for unconventional mediums (underground and underwater) that provides higher data rate, instant communication, and relative simpler

TABLE I
COMPARISON OF DIFFERENT MODE OF COMMUNICATION IN DIFFERENT MEDIUMS

Mode of communication	Performance in different mediums		
	In-Air	Underwater	Underground
Acoustic communications	Not preferred due to slow speed and low data rate	Preferred choice because of long range but challenging due to extreme multi-path, high Doppler and low data rate	Not preferred due to slow speed and low data rate
EM communications	Preferred choice for air because of high speed, high data rate, and long range	Not preferred due to rapid attenuation and high eddy current losses	Not preferred due to extremely less penetration capability in solids
Optical communications	Preferred choice for air due to high speed, high data rate, and low cost	Not preferred due to scattering, and need of line of sight, however is often used for short range applications due to high data rate capabilities	Not preferred due to less penetration underground
MI communications	Not preferred because of short range, but preferred in body area networks, and indoor applications because of its penetration capabilities	Preferred choice because of simple physical layer, seamless penetration, instant speed and high data rate	Preferred choice because of simple physical layer, seamless penetration, instant speed and high data rate

physical layer, as compared to acoustic communications. Furthermore, MI offers a unique capability to have similar performance in air, underground, and underwater medium because of the similar magnetic permeability of these mediums [2], [3]. For air, MI has extensively been used in the area of wireless power transfer applications [4], [5], [6]. Moreover, due to the physical layer advantages, such as no multipath, no Doppler effect, instant speed, data rate, and network efficiency [7], MI has become an alternative technology to be used for underground and underwater medium. With the increasing demand of MI communications for underwater and underground applications, significant research and advancements have been done by the research community, such as modeling [8], [9], coil designing [10], range extension through relaying [11], [12], localization [13], [14], [15], routing protocols [16], and cross-layer design protocol [17], [18]; but on the other hand, MAC protocols for MIWSNs are still unexplored. Similarly with real-time MI applications, such as exploration of natural resources, monitoring of the underwater environment, or real-time military surveillance [19], the need for deploying multiple sensor nodes in close vicinity arises. Consequently, these multiple nodes form a wireless sensor network that requires frequent exchange of messages or notifications about different events. This necessitates the implementation of an MAC protocol for a given MIWSN to efficiently utilize the available channel, manage heavy packet collisions, avoid delayed communication, and reduce unnecessary energy wastage. To meet this demand of an MAC protocol implementation for MIWSNs, we present a simple yet energy efficient MAC protocol implementation.

To implement an MAC protocol for MIWSNs, it is also important to realize that MIWSNs exhibit low propagation delay and can operate at relatively higher frequencies, similar to EM-based sensor networks. Therefore the existing MAC protocols available for EM-based communications can easily be borrowed for MI-based communications. However, these EM-based MAC protocols [20], [21], [22], [23], [24], [25],

[26], [27], [28], [29] cannot be directly applied to MIWSNs and need to be customized because of the directional nature of magnetic fields. On the other hand, MI-based wireless sensor networks can effectively adopt a simpler protocol model instead of complex ones, owing to their straightforward physical layer characteristics, while still selecting an appropriate EM-based MAC protocol. This article, thus chooses and customizes the implementation a well accepted carrier sense multiple access (CSMA)-based scheme already available for EM-based networks to make it compatible with the MI sensor node designed in our previous work [30], [45]. The main contribution of our work is summarized as follows.

- 1) Customized implementation of a simple yet energy efficient MAC protocol using a 3-D omnidirectional MI transceiver.
- 2) Exploring the suitability of the implemented MI-MAC protocol on all the possible configurations of a 3-D omnidirectional MI transceiver.
- 3) Evaluation of the customized implementation of MI-MAC in terms of energy consumption.
- 4) Innovating a novel packet exchange method on the customized implementation of MI-MAC to achieve both low power consumption and high throughput performance.

II. PHYSICAL LAYER DETAILS

This section presents the theoretical model of MI communications and physical layer parameters of the MI sensor node developed in our previous work [30].

A. Physical Layer Model

A basic MI communication link established between a single coil transmitter and a single coil receiver is shown in Fig. 1. The transmitted magnetic field generated by the time-varying current

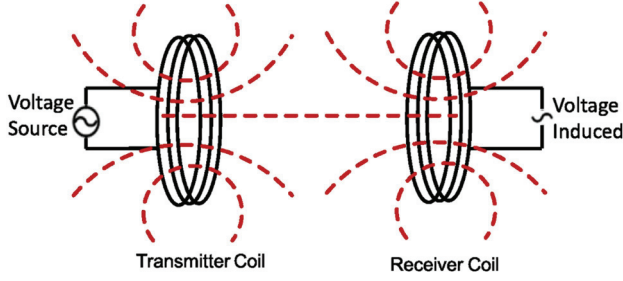


Fig. 1. Basic MI communications model where the transmit coil is connected with an alternating source to generate the magnetic field. The receiver coil couples with the transmit coil and induces voltage in the sensor node.

passing through the transmitter coil can be written as

$$\mathbf{B} = \frac{\mu_o \mu_r N I(t) A}{(4\pi d^5) \hat{B}}. \quad (1)$$

It is important to mention here that since the magnetic permeability of the medium denoted by μ_r (Nomenclature) for air, water, and soil is quite similar, hence the magnetic field produced in water, air, and soil is similar too [7], [8], [31].

The magnetic field ($\mathbf{B}$) generated through the transmitter coil then resonates the receiver coil and induces voltage given by [30] as

$$V_{Rx} = \mu_d \omega N A B Q \cos \alpha. \quad (2)$$

Furthermore, the strength of the magnetic field decays faster compared to the EM field and is inversely proportional to the cubic of the distance d ($(1/d)^3$), with power decaying at a rate of $(1/d)^6$. The received power is given by [32] as

$$\begin{aligned} P_{Rx} &= \frac{P_{Tx} Q_{Tx} Q_{Rx} \eta_{Tx} \eta_{Rx} \kappa^2(d)}{P_{noise}} \\ &= \frac{P_{Tx} Q_{Tx} Q_{Rx} \eta_{Tx} \eta_{Rx} \frac{r_{Tx}^3 r_{Rx}^3}{(d^2 + r_{Tx}^2)^3}}{P_{noise}} \\ &\simeq \frac{\sigma}{P_{noise} d^6}; \quad r_{tx} \ll d \end{aligned} \quad (3)$$

where $\sigma = P_{Tx} Q_{Tx} Q_{Rx} \eta_{Tx} \eta_{Rx} r_{Tx}^3 r_{Rx}^3$ represents the distance bubble factor defined in [32], and defines the communication range. The communication range, as can be seen in (3), depends on the transmit power, high quality factor of transmitter and receiver coils, and noise power. The noise model for MI communications has also been developed where the dominant source of noise is found as thermal noise only [33], [34] and is given by [19]

$$N_t \approx KCT \quad (4)$$

where $K = 1.38 \times 10^{-23} J/K$ is the Boltzmann constant, C is channel bandwidth, and T is temperature in Kelvin.

B. MI Sensor Node Details

The block diagram of the low power MI sensor node developed in our previous work [30] is shown in Fig. 2 and the parameters are provided in Table II. The MI sensor node is

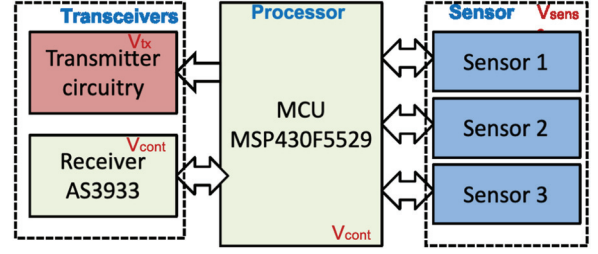


Fig. 2. Block diagram of the sensor node built in [30] showing the three fundamental blocks: transceiver, processor, and sensor.

TABLE II
MI SENSOR NODE PARAMETERS

Modulation	OOK
DataRate	1 Kbps
Bandwidth	5 KHz
Encoding	Manchester
Center Frequency	125 KHz
Source Power	3.6 V
Transmitter Circuitry	12 V
Receiver Sensitivity	80 Vrms

connected to a 3-D coil (spherically arranged) to achieve more robust and omnidirectional MI communication.

To achieve the goal of a low power MI sensor node, the transceivers and the processor are chosen after thorough consideration. The microcontroller (MCU) is a low power controller that can work in extreme low power modes by shutting down most of its peripherals when programmed. Similarly, the receiver IC (a digital integrated circuit chip: AS3933 [35]) is a watchdog receiver with unique features that listens to the channel and allows other devices to be in sleep mode. The receiver block has three independent input ports that are connected to the three coils and has the ability to record the strength of the incoming signal at each port.

As the receiver IC is a watchdog receiver, it listens to the channel and generates a wakeup signal that can serve as an interrupt to the MCU indicating an incoming signal at the front end. The receiver IC can be programmed with two options: 1) where the receiver IC generates a wakeUp signal only when the incoming signal contains a unique ID, and 2) where the receiver IC generates a wakeUp signal by detecting a carrier signal only. Our MAC implementation utilizes both these features to our advantage. Option 2) is utilized to sense the channel and detect if the channel is busy or free before transmission, and option 1) is used when the receiver IC is in listening or receiving state. The software (state machine) implementation of the sensor node is provided in the Algorithm 1.

III. DESIGN DECISIONS AND IMPLEMENTATION OF MEDIUM ACCESS CONTROL PROTOCOL FOR MAGNETO INDUCTIVE WIRELESS SENSOR NETWORKS

The main objective of our work is to implement an MAC layer protocol for MIWSN that is simple yet energy efficient. To achieve the goal of a simple MAC protocol we choose to

Algorithm 1: Software Implementation of MI-MAC Protocol.

```

1: function MAIN(void)
2:   State = Idle
3:   switch State
4:   case Idle
5:     Turn off Tx circuitry power
6:     Switch MCU to low power mode
7:     Configure Rx IC to detect Carrier + Node ID
8:     Enable Interrupt
9:     SLEEP
10:    break;
11:   case Receive
12:     Switch MCU to active mode
13:     Receive & decode data incoming packet
14:     Record the strongest Tx/Rx coil ID
15:     if Packet ID ==  $W \parallel \text{ACK}$  then
16:       State = Transmit; break;
17:     else
18:       if Packet ID == Data then
19:         State = Idle; break;
20:   case Transmit
21:     Switch MCU to active mode
22:     Packetize data
23:     Channel_Flag = SENSE CHANNEL
24:     if Channel_Flag == Free then
25:       Turn On Tx Circuitry
26:       if Packet ID ==  $W$  then
27:         Transmit packet with all 3 Coils
28:       else
29:         if Packet ID ==  $\text{ACK} \parallel \text{Data}$  then
30:           Transmit packet with strongest coil
31:         Turn Off the Tx Circuitry
32:         State = Idle; break
33:   function SENSE CHANNEL
34:     Configure Receive IC to detect carrier only mode
35:     Listens to the channel
36:     if Carrier_Detected then
37:       Set  $t = \tau_{\text{wait}}$  and Enable interrupt
38:       return Channel_Flag = Busy
39:     else
40:       if !Carrier_Detected then
41:         return Channel_Flag = Free
42:   function INTERRUPT HANDLER
43:     if Interrupt ==  $\text{Timeout} \parallel \text{Internal}$  then
44:       State = Transmit;
45:     else
46:       if Interrupt == WakeUp Signal then
47:         State = Receive;

```

use a well accepted and widely used carrier sense multiple access (CSMA)-based scheme as it is easily implemented in a distributed and low-complexity manner. Furthermore CSMA scheme is robust to time-varying networks and therefore is a

perfect candidate to be implemented in MI-based communication. Our second goal of energy efficiency stems from the fact that wireless sensor networks are energy hungry and monitoring applications require the sensor nodes to operate and survive for a longer time without replacing the source power (batteries). Several MAC protocols are available in literature for both terrestrial [20], [21], [22], [23], [24], [25], [26], [27], [28], [29] and underwater [36], [37], [38], [39], [40], [41], [42], [43] aiming to achieve low power consumption. To reduce energy consumption and prolong lifetime, the sensor network MAC protocols usually require cycling the sensor node hardware between high-power active states and low-power sleep states [44]. This approach plays an important role to conserve energy especially in states where unwanted energy is wasted. We, therefore, learn from the techniques already used for energy efficient MAC protocols in wireless sensor networks, adopt a similar approach, and implement a simple and energy efficient MAC protocol for MIWSNs.

As mentioned in Section I, the MAC protocol is implemented using the sensor node designed in [30] (Fig. 2). It can be seen that the sensor node provides an independent power source to each fundamental block (transceiver, processor, sensor), to allow the sensor node to turn-ON the active blocks and turn-OFF the inactive blocks. The active and inactive blocks are determined, depending on the state the sensor node is in. The approach helps significantly to reduce the overall energy consumption of the sensor node especially the energy wasted during idle listening, overhearing, and use of packet overhead as explained in the following.

- 1) *Idle Listening*: When a sensor node is listening to the channel and waiting for an incoming packet, a handsome amount of energy is wasted. In our MI-MAC implementation, we keep this consumption minimum as other parts of the sensor node are turned OFF and only receiver IC is drawing current from the power source.
- 2) *Packet Overhearing*: When a sensor node detects an unintended signal and spends energy to still decode the signal, there is a huge loss of energy. In our MI-MAC implementation, the receiver IC generates a wakeUP signal only when the incoming signal contains the unique ID. The MCU therefore remains in low power mode and does not decode the packet unless it is the destined sensor node.
- 3) *Control Packet Overhead*: When a sensor node spends extra energy by using additional control and redundant information to the actual data. We keep the overhead consumption also at its minimum by choosing three types of packets of different length.

The details of the MI-MAC protocol implementation are further described in the following subsections.

A. Low and High Power States

The MI sensor node has been designed with the flexibility to be programmed into different modes, each with varying levels of current consumption. This adaptability allows the sensor node to achieve low power consumption, which is one of our primary goals. To achieve this low-power objective, the sensor node operates in one of four states during a given time period: 1) idle,

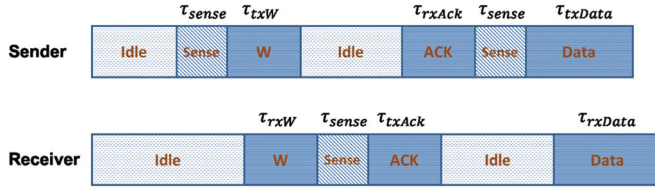


Fig. 3. Complete communication cycle between a Sender and Receiver, where the Sender node starts with a W packet. The Receiver node after successfully receiving the W packet, acknowledges with an ACK packet. Upon receiving the ACK packet, the Sender then sends out the whole Data packet. Furthermore, it can be noted that each node first sense the channel and then transmits the packet.

TABLE III
ACTIVE AND IN-ACTIVE COMPONENTS IN EACH STATE

	Listen/Idle	Receive	Sense	Transmit
Microcontroller	Sleep	ON	ON	ON
Receive Circuitry	ON	ON	ON	OFF
Transmit Circuitry	OFF	OFF	OFF	ON
Sensors Power	OFF	OFF	OFF	ON/OFF

2) receive, 3) sense, and 4) transmit. The complete data transfer process between two nodes is illustrated in Fig. 3, which clearly depicts all the states involved. Furthermore, to implement the MI-MAC effectively, the state-machine level implementation of the protocol is provided in Algorithm 1, and its functionality is explained in the following subsections.

- 1) *Idle State*: The sensor node in an Idle state is listening to the channel. As shown in the Table III, the processor turns-OFF most of the components (except receiver circuitry) to keep the power consumption as minimum as possible. Moreover, the processor also goes to a deep low-power mode afterward. The sensor node remains in an Idle state until one of the following two conditions is met: First, when it needs to transmit data or initiate communication with other nodes. Second, the sensor node may wake up from the Idle state in response to an incoming interrupt, typically triggered by a timer interrupt or some other external event.
- 2) *Transmit and Sense State*: In case of transmission, the sensor node will first sense the channel, where the receiver is programmed to listen to the channel and look for the carrier signal. During channel sensing, the power consumption is slightly higher than the Idle state as the processor is also active along with the receiver. If the channel is free, the sensor node enters the Transmit state, prepares the packet, and sends it out. While preparing the packet, if the sensor node has to acquire data from the sensor, then the processor will turn-ON the sensor's power. Otherwise, only the transmitter circuitry and the processor will be turned-ON in the Transmit state. It can be noted that energy consumption is higher in the Transmit state, as the transmit circuitry draws a significant amount of current while sending out the data. After successful transmission, the sensor node returns to the Idle state.
- 3) *Receive State*: In case of reception, as each sensor node in a network is identified by a unique ID and that is written

Carrier	Preamble	Target ID	Packet ID	Tx ID	Tx Coil ID	EOF
1 byte	1 byte	4 bytes	1 byte	4 bytes	1 byte	1 byte

WakeUp Packet = 13 bytes

Carrier	Preamble	Target ID	Packet ID	Tx-Rx Coil ID	EOF
1 byte	1 byte	4 bytes	1 byte	1 byte	1 byte

Acknowledgment Packet = 9 bytes

Carrier	Preamble	Target ID	Packet ID	Data Packets	EOF
1 byte	1 byte	4 bytes	1 byte	16 bytes	1 byte

Data Packet = 24 bytes

Fig. 4. Three packet types: W, ACK, and Data packets.

to the receiver in the Idle state, the receiver looks for the incoming signals and does not interrupt the processor until the incoming signal contains the unique ID. If the unique ID is matched, the sensor node enters the Receive state. During the Receive state, the active components are the processor and receiver IC but the energy consumption is a bit higher than channel sensing state as the processor uses some energy to process the data. Table III lists the active and inactive components for each state.

B. Packet Types

Fig. 4 shows the three packet types used for the data transfer: 1) WakeUp (W), 2) acknowledgment (ACK), and 3) data packet. Three packets of different lengths are chosen to best utilize the channel and avoid unnecessary redundant data. All the three packets start with one byte carrier, followed by another byte of preamble, and four bytes of target ID to let the receiver node set up and check whether the incoming signal is a desired one. The seventh byte then identifies the packet type: W, ACK, or Data. All the three packets end with one byte end of frame (EOF).

WakeUp packet is a handshaking packet (13 B) sent by the sender node to wake up the receiver node from the Idle state and initiate communication. For the wakeUp packet, the packet ID is followed by a four-byte Tx ID, which contains the sender ID information. The packet also includes information about the transmit coil used by the sender node to inform the receiver node about the best coil suited to communicate between the transmit and receive nodes.

After successful reception of the W packet, the receiver replies with a nine-byte ACK packet. The ACK packet after the seven bytes contains the information about the optimal coil pair used for transmitter and receiver to be used for further communication.

Once the sender node receives the ACK packet, the two nodes are now ready to exchange data packets. The data packet may contain the sensor data or other information needed to be transmitted. The maximum packet size for the data packet is set to 24 B.

C. Channel Sensing and Collision Avoidance

To avoid collision, a simple channel sensing approach has been implemented that senses the channel before any transmission. During the channel sensing operation, the processor wakes

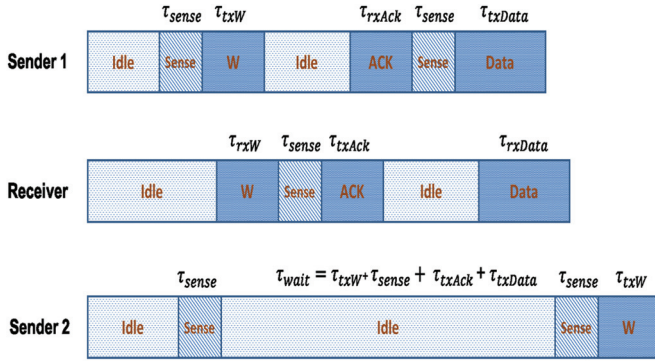


Fig. 5. Data transfer of packets when two senders want to transmit data at the same time. The sender 1 transmits data while, sender 2 waits for τ_{wait} to transmit data.

up from the Idle state and programs the receiver IC to detect any carrier being transmitted. Unlike the Idle state, the receiver will immediately inform the processor about unavailability of the channel and not wait for the target ID. Once the processor is informed about the unavailability, the processor will go to deep low-power mode and enter idle state for τ_{wait} time, whereas

$$\tau_{wait} = \tau_{txW} + \tau_{sense} + \tau_{txAck} + \tau_{txData} + \tau_{safe} \quad (5)$$

and τ_{txW} , τ_{txAck} , τ_{txData} is the time the sensor node takes to transmit the W, ACK, and Data packet; τ_{sense} is the time the sensor node takes to sense the channel before transmitting the packets; and τ_{safe} is the safety time (assigned a random value between 0τ to 0.5τ) to cover the time the sensor nodes use during sensing and processing. After τ_{wait} time the processor wakes up from the Idle state, enters the Sense state again, and looks for a free channel. If no activity is detected for τ_{sense} time, the processor will enter the Transmit state to send the data (Fig. 5). The receiver at this point is waiting for the Data packet. In case the data packet is lost or not received in $\tau_{sense} + \tau_{txData}$ time, the receiver will resend the ACK packet asking the Sender to resend the Data packet. Moreover, it may be noted that this is highly unlikely case, as the sender 2 gets in to a waiting state of t_{wait} , which already incorporates wait for data packet.

D. Timeout and Retransmission

As mentioned, the sender node after transmitting a WakeUp packet goes to an Idle State and waits for an ACK packet from the receiver node. However, in case of a collision, the WakeUp packet may not reach the receiver node, and the sender node will have to wait forever. To avoid this, the microcontroller utilizes a timer during the *Idle state*. The microcontroller waits until τ_{noAck} and retransmits the WakeUp packet. The wait time is set equivalent to the time the sender node takes to transmit the WakeUp packet, plus the time the receiver node takes to transmit the ACK packet along with a safe time

$$\tau_{noAck} = \tau_{txW} + \tau_{txAck} + \tau_{safe}. \quad (6)$$

IV. ENERGY EFFICIENT MULTICOIL CONFIGURATION FOR MAGNETO-INDUCTIVE WIRELESS SENSOR NETWORKS

The magnetic field generated through a transmitter coil is directional in nature (Fig. 1), where it is stronger along its axis and minimum at 90° . To couple strongly with the transmitter coil, the receiver coil thus needs to be perfectly aligned to the transmitter coil. As in practical scenario, it is often not possible to fix a sensor node at a specific location and orientation; 1-D coils are thus less robust for MI communications. Therefore, a multidimensional coil system is used for MI communication systems to achieve omnidirectional and more robust communication. In literature, two common configurations of the 3-D coil systems are available, and these configurations have rather different performances. Configuration 1 uses all the three coils to transmit simultaneously, whereas configuration 2 uses the coils to transmit sequentially.

Fig. 6(a) shows implementation of the data transfer packets with configuration 1 and Fig. 6(b) shows implementation of data transfer packets with configuration 2. It can be seen that, in configuration 1, each packet is being transmitted by each of the three coils. This configuration is preferably used for low power consumption scenarios because it takes less power to excite one coil at a time rather than three coils, as in configuration 2. But at the same time the configuration 1 takes thrice the time taken by configuration 2. This makes a tradeoff between the two configurations for power consumption versus time it takes to complete one communication between the two nodes. An MAC protocol requires both of the two characteristics: 1) low power consumption to prolong the life time of the sensor node, and 2) less time slots to communicate between the two nodes so that the channel is not kept occupied for longer time and more nodes can talk in a given time. As the network goes bigger and bigger both of these characteristics become more important.

Considering the importance of both the metrics we implement a novel scheme of data transfer between the nodes using configuration 1. We take the advantage of low power consumption of configuration 1 and at the same time limit the time slots to occupy the channel for lesser time [Fig. 6(c)]. In the new presented scheme, when the sender initiates the communication, it sends the WakeUp packet using all the three coils. When the receiver receives the packet, it decodes the packet and identifies the strongest coil the signal was received with. The receiver then uses the strongest coil only to send the ACK packet. This way both the sender and receiver know the strongest coil to communicate and afterward only the strongest coil is used. This scheme thus helps to avoid the multiple transmission after the wake-up stage and also keeps the minimum power consumption. The algorithm of the whole data transfer implemented in the microcontroller is presented here.

A. Special Case

Configuration 3 helps to exploit the directional nature of the MI coils, and helps to increase the overall throughput of the network. Fig. 7 shows this special case, where Node A (Tx) wants to communicate with Node B (Rx). Since coil 1 of both Node A and Node B is perfectly aligned with each other, both the

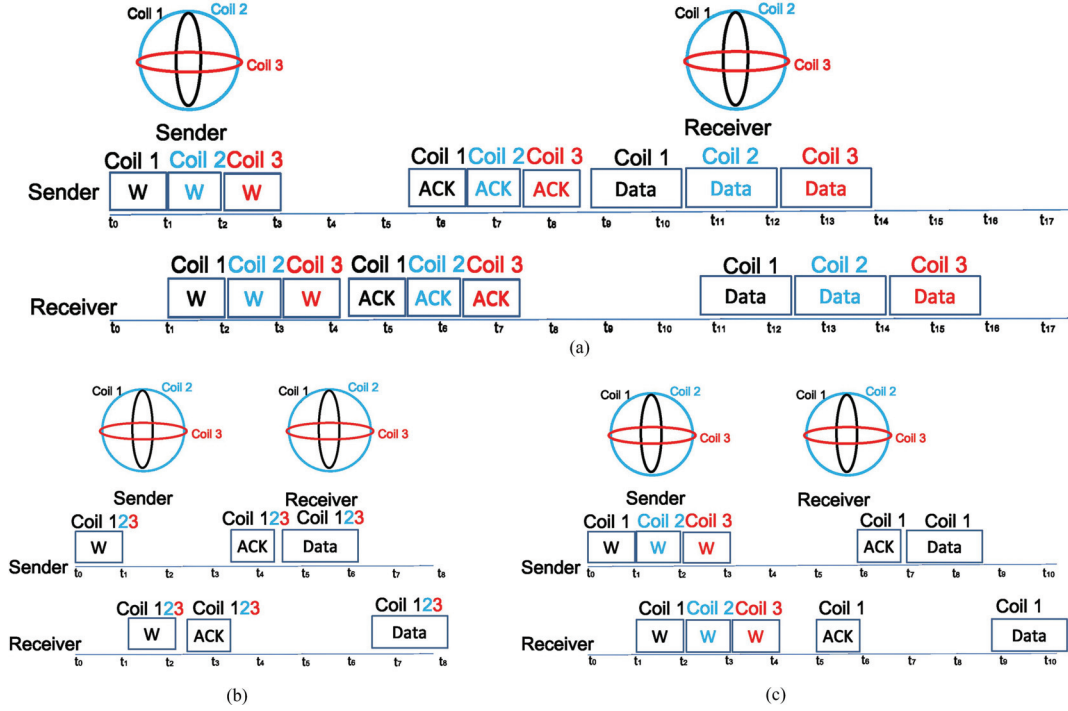


Fig. 6. Time needed to transmit the packets with configuration 1, configuration 2 and configuration 3. (a) Configuration 1: When all the three coils are set to transmit individual packets sequentially. (b) Configuration 2: When all the three coils are set to transmit simultaneously. (c) Configuration 3: When the three coils are set to transmit only the WakeUp packet and use only the strongest coil to communicate to the rest of the packets.

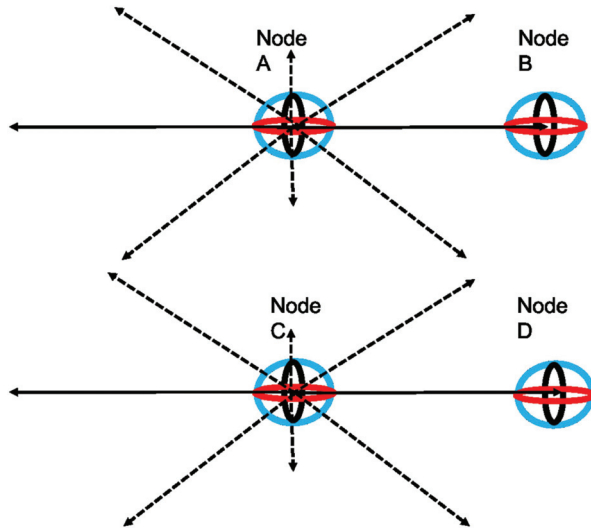


Fig. 7. Special case: When two pairs Node A–Node B, and Node C–Node D can communicate at the same time without collision.

nodes will communicate using coil 1 only. While Node A and Node B are exchanging packets, there exists a pair of Node C and Node D in the vicinity that are parallel to Node A and Node B. Node C and Node D also have coil 1 as the strongest pair for them to communicate. Since the magnetic fields produced by Node A and Node B are directional, they will not be able to reach Node C and Node D, thus allowing Node C and Node D to communicate during the same time. This special case can allow

an overall increase in the network throughput and the effect is shown in the results.

V. PERFORMANCE EVALUATION

As mentioned in Section I, MI technology is relatively new and research on its application in wireless sensor networks is limited. Therefore, it would be unjust to directly compare the MAC protocols used in traditional wireless sensor networks or underwater wireless acoustic sensor networks with our proposed MI-MAC protocol. Nevertheless, it is essential to assess the performance of the MAC protocol to offer researchers valuable insights into its strengths and limitations. Furthermore, the primary objective of this article is not to introduce a new MAC protocol, but rather to demonstrate the suitability of the MI-MAC protocol on our specially designed sensor node. As mentioned earlier, the sensor node can be utilized in two possible transmit configurations. Therefore, our evaluation focuses on the implementation of the MI-MAC protocol for both of these configurations as well as the hybrid configuration introduced earlier. To assess the efficacy of the MI-MAC protocol, we have chosen two crucial metrics: 1) energy consumption and 2) throughput performance. By conducting performance evaluations, we aim to showcase how the hybrid configuration, among the possible transmit configurations, achieves optimal results in terms of both energy efficiency and throughput.

A. Power and Energy Consumption

We introduce two types of energy consumption: 1) energy consumed during the *Idle*, *Receive*, *Sense*, and *Transmit* state

TABLE IV
CURRENT CONSUMPTION IN OPERATING MODES

	Idle State	Receive State	Sense State
Node 1	74 μ A	0.53 mA	0.77 mA
Node 2	67 μ A	0.50 mA	0.73 mA
Node 3	43 μ A	0.49 mA	0.73 mA
Node 4	44 μ A	0.42 mA	0.71 mA
Node 5	73 μ A	0.52 mA	0.76 mA

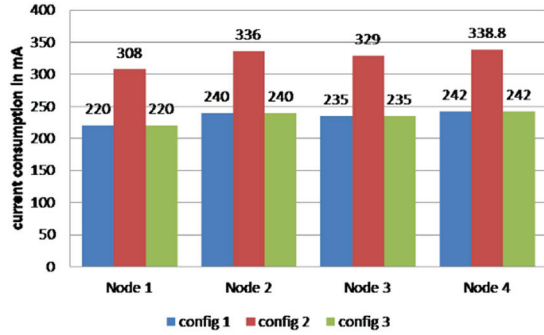


Fig. 8. Current consumption during the transmit state for configuration 1, configuration 2, and configuration 3.

when there is no collision and 2) the additional energy that is consumed during retransmission when there is collision.

- 1) *Without Collision*: As mentioned in the Section III-A, the sensor node stays in one of the four states: Idle state, Receive state, Sense State, and Transmit state. We, therefore, program the sensor node to each state and measure the current drawn by the sensor node in each state. Table IV shows the current consumed during the idle, receive, and sense state. The sensor node will remain in idle state for most of the time and listens to the channel. This state consumes the lowest energy as all the components are turned-OFF, with only receiver circuitry working actively. The average current consumed during the *Idle state* was recorded as 60 μ A. During the *Receive state*, the processor also, wakes up from the deep low power mode, and start processing the data. This draws more current, and thus, the average current in the *Receive state* was recorded as 0.49 mA. Similarly, during the *Sense state*, both receiver and microprocessor are actively working and exchanging messages. The current drawn in the *Sense state* is a little more than the one in *Receive state* and was recorded as 0.74 mA.

Fig. 8 shows the current consumed during the transmit state for all the three configurations. As configuration 1 and configuration 3 uses only one coil to transmit at a given time, the current consumption is 220 mA. The configuration 2 uses all the three coils to transmit at a given time, which adds more impedance and draws more current. It can be noticed that configuration 2 consumes 140% more than configuration 1 and configuration 3.

We further draw the comparison of the total energy consumed by the three configurations during one full exchange of data packets between the sender and the receiver

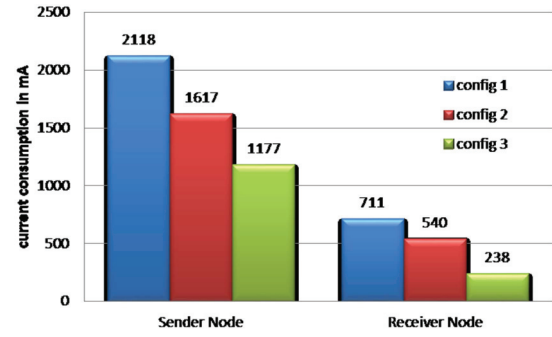


Fig. 9. Total current consumption for both sender and receiver node in configuration 1, configuration 2, and configuration 3.

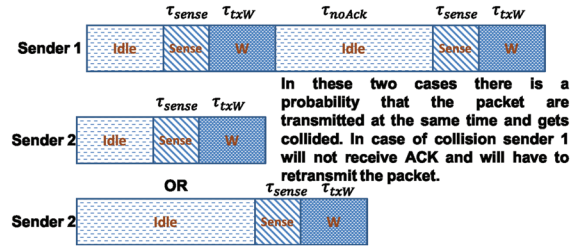


Fig. 10. When two sender nodes get to transmit at the same time and the sender has to retransmit the data due to collision.

when there is no collision. It can be seen from Fig. 6, that the sender node with configuration 1 remains in transmit state for 9τ time, in receive state for 3τ time, in idle state for 5τ time, and in sense state for 2τ time. For configuration 2, the sensor node remains in transmit state for 3τ time, in receive state for 1τ time, in idle state for 2τ time, and in sense state for 2τ time. For configuration 3 the sensor node remains in transmit state for 5τ time, in receive state for 1τ time, in idle state for 2τ time, and in sense state for 2τ time. The total energy thus consumed by each sensor node can be calculated as the energy spent in the given state multiplied by the time it takes in the given state. Similarly, the receiver node with configuration 1 remains for 3τ during transmit state, 9τ during receive state, 6τ during idle state, and 1τ during sense state. For configuration 2, the sensor node remains for 1τ during transmit state, 3τ during receive state, 3τ during idle state, and 1τ during sense state. For configuration 3 the sensor node remains for 1τ during transmit state, 5τ during receive state, 2τ during idle state, and 2τ during sense state. The total energy thus consumed by each sensor node can be calculated as the energy spent in the given state multiplied by the time it takes in the given state. (Fig. 9 shows the current for both sender and receiver.)

- 2) *With Collision*: Fig. 10 shows the possibility when two packets are transmitted at the same time. This situation may arise when the Sender 2 starts to sense the channel a little before or after the Sender 1 starts transmission. In this case, the two packets may collide, and the sender 1 may not receive ACK. Sender 1 waiting until the τ_{noAck}

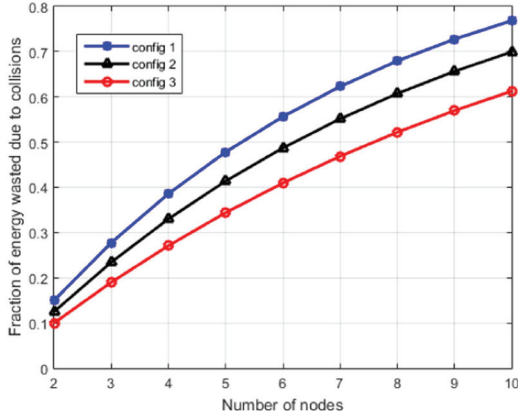


Fig. 11. Transmit energy wasted due to collisions for all the three configurations.

will sense the channel again and retransmit the data. The energy to retransmit the same packet is considered as the wasted energy.

The nodes can start transmission anytime in the interval with an independent identically distribution (i.i.d.), with τ as the transmit duration. Referring to Fig. 10, taking sender 1 transmission as a reference point in this figure, it can be seen that WakeUp packet may collide, if sender 2 sends the WakeUp packet either in the first cycle or during the the next cycle. Hence, the probability that sender 1 packet collides with sender 2's packet is $P[\text{collision}] = \tau / (\tau_{\text{noAck}})$. Thus, the probability that a sender node's transmission collides with at least another node's transmission over one whole transmit cycle is then given by

$$\begin{aligned}
 P[\text{A node collides with at least one other node}] &= 1 - P[\text{A node does not collide with any other node}] \\
 &= 1 - \left[\left(1 - \frac{2\tau}{\tau_{\text{noAck}}} \right)^{N-1} \right] \quad (7)
 \end{aligned}$$

where N is the number of nodes in this network. Considering that each node uses the same energy for transmission and each transmission is independent of other transmissions, the expected value of the total transmit energy wasted due to collisions is shown in Fig. 11 with number of nodes for all the three configurations. It is interesting to know that, configuration 1 consumes low power during the Transmit state but consumes the highest power as a whole because of transmitting the packets in configuration 1 three times. Configuration 2 uses 140% more current but since there are fewer packets to send, the consumption is lower than the configuration 1. Configuration 3 on the other hand outperforms both the configuration, because of lower current consumption in transmit state and fewer packets to send.

Figs. 12 and 13 show the total current consumption of the sender and receiver node, respectively, for all the three configuration during the four states used in one complete data

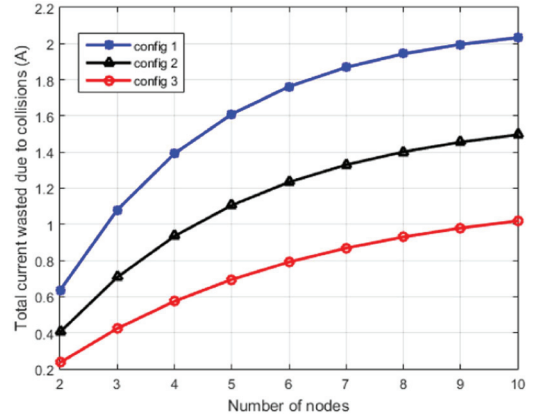


Fig. 12. Total current consumed by the transmit node for all the three configurations during the complete data transfer including all the four states.

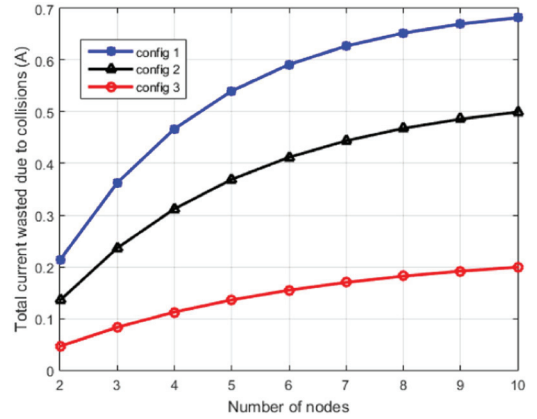


Fig. 13. Total current consumed by the receiver node for all the three configuration during the complete data transfer including all the four states.

transfer when there is collision. It can be clearly seen that the configuration 3 outperforms the other two configuration in terms of power consumption in both sending and receiving.

B. Wait Time and Throughput

Fig. 14 shows the time slots the sensor node has to wait before the transmission. It can be seen that for configuration 2, the wait time is lowest, while for configuration 1 the wait time is highest and will result in poor network performance. The configuration 3 on the other hand has a little more wait time than configuration 2 as it uses more packets during the WakeUp stage. As discussed, the configuration 3 also allows a special case where two nodes can transmit at the same time, and it can be seen that the special case helps to improve the network performance. As the number of nodes in a network increases, the wait time also increases and eventually this metric becomes important to evaluate the network performance.

Fig. 15 shows the number of bytes the sensor node transmits in one complete data transfer. It can be noted that configuration 1 needs to transmit 138 bytes for a complete data transfer when there is no collision. Configuration 2 needs to transmit 46 B, and

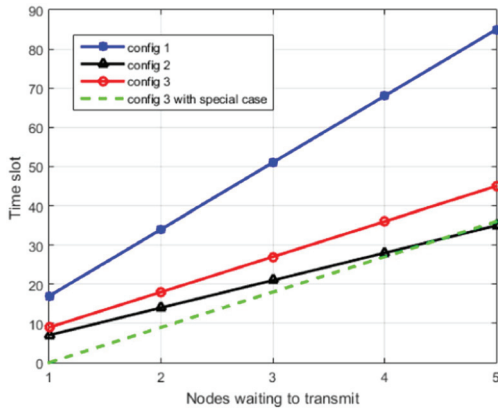


Fig. 14. Time slots the nodes have to wait to start transmission.

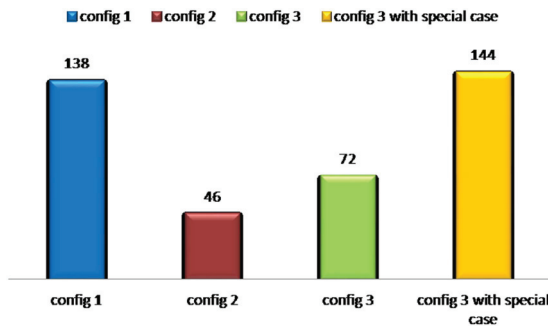


Fig. 15. Number of bytes the sensor node transmits in one transmit cycle.

configuration 3 needs to transmit 72 B for one set of data transfer. This is important to note that, actual information bytes are 46 B and the configuration 1 uses 96 extra bytes to transmit the same amount of information. Similarly configuration 2 uses 24 extra bytes to transmit the same amount of information. These extra bytes can increase the network traffic and drastically effect the network performance when the network grows bigger. This is also interesting to know that the special case for configuration 3 helps in network performance as it sends twice (92 B) the actual information in one complete cycle with 48 extra bytes. There are more extra bytes, but at the same time the throughput is doubled.

VI. CONCLUSION

This article presents the design of an MAC layer protocol that can be deployed in an MIWSN. The primary objective of this MAC protocol is to minimize energy consumption effectively. 3-D MI wireless sensor nodes in general are designed with two possible configurations. Configuration 1 employs all three coils for simultaneous transmission (resulting in higher power consumption), whereas Configuration 2 arranges the three coils to transmit sequentially (requiring a longer time). The study not only evaluates the proposed protocol for the two potential MIWSN configurations but also proposes a novel hybrid configuration, where the three coils are effectively utilized in terms of power consumption and time efficiency. The article evaluates

the energy and network performance of all three configurations, clearly demonstrating how configuration 3 outperforms in crucial aspects, such as power consumption, network latency, and throughput.

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