Towards Microscale NFC-Enabled IoT Sensors: Physical and MAC Layer Design Analysis

MICHAEL OKWORI\textsuperscript{1}, (Student Member, IEEE), ALI BEHFARNIA\textsuperscript{2}, (Student Member, IEEE), AND ALI ESLAMI\textsuperscript{3}, (Member, IEEE)
Department of Electrical Engineering and Computer Science, Wichita State University, Wichita, KS 67260, USA
Corresponding author: Michael Okwori (mxokwori@shockers.wichita.edu)

This work was supported in part by the National Science Foundation under Grant OIA-1656006, and in part by the State of Kansas through the Kansas Board of Regents.

ABSTRACT Microscale sensors provide critical solutions in diverse fields, ranging from measurement, automation, and control in industrial, agricultural, and biomedical applications. However, their development is limited by many requirements and challenges, such as efficient powering and the selection of suitable wireless communication technologies. A number of wireless communication technologies have been deployed in these sensors, including terahertz (Thz) radio frequency and ultrasound. Designing sensors in micro-scale imposes challenges for any communication technique deployed. This paper investigates the use of magnetic induction-based backscatter communication in a microscale sensor. The aim here is to provide both physical and media access control (MAC) layer design analysis for a microscale mote that is powered inductively and communicates with a reader using backscattering. Magnetic induction-based communication and powering are demonstrated via analysis and simulation for the mote. Then, low-power modulation, error-correction coding, and suitable low-power MAC schemes with evidence of feasible implementation in microscale are explored. Results of the performance analysis indicate that the proposed design achieves communication at a range of at least a few centimeters (5–6 cm) with an acceptable bit error rate (BER). Finally, MAC layer analysis reveals the optimum number of motes to be deployed for various read delays and transmission rates.

INDEX TERMS Microscale mote, near-field communication, IoT sensor, low-power modulation, resource-constrained MAC.

I. INTRODUCTION

Miniaturization of sensors to microscale holds great promise for enabling various applications in smart homes, smart cars, smart protective skins on air planes, biomedical wearables and implantables, industrial automation and control, smart agriculture, and smart power grids [1]. To achieve this miniaturization, ongoing research efforts currently involve the development of nanoelectronic components and the investigation of battery-less or external powering techniques. Also, a variety of communication techniques are being researched for deployment of these tiny sensors. Some of the approaches considered include the use of inductive coupling (1–49 MHz), radio-frequency communication (401–406 MHz, 2.36–2.4 GHz), ultrasonic communication (1–3 MHz), and optical and terahertz (THz) communication (300 GHz–430 THz) [2]. Each of these communication techniques demonstrates varying performance, depending on the various application scenarios. Terahertz communication employs electromagnetic waves in a THz frequency band to communicate data and requires an antenna size of a few micrometers. This small antenna satisfies the size requirement of microscale sensors [3], [4] and can potentially provide a large bandwidth. There have been some remarkable efforts in designing, building, and testing sensors using THz communication [5]–[7], thereby achieving good communication links and small sizes. Despite its many advantages, THz communication undergoes extremely high attenuation in a dense communication medium, making it unsuitable for some applications. Ultrasonic waves propagate very well in water and appear suitable for internet of things (IoT) applications in liquid bodies, making them a viable option for short range communications. Also, piezoelectric sensors are suitable for power-scavenging applications [2]. Some meritorial research has been carried out in applying ultrasonic waves in small sensors [8], [9]. The challenge here is that
ultrasonic waves suffer degradation in applications where the sensors are located in liquid and the reader is located in the air. Also, the small size of the sensors causes a large resonating frequency, which results in an exponential increase in signal attenuation.

Optical communication offers an interference-resistant option because signals are converted from electrical to infrared waves before transmission, and then converted back to electrical signals at the receiver. It has been successfully applied in miniature sensors in transcutaneous applications [10], [11]. The application of optical communications, however, is hindered by attenuations due to reflection, scattering, and absorption issues (see [2] and references therein).

An alternative means of communication involves the use of magnetic fields. Magnetic induction for powering and near-field communication (NFC) with IoT devices has been studied in the literature (e.g., see [1] and references therein). The performance of NFC, unlike that of ultrasonic and THz communications, is affected minimally by the environment of application. This is due to the fact that magnetic permeability of many potential mediums such as air, water, soil, and human body is similar [12]. In fact, the performance improves in presence of ferromagnetic materials such as a number of common metals. However, the communication range of NFC could be limited to small distances, as the magnetic power decays with inverse of the distance-cubed [13]. While communication ranges of a few centimeters have been achieved, the smallest sensors are at least a few millimeters in each dimension [14] (see Section II).

In this work, we investigate physical and media access control (MAC) layer designs for a sub-millimeter mote that is externally powered and communicates using magnetic induction with a handheld device. We assume that the mote has a communication circuitry, an inductive coil, and a micro- (or nano-) sensor, all encased in a cube. When an NFC-enabled reading device is in close proximity to the mote, the two coils are coupled, and power is induced in the mote. The mote then uses backscatter communication to send its measured data to the reader.

The main contributions of this paper are summarized as follows:

- We model the magnetic induction-based communication for a microscale coil in the mote, and we provide a detailed analysis demonstrating that communication can be achieved within the reception sensitivity of today’s handheld devices. In our analysis, we illustrate the trade-offs that emerge from the selection of subcarrier frequencies and the range of communication.
- We propose a physical layer design for the mote with simple and energy-efficient modulation and error-control coding techniques. We then evaluate the performance of the physical layer via simulation and show that the proposed design can achieve communication at a distance of a few centimeters (5–6 cm).
- We investigate the implementation requirements and performance of simple and efficient MAC schemes for the mote. We also provide evidence of the feasibility of their implementation at microscale. The simulation results provide guidance for selecting optimum mote design parameters and utilization specifications.

The rest of the paper is organized as follows. The physical layer and MAC layer designs of related works, with emphasis on the dimensions of the prototypes, are presented in section II. Section III provides a detailed design and simulation results of the mote’s physical layer. Section IV outlines the evidence of the feasibility of the implementation of selected MAC layer schemes in microscale, and also presents the simulation analysis to determine the MAC layer design parameters and utilization specifications. Section V presents the performance comparison of the MAC schemes. Section VI concludes the paper.

II. RELATED WORKS

Extensive research has been done in the field of magnetic induction powering and communication in the following categories: antenna and wireless channel modeling, networking protocols, connectivity, and capacity analysis [15]. The authors in [16] identified several open issues in magnetic communication, including channel modeling in 3D space, extending communication range, antenna coil design, transceiver design, energy modeling, error-control techniques, and routing protocol design. Research studies on these open issues involve either simulations or developed prototypes.

A number of related works, that led to developing prototypes are reported in [17], [18], but their dimensions are all above the sub-millimeter scale proposed in this work. The authors of [17] reported an NFC-based sensor that can be implanted via a 14-gauge syringe needle. They successfully manufactured the sensor with dimensions of $1 \times 1 \times 10 \text{ mm}^3$, and capable of achieving transmission and reception ranges of 50 cm and 20 cm, respectively. However, the sensor cannot be powered exclusively using NFC but rather requires a battery to power its chip. In [18], an inductively powered arterial-pulse sensor was presented. The authors were remarkably able to use only biodegradable materials for the sensor and achieved dimensions of $5 \times 20 \text{ mm}^2$ and $10 \times 10 \text{ mm}^2$ for the sensor and inductive coil, respectively. A low-cost and energy-efficient magneto-inductive sensor node was designed and evaluated in [19]. The design utilized a 3D coil in three different configurations and implemented a carrier sense multiple access protocol software in a low-power mode microcontroller. During testing, the authors utilized 29 turns of a coil with a radius of 0.104 m and a current of 0.8 A with a frequency of 125 kHz. The dimensions of the sensor node are $7.5 \times 2 \text{ cm}$, which is orders of magnitude larger than our focus in this work. The authors of [20] proposed a protocol stack of a magnetic field area network. A time-division multiple access (TDMA)-based scheme was
utilized in the MAC layer. A 128-kHz signal, Manchester and non-return-to-zero coding scheme, and BPSK modulation were deployed at the physical layer. The protocol stack was implemented on a prototype board that is orders of magnitude larger than microscale.

A model for magnetic induction communications for wireless underground sensor networks was presented in [13]. That model provided a detailed analysis of the path loss and the bandwidth of magnetic induction-based communication in a soil medium. At the physical layer, the model utilized an operating frequency of 10 MHz and a 2PSK modulation scheme, and both the receiver and transmitter were made of five turns of a copper coil with a radius of 0.15 mm and diameter of 1.45 mm. This very comprehensive model did not consider the MAC layer. An energy-efficient scheme for wireless sensor network (WSN) IoT applications was presented in [21]. The authors assumed the physical layer could transmit data at one of nine discrete levels, ranging from 0.05 mW to 25 mW, in their design of a distributed power controlled contention-based protocol. These varying discrete levels ensure that minimum power is utilized in transmitting data to neighboring nodes. Another similar energy-efficient MAC scheme for a WSN was presented in [22]. Both works focused on the protocol design and did not consider the dimensions of the actual node. Our work is different from these because we consider the feasibility of implementing our proposed scheme in microscale, in addition to it being energy efficient.

Though quite a number of research studies have been done in the area of modeling and prototyping magnetic induction-based sensors, our work focuses on designs of the physical and MAC layers for a microscale mote. In addition to the simulations, we touch upon the feasibility of building the models in microscale.

III. PHYSICAL LAYER DESIGN

This section presents the physical layer design of the mote. We describe the structure and parameters of this layer, and provide simulation and analysis of the power transmitted to the mote and power received from the mote. The trade-off between the communication range achieved and the bandwidth is also highlighted. Finally, we present a selection of modulation schemes and error-correction codes and highlight the feasibility of implementation in microscale.

A. STRUCTURE AND PARAMETERS

Fig. 1(a) shows the structure and parameters of transceiver antennas. Tri-directional (3D) coils are considered in order to address the problem of alignment. It is also assumed that the source voltage in the reader \((V_r)\) is equal to 3.8 v (voltage of iPhone 6 [23]). The analysis in this paper considers three resonant frequencies: 1, 13.56, and 100 MHz, that is, medium, high, and very high frequency, respectively [24]. Parameters of the coil in a microscale mote are selected in a way that each dimension of the cube \((s)\) does not exceed 500 \(\mu m\). It should be noted that, due to the skin effect, frequency affects the unit resistance of the coils (i.e., \(R_{0r}\) and \(R_{0m}\)) [25] and, hence, their impedance \((Z)\), which in turn influences the transceiver power.

\[ Z = \frac{R_i + j \omega L_i}{Z_m + Z_r} \]

\[ Z_m = \frac{Z_m + Z_r}{Z_r} \]

\[ Z_r = Z_m + Z_{lr} \]

\[ Z_{lr} = \frac{\omega^2 M^2}{Z_r} \]

\[ V_r = (\omega M + \frac{V_r}{Z_r}) \]

\[ V_m = (\omega M + \frac{V_m}{Z_m}) \]

\[ P_{tx} = \frac{V_r^2}{2} \]

\[ P_{rx} = \frac{V_m^2}{2} \]

\[ P_{tx} = \frac{V_r^2}{Z_{lr} + Z_r} \]

\[ P_{rx} = \frac{Z_L V_m^2}{Z_{lr} + Z_m + Z_r} \]

B. MAGNETIC INDUCTION-BASED COMMUNICATION

Inspired by passive radio-frequency identification (RFID), we employ load modulation (a.k.a. modulated backscatter) to transmit data from the mote to the reader. With this aim, the mote employs an on-off switching circuit controlled by data to change the voltage at the reader and transfer information. Load modulation works in a “near field” where the distance between a transmitting coil and a receiving coil does not exceed \(\frac{\lambda}{2\pi}\), where \(\lambda\) is the wavelength. Since the resonance frequencies considered in this paper are less than 100 MHz (i.e., \(\lambda \geq 3\) m) and the communication range is within a few centimeters, load modulation can be safely employed.

C. POWER TRANSFER

The power transmitted by the reader \((P_{tx})\) and power received at the mote \((P_{rx})\) can be obtained as:

\[ P_{tx} = \frac{V^2}{Z_{lr} + Z_r} \]

\[ P_{rx} = \frac{Z_L V^2}{Z_{lr} + Z_m + Z_r} \]
FIGURE 2. Reader transmitted power ($P_{tx}$) and received power at the mote ($P_m$). Parameters are chosen as follows: $d = 5 \text{ cm (distance between devices)}$, $f_c = 1, 13.56, 100 \text{ MHz (resonance frequencies)}$, and $f_s = \frac{f_c}{2^n}$ (subcarrier frequency).

reader’s impedance on the mote, $V_{rm}$ is the induced voltage by the reader on the mote, and $Z_L$ is the impedance of the load at the mote. The equations for these parameters along with the equivalent circuit of the coils are presented in Fig. 1(b). The analysis leading to eqs. (1) and (2) is well known, and its details can be found in [13].

Fig. 2 shows both $P_{tx}$ and $P_m$ versus frequency. Here, it is assumed that $d = 5 \text{ cm}$. As can be seen, both $P_{tx}$ and $P_m$ peak at the resonance frequencies. The value of the peaks for $P_m$ at $f_c = 1 \text{ MHz}$, $f_c = 13.56 \text{ MHz}$, and $f_c = 100 \text{ MHz}$ are around $-30 \text{ dBm}$, $-15 \text{ dBm}$, and $-10 \text{ dBm}$, respectively. We believe that this range of power is sufficient for our mote, which utilizes basic components such as logic gates, timing clocks, and registers. For instance, a low-power shift register design in nanoscale that consumes an average transient power of $67.2 \text{ nW (−41.73 dBm)}$ is demonstrated in [26]. In [27] a typical mote of size $5 \times 5 \text{ mm}$ is comprised of a chip and antenna requires a power of $10.7 \mu\text{W (−19.71 dBm)}$. The chip integrates all the complex components required to reconfigure the forward and reverse data links, uniquely identifies each mote, and enables multiple motes to communicate with an external reader. Some other similar-sized motes have power consumption in the range of $-20 \text{ dBm}$ to $-10 \text{ dBm}$ [14]. The transmitter and receiver in [17] consume $-13.62 \text{ dBm}$ and $-14.44 \text{ dBm}$, respectively, while [28] requires $-8.35 \text{ dBm}$ and $-24 \text{ dBm}$ for the stimulating and non-stimulation modes, respectively. Our mote is orders of magnitude smaller than the reported devices; hence, its power consumption is expected to be less.

It is noteworthy that the sideband frequency ($f_s$) can be efficiently obtained from the $f_c$ using a frequency divider shift register. That is, $f_s = \frac{f_c}{2^n}$, where $n$ is the length of the shift register. For instance, in Fig. 2, it is assumed that $n = 4$ that yields $f_s = 62.5 \text{ KHz}$, $f_s = 847.5 \text{ KHz}$, and $f_s = 6.25 \text{ MHz}$ for $f_c = 1 \text{ MHz}$, $f_c = 13.56 \text{ MHz}$, and $f_c = 100 \text{ MHz}$, respectively. As shown, increasing $f_s$ leads to higher sideband attenuation ($A_s$), hence lower backscattered power at the reader.

FIGURE 3. Backscattered induced power in external reader due to mote versus separating distance between two devices.

D. ACHIEVABLE BACKSCATTED POWER

The sensitivity of the reader plays a vital role in detecting the backscattered power from the mote. Sensitivity is the lowest signal power from which useful information can be obtained. For example, the reference signal receive power (RSRP) as the LTE signal strength indicator could range from $-45 \text{ dBm}$ for excellent signals to $-140 \text{ dBm}$ for poor signals [29]. With this in mind, we assume that $-105 \text{ dBm}$ is a sufficient received power at the reader. To understand the level of received power in our design, Fig. 3 shows the magnitude of backscattered power in the reader ($P_{re}$) relative to the distance between the two devices. We use the parameters in Fig. 1(a) in
this simulation, wherein wires are copper and \( \mu = 1 \) (relative permeability). As shown in Fig. 3, a communication range of few centimeters is feasible with the assumption of \(-105 \text{ dBm}\) as the received power threshold. The received backscatter signal (from the mote) experiences a total loss, equal to roundtrip path loss \((2 \times \text{PL})\) plus sideband attenuation \((A_s)\). In other words,

\[
P_{re} = P_t - [2(\text{PL}) + A_s],
\]

where

\[
\text{PL} = P_m - P_{tx}.
\]

The value of \(A_s\) depends on the selected subcarrier frequency (see Fig. 2). In Fig. 3, we have assumed that \(f_s = \frac{f_c}{27}, \ f_s = \frac{13.56}{27}, \ \text{and} \ f_s = \frac{100}{27}, \) for \(f_c = 1 \text{ MHz}, f_c = 13.56 \text{ MHz}, \ \text{and} \ f_c = 100 \text{ MHz}, \) respectively. To mitigate \(A_s\), we increase \(n\) (the frequency divider factor) for higher \(f_s\).s.

**E. RANGE-BANDWIDTH TRADE-OFF**

The value of \(f_s\) affects both the total loss and available bandwidth. One could choose lower \(f_s\)s to obtain better range and \(A_s\), but this improvement is attainable at the price of a lower bandwidth. Therefore, it is vital to select the value of \(f_s\) to support a sufficient communication range as well as an acceptable bandwidth. Fig. 4 represents the maximum achievable \(f_s\) with respect to distance between the two devices. To obtain this figure, we use the parameters shown in Fig. 1(a), while setting \(P_{re} = -105 \text{ dBm}\) in eq. (3). Then, using eqs. (1), (2), and (4), we derive \(A_s\) from eq. (3) for different ranges. Finally, we obtain the achievable \(f_s\)s according to the values of \(A_s\)s (see Fig. 2). The trade-off between achievable range and sideband frequency is demonstrated in Fig. 4 for three carrier frequencies. As can be seen, at any given distance, a higher carrier frequency leads to a larger bandwidth.

**F. MODULATION AND ERROR-CORRECTION CODING**

Taking complexity and power consumption into consideration, we select amplitude shift keying (ASK) and binary phase shift keying (BPSK) as the simplest digital modulation techniques for load modulation in the mote, and Hamming (15,11) and Reed-Solomon (RS) (31,26) codes as short linear block codes for error-correction coding. The ASK and BPSK modulation schemes proposed can be implemented in \(\mu m\) scale [30], [31]. The data rate deployed depends on the application of the mote and the rate of sensor measurements. A high rate requires either a higher symbol rate/clocking frequency or a higher number of bits encoding each symbol [32], thereby increasing the size of the mote. As for error-correction coding, since the mote solely sends information, it needs to only implement the encoding circuit. The decoding circuit that requires more power and complexity is embedded at the reader.

In order to set up the simulation, we apply the parameters used in Fig. 1. Thermal noise is expected to be around \(-120 \text{ dBm}\) for a bandwidth of 200 KHz and temperature of 290\(^\circ\)K. Also, the noise figure, which is added by electronic circuits, is expected to be 15 dB or less [33]. Taking the worst-case scenario, we assume \(-105 \text{ dBm}\) to be the total noise at the reader. We also assume that \(f_c = 13.56 \text{ MHz}\) and \(\mu = 1\).

Fig. 5 depicts system performance in terms of bit error rate (BER) for ASK, BPSK, BPSK alongside the Hamming code, and BPSK alongside the RS code. As can be seen, the BER for distances above 6 cm reaches beyond 0.01 in all cases. In many applications, it is safe to assume that a BER of about \(10^{-3}\) would be acceptable. According to Fig. 5, this BER is achievable for distances between 5 and 6 cm. When comparing the performance relative to both modulation and error-correction coding, BPSK along with
TABLE 1. Required Components and Evidence of Microscale Implementation for Considered MAC Schemes.

| Requirements                     | Slotted ALOHA | CDMA | Implementation in Microscale |
|----------------------------------|---------------|------|-----------------------------|
| Unique Address                   | ✓             | ✓    | Shift Registers [26]        |
| Synchronization                  | ✓             | ✓    | J-K Flip-Flop Synchronization Circuit [34] |
| Internal Clocks                  | ✓             | ✓    | Ferromagnetic Cladding [35]  |
| Random Number Generators         | ✓             | ✓    | Feedback Shift Registers [36]|
| Spreading Codes                  |               | ✓    | Pre-Generated and Stored on Shift Registers [37]|
| Chipset and Data Multiplier      |               | ✓    | XOR Gates [38]              |

FIGURE 5. Performance of using error-correction coding in the system: bit error rate (BER) versus various separating distances between reader and mote.

the RS code performs the best. Depending on the application and required BER, the respective combination of modulation and error-correction coding can be chosen according to the information from this figure.

IV. MAC LAYER DESIGN

In this section, we present the analysis and design of the MAC layer. First, we investigate the requirements of two MAC schemes: slotted ALOHA and code-division multiple access (CDMA), and report evidence of the feasibility of implementing each scheme in microscale. We then consider design parameters for each of the schemes. Finally, we compare the performance of the schemes for two selected read durations.

A. FEASIBILITY OF MICROSCALE IMPLEMENTATION OF MAC SCHEME

The probability of failure of microscale sensors warrants the deployment of a large number to capture readings that can be averaged to obtain more accurate and realistic measurements. MAC layer protocols are very well advanced and widely deployed, but their implementation in microscale needs to be investigated and analyzed. Here, we investigated the implementation of two selected lightweight MAC schemes: slotted ALOHA and CDMA in microscale, and reported the evidence of feasibility of implementation in Table 1. This table shows the required component of each scheme as well as the evidence of their implementation in microscale from the literature.

B. SIMULATION AND RESULTS OF MAC ANALYSIS

Monte Carlo simulations are performed to investigate key design parameters of both the slotted ALOHA and the CDMA. For the slotted ALOHA, we investigate the relationship between three parameters: time duration to obtain readings from all motes (Read – Time), transmission data rate of the motes (Rate), and number of motes contending for access at a particular location (Number of Motes). Simulations are carried out for packet lengths of 8 and 64 bytes.

In the simulation, we set the Read – Time to values between 2 and 10 seconds in steps of 2 seconds, and evaluate the Number of Motes with successful transmissions. Our interest here is to recommend the number of motes to be deployed for various values of Rate and Read – Time. In our simulation of the slotted ALOHA, we assume that each mote would have one data packet for transmission. It is also assumed that the reader is capable of processing all received packets during one slot duration. As a result, no queues are formed at either the mote or the reader. Our analysis does not consider the time taken to receive packet acknowledgments, and it is assumed that packet failures are due to collisions as a result of multiple transmissions on a slot. We ran 100 simulations to obtain the average number of successful motes out of the Number of Motes.

The focus of our simulation of the CDMA is to determine how many motes can successfully communicate with the reader in a reading session. We evaluate this by randomly assigning static spreading codes of lengths 4, 8, 16, 32, and 64 to the motes, and uniformly sampling from the pool of motes. Our analysis is based on the assumption of equal transmission energy for motes and synchronization of the start time of transmissions. Also, we only consider multiple access interference due to data transmissions of other motes.

Results of the slotted ALOHA analysis are shown in Fig. 6. For rates varying from 1 to 4 kbps, we obtain the highest number of contending motes that achieve successful transmission with a specific delay (D). This was done for data packet lengths (L) of 8 and 64 bytes. From this, we can infer what combinations of delay, data rate, and number of motes are feasible. For instance, for a mote operating at 2 kbps with a delay of 10 seconds and a packet length of 64 bytes, 9 motes can be successfully read in the interrogation zone. Similar deductions can be made for a data-packet length of 8 bytes.
The packet length utilized depends on the application requirement. From this analysis, the optimum number of motes for deployment can be recommended for any choice of data rate and delay.

Results of the CDMA analysis are shown in Fig. 7. The results show a positive correlation between the number of successful motes and the length of codes. For every code length, the number of successful motes rises to a peak and then drops as the number of motes contending for access increases beyond a particular point. This can be employed to minimize resources while meeting application requirements.

**FIGURE 6.** Recommended number of motes (N) to achieve all successful transmissions for various rates and allowable delays.

**FIGURE 7.** Number of successful transmissions for various number of motes using static CDMA codes of length C.

**V. PERFORMANCE COMPARISON OF MAC SCHEMES**

In this section, we present a performance comparison of the two MAC schemes for two read durations: short and long, set to 128 slots and 1280 slots, respectively. For the simulation, packet length is set to 64 bytes and transmission rate to 20 kbps, resulting in a short-read duration of 3.28 seconds and a long-read duration of 32.8 seconds. The short-read duration is analyzed for time critical applications, wherein the reader sweep or read time is approximately 3.5 seconds, while the long-read duration is for applications with a reader sweep time of approximately 33 seconds.

Figs. 8 and 9 show results of the comparison of the two MAC schemes. In Fig. 8, we evaluated the performance for a short-read time set to 128 slots for the slotted ALOHA and a spreading code length of 128 for the CDMA scheme. The spread signal from a code length of 128 will take the same transmit duration as 128 slots in the ALOHA. Results show the superior performance of CDMA for all numbers of motes beyond 20, with a decline in performance at 120 motes. This superior performance of the CDMA is due to ALOHA’s low utilization efficiency of the 128 available slots, because most slots are not selected in the random back-off process and therefore remain empty. For long-read times, the analysis in Fig. 9 shows superior performance of the slotted ALOHA scheme for a number of deployed motes up to 50, beyond which performance begins to oscillate around that of the CDMA. For a much longer read duration, by either increasing the communication rate or the number of available slots, the ALOHA scheme will read all deployed motes. The increase in duration has no impact on CDMA performance. We can infer from the results that for applications that require a short-read time, CDMA will be a better choice but at the expense of implementing more complex procedures in microscale. Slotted ALOHA can be used in applications where long-read durations can be tolerated.

**VI. CONCLUSION**

In this paper, we have demonstrated that communication via magnetic induction can be established between a microscale mote and an external reader. We have also investigated
the feasibility of implementing, at microscale, suitable low-power modulation, error-correction coding schemes, and MAC schemes. The physical layer analysis shows that communication ranges of 5 to 6 cm are achievable with acceptable BER and low complexity. MAC analysis results provide guidelines for selecting mote design parameters and mote utilization specifications. In summary, it was found that magnetic induction is a formidable candidate for communication between microscale sensors and external readers such as NFC-enabled handheld devices.

REFERENCES

[1] F. K. Shaikh, S. Zeadalley, and E. Esposito, "Enabling technologies for green Internet of Things," IEEE Syst. J., vol. 11, no. 2, pp. 983–994, Jun. 2017.
[2] A. K. Teshtone, B. Kibret, and D. T. H. Lai, "A review of implant communication technology in WBAN: Progress and challenges," IEEE Rev. Biomed. Eng., vol. 12, pp. 88–99, 2019.
[3] L. Zakrjasek, E. Einarsson, N. Thawdar, M. Medley, and J. M. Jornet, "Lithographically defined plasmonic graphene antennas for terahertz-band communication," IEEE Antennas Wireless Propag. Lett., vol. 15, pp. 1553–1556, 2016.
[4] J. M. Jornet and I. F. Akyildiz, "Graphene-based plasmonic nano-antenna for terahertz band communication in nanowire sensors," IEEE J. Sel. Areas Commun., vol. 31, no. 12, pp. 685–694, Dec. 2013.
[5] J. M. Jornet and I. F. Akyildiz, "Graphene-based nano-antennas for electromagnetic nanocommunications in the terahertz band," in Proc. IEEE 4th Eur. Conf. Antennas Propag., Apr. 2010, pp. 1–5.
[6] J. M. Jornet and I. F. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band," IEEE Trans. Wireless Commun., vol. 10, no. 10, pp. 3211–3221, Oct. 2011.
[7] N. Akkari, J. M. Jornet, P. Wang, E. Fadel, L. Elrefaei, M. G. A. Malik, S. Almasri, and I. F. Akyildiz, "Joint physical and link layer error control analysis for nanonetworks in the terahertz band," Wireless Netw., vol. 22, no. 4, pp. 1221–1233, May 2016.
[8] M. Peisino and P. Ryser, "Deeply implanted medical device based on a novel ultrasonic telemetry technology," Ph.D. dissertation, Ecole Polytechnique Federale de Lausanne, Lausanne, Switzerland, 2013.
[9] L. Galluccio, T. Melodia, S. Palazzo, and G. E. Santagati, "Challenges and implications of using ultrasonic communications in intra-body area networks," in Proc. 9th Annu. Conf. Wireless Demand Netw. Syst. Services (WONS), Courmayeur, Italy, Jan. 2012, pp. 182–189.
[10] M. Schuetter, F. Kohler, J. S. Ordonez, and T. Stieglitz, "Hermetic electronic packaging of an implantable brain-machine-interface with transcranial optical data communication," in Proc. Annu. Int. Conf. IEEE Eng. Med. Biol. Soc., San Diego, CA, USA, Aug. 2012, pp. 3868–3889.
[11] M. Nafzari and J. M. Jornet, "Metallic plasmonic nano-antenna for wireless optical communication in intra-body nanonetworks," in Proc. 10th EAI Int. Conf. Body Area Netw., Sydney, NSW, Australia, 2015, pp. 287–293.
[12] I. F. Akyildiz and E. P. Stuntebeck, "Wireless underground sensor networks: Research challenges," Ad Hoc Netw., vol. 4, no. 6, pp. 669–686, Nov. 2006.
[13] Z. Sun and J. F. Akyildiz, "Magnetic induction communications for wireless underground sensor networks," IEEE Trans. Antennas Propag., vol. 58, no. 7, pp. 2426–2435, Jul. 2010.
[14] A. S. Rekhi, B. T. Khuri-Yakub, and A. Arabbian, "Wireless power transfer to millimeter-sized nodes using airborne ultrasound," IEEE Trans. Ultrason., Ferroelect., Freq. Control, vol. 64, no. 10, pp. 1526–1541, Oct. 2017.
[15] H. Guo, Z. Sun, and C. Zhou, "Practical design and implementation of metamaterial-enhanced magnetic induction communication," IEEE Access, vol. 5, pp. 17213–17229, 2017.
[16] V. Modi and C. P. Gupta, "Magnetic induction based routing in underwater wireless sensor networks," in Proc. 2nd Int. Conf. Inventive Commn. Comput. Technol. (ICICCT), Apr. 2018, pp. 223–228.
[17] Y. Shi, M. Choi, Z. Li, Z. Luo, G. Kim, Z. Foo, H.-S. Kim, D. D. Wentzloff, and D. Blaauw, “A 10 mm” inductive coupling radio for syringe-implantable smart sensor nodes,” IEEE J. Solid-State Circuits, vol. 51, no. 11, pp. 2570–2583, Sep. 2016.
MICHAEL OKWORI (Student Member, IEEE) received the B.Eng. degree in electrical and computer engineering and the M.Eng. degree in communication engineering from the Federal University of Technology Minna (FUT Minna), Nigeria, in 2007 and 2014, respectively. He is currently pursuing the Ph.D. degree with the Department of Electrical Engineering and Computer Science, Wichita State University, Wichita, KS, USA. His research interests include mobility management in IP networks, microscale sensor networks, applications of machine and deep learning, and gene network analysis in bioinformatics.

ALI BEHFARNIA (Student Member, IEEE) received the B.S. degree in electrical engineering from the University of Tabriz and the M.S. degree in electrical engineering from the Iran University of Science and Technology (IUST). He is currently pursuing the Ph.D. degree with the Department of Electrical Engineering and Computer Science, Wichita State University, Wichita, KS, USA. His research interests include resilient cyber-physical systems, error-control coding, game theory, applications of machine and deep learning, and communications over wireless networks. In 2016, he was a recipient of the Bright Future Award from Wichita State Ventures and the Donald D. Sbarra Endowed Fellowship.

ALI ESLAMI (Member, IEEE) received the Ph.D. degree in electrical and computer engineering from the University of Massachusetts Amherst, in 2013. From August 2014 to June 2015, he was a Visiting Research Scholar of information initiative at Duke (iid). He was a Postdoctoral Research Fellow with Texas A&M University, College Station, TX, USA, from March 2013 to April 2015. He is currently an Assistant Professor of electrical engineering and computer science with Wichita State University, Wichita, KS, USA. His current research interests include nanocommunications, applications of coding theory in biology, resilient design of cyber-physical systems, fault-tolerant quantum computing, and big-data storage systems. He is a member of the IEEE Communications and Computer Societies. From 2016 to 2017, he was a recipient of the Wichita State’s Young Faculty Risk Taker Award. He has served as the Session Chair for several IEEE conferences and workshops as well as a reviewer for numerous IEEE journals. He has also served on several NSF review panels.

* * *