A Mobile-Enabled Micro Communication Device for Biosensing

Phanikumar Vuka, Ali Behfarnia, and Ali Eslami

Abstract- **Our goal is to design and ultimately prototype a communication device that can circulate inside the human body and communicate with a wearable or handheld device such as a cell phone. Despite tremendous efforts in miniaturized medical implants, we are still far from designing micro-devices supporting a communication range of even few centimeters. Main reason is the limitations dictated by the size on powering and communication of such devices. We propose a *magnetic-induction* communication system that can meet these unique limitations. This paper provides a comprehensive study and comparative analysis of this system.**

I. BACKGROUND

Imagine if you could monitor the function of your vital organs in real time on your cell phone, by measuring their temperature, concentration of glucose, oxygen, and other chemicals. Cell phones are connected to servers with tremendous processing power and memory, capable of analyzing huge chunks of data in a very short time to look for abnormalities. If these capacities could be utilized, the doctor and the lab both could be brought to our cell phone. The key to this new era of health care is the production of tiny devices that can make measurements inside the human body and communicate them to our cell phones or wearables. Such devices are also the gateway to nanomedicine by enabling nanorobots and smart drug delivery, among others. We refer to such devices as *bio-motes*. Despite the tremendous effort in nano-communications and miniaturized medical implants, we are still far from designing bio-motes even in micro scale. Main reasons are limitations dictated by the **size** on the operation of such devices, particularly challenges in their **powering** and **communications**. In this paper, we take a practical approach towards addressing these challenges, which could lead to implementation, fabrication and ultimately mass production of bio-motes.

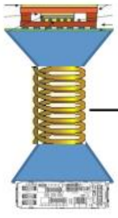

Figure 1. Bio-mote with the inductive coil and biosensor.

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The design is focused on a bio-mote that can send *a* (any) signal from inside the body to a device outside the body with dimensions of a cell phone. The focus is not on an ideal high-data-rate bio-mote or a network of them; rather it is on the simplest bio-mote that works.

A variety of approaches has been taken in the literature towards realizing bio-motes. In telecommunications, nano-communications and nano-communication networking deal with designing such devices, where three major approaches have been taken by the researches: Terahertz (THz) RF communication [1], ultrasonic communication [2], and optical communication [3]. THz communication employs electromagnetic waves in terahertz frequency band to communicate the data. THz communication for bio-motes suffers from two major problems among others. First, it undergoes extremely high attenuation in body tissues. THz waves only have a penetration depth of up to a few hundred micrometers in fresh tissue [4], limiting their effective communication range inside the body to less than 1 or 2 cm. This necessitates the use of a *network* of bio-motes to enable deep tissue measurements. However, since THz communication requires line-of-sight, implementing a THz network of nano-devices working in an uncontrolled environment such as the human body will be extremely difficult. Optical and (near) infra-red communications also suffer from the same issues as above [5]. Ultrasonic communication uses acoustic waves with frequency over 20,000 cycles per second to transmit data. Acoustic waves are known to propagate better than their RF counterpart in media composed mainly of water. On average, 65% of the human body consists of water. In addition, the FDA allows an intensity of 7.2 mW/mm2 for diagnostic ultrasound applications, which is about two orders of magnitude higher than the safe RF exposure limit in the body (10-100 μW/mm2 [6]). Despite these advantages, ultrasonic communication needs to overcome major challenges before it can be implemented in bio-motes. Attenuation of acoustic waves inside the body increases with frequency and distance exponentially. In addition, due to a large impedance mismatch at the air-tissue interface, more than 99.95% of the acoustic energy is reflected back into the tissue [7]. Attenuation and reflection together imply that in order to use ultrasonic communication for deep tissue measurements (i) a network of bio-motes is needed, (ii) one or more interrogators must be implanted on the skin to receive the ultrasonic signal. Therefore, ultrasonic nano-communication poses the same challenges as the THz approach if not more.

II. Proposed Solution And Results

We propose to use magnetic field as a better mode of communication to realize bio-motes without using a network or an interrogator as required by other modes of communication. To the best of our knowledge, this paper is the first to propose and perform a comprehensive study on magnetic-induction based communication of mobile micro- and nano-devices.

Fig. 1 shows a sample configuration of a bio-mote, which includes a (dumbbell-shaped) substrate, a communication circuit, an inductive coil, and a nanobiosensor. As shown in Fig. 2, when the mote is close enough to the cell phone (within cell phone's *interrogation zone*), its coil will be *coupled* with the one in the phone. The mote then uses the same coil to send the 0s and 1s in its measurement data by, respectively, decreasing and increasing the strength of this magnetic coupling. This is a very simple communication technique called *backscattering* .

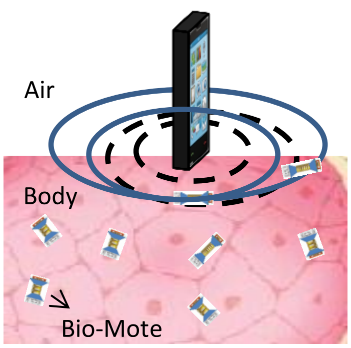

Figure 2. Cell phone (reader) powering on and Communicating with motes in its interrogation zone.

A. Powering

The power available at the bio-mote determines its capabilities (data rate, modulation, communication distance), We propose a hybrid model for the bio-mote in which powering is accomplished through ultrasound and communication through Magnetic Induction. Piezoelectric effect of ZnO nanowires have been extensively studied [10][11] to power nano-machines. Such material can generate voltage when exposed to mechanical vibration generated by an external source using ultrasound waves, or by human body (heartbeat, air vents etc). It has been shown that the produced voltage when rectified and stored in the scale of micrometers can charge a nano capacitor for up to 0.4V [12]. We would be using this scheme to power the bio-mote, and all the calculations presented in this paper consider 0.4 V as the available voltage at the bio-mote.

B. Communications System

Every communication system is formed of three main blocks: modulation, error detection/correction, and anti-collision. A block diagram of bio-mote's communications system is shown in Fig. 3. We have investigated various techniques to achieve respective task of every block, and compared their performances. Here, we briefly explain our design approach for each block. For error correction**,** we considered Hamming and Reed-Solomon codes that can detect or correct errors. Both the coding techniques are a choice for bio-motes since their implementation can be done using flip-flops that consume ultra-low space and power [8]. A number of low power modulation techniques such as ASK, Delta, OOK, DFSK, FSK, QCPSK, and PSK modulations were investigated in terms of size and power [9]. Most high-level modulation techniques require complex circuitry to be implemented. Therefore, we focused on evaluating our design for ASK and BPSK as most practical choices when it comes to micro- and nano-scale implementation.

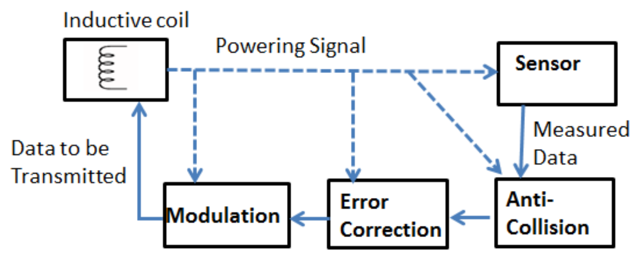

Figure 3. Block diagram of powering and communications systems of the bio-mote.

Table I. Parameters used for the numerical analysis

Parameters	**Value**
Noise Power- AWGN	-80 dB
Carrier Frequency - f_c	13.56 MHz
Magnetic Permeability of the Core - μ_B	1
Side-Band Attenuation	40 dB

Channel

The magnetic induction channel is modelled using the parameters defined in [16]. The model is used to plot the graph in Fig 4 for the voltage induced at the reader. As can be seen, this voltage decreases exponentially with distance. Given that a voltage of 0.4 V is available at the mote for transmission, this figure shows that the induced voltage at the receiver will be few millivolts. Table I lists other channel parameters such as noise power and operating frequency. *Side-band attenuation* is introduced due to the fact that the mote needs to transmit over a sub-carrier (rather than the carrier frequency) such that the received signal at the phone could be filtered using a band-pass filter. If the mote uses the same frequency as the phone, the backscattered signal would be impossible to recover at the phone since it is much smaller than the original voltage on the phone's coil.

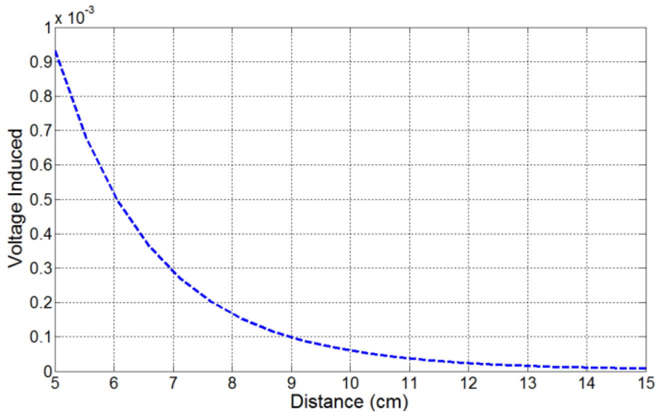

Figure 4. Magnitude variation of transmitted signal over distance with initial magnitude of 0.4V propagating in a channel similar to the human body.

Modulation

Amplitude shift keying (ASK) and binary phase shift keying (BPSK) are among the simplest digital modulation technique implemented in various wireless telemetry bio-devices and biomedical implanted devices [13].

Bit error rate (BER) is one of the general parameters used to analyze the performance of communication system. Different modulation and channel coding schemes are adopted in order to reduce the BER. The graph in Fig. 5 shows the impact of distance and modulation on the maximum achievable BER for two modulation schemes. Since the channel introduces attenuation and noise, BER tends to increase with the distance between the transmitter and receiver. Given the distance, the BER could be improved by adopting different modulation techniques depending upon the channel. For example, if the desirable BER is 0.001, the graph shows that the communication range is 3 cm using ASK modulation and 4 cm using BPSK modulation. BPSK performs better than ASK but with the cost of added circuit complexity.

Error Correction Coding

Linear block codes are the most commonly used codes in various applications of digital communication systems [14]. Hamming code and Reed-Solomon codes are two examples of linear block codes.

Hamming codes are widely employed for error control in various applications from data storage systems to on-chip micro-networks because of their implementation flexibility as well as low codec complexity [15]. The Hamming code has an ability to detect and correct the data error received by the receiver. A Hamming code (*n*, *k*) has a code length of *n* and message length of *k*. Hamming codes are constructed

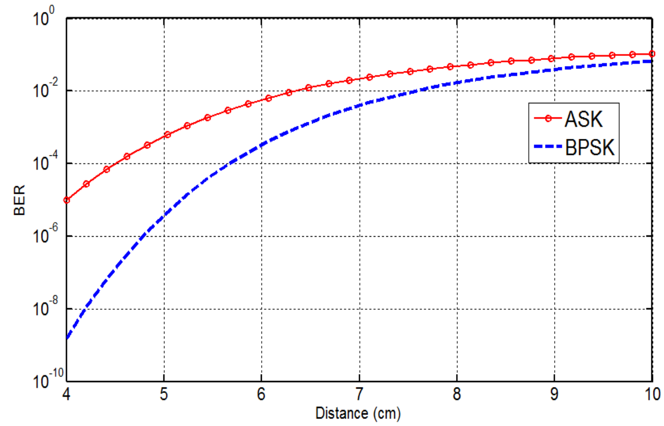

Figure 5. BER vs Transmission Distance, Assuming an AWGN channel the Theoretical BER which can be achieved by the reader with a coil made of gold and with radius r_C = 5 cm when placed at various distances with respect to the bio-mote with a coil made of copper operating at 13.56 MHz with radius is r_r = 30 µm.

using parity check (H) and generator matrices (G). Number of errors that can be corrected depends upon the minimum Hamming distance between the code words: if it is ‘d’ then it can detect d-1 errors or correct $\frac{d-1}{2}$ errors. For Hamming (7,4) code, the minimum distance is 3 thereby correcting only a single error. Implementation of Hamming codes can be done using flip flops formed of XOR gates, which occupy very small die area [8].

Reed-Solomon (RS) codes perform better than hamming codes with the ability to correct both random and burst error bits at the received data packets. RS codes are constructed using generator polynomials whose degree is *2t* where *n-k* = *2t*. An RS code of (*n*, *k*) can correct *t* errors where *t* = *(n-k)/2* when *n-k* = even, and *t* = *(n-k-1)/2* when *n-k* = *odd*. For example, the RS (31, 26) can correct 2 errors (*n-k* =*5* = odd). In order to reduce the BER to an acceptable value in most applications, a communication system needs to use an appropriate channel coding scheme. The graph in Fig. 6 shows the impact of using different coding schemes, namely, the single error correcting Hamming (15, 11) and the double error coding RS (31, 26) over the ASK and BPSK modulated signal. Choice of an error correction coding scheme depends on the required communication range for a given channel. From Fig. 6 for distances approximately more than 7 cm, 6 cm for BPSK and ASK respectively both the error coding schemes have the same performance. For distances less than 6 cm, Reed Solomon performs considerably better than the Hamming code. For example, at a distance of 4 cm, RS code results in one order of magnitude improvement in BER over the hamming code.

Error control coding could also be used in the form of the error detection. However, without correction, the mote

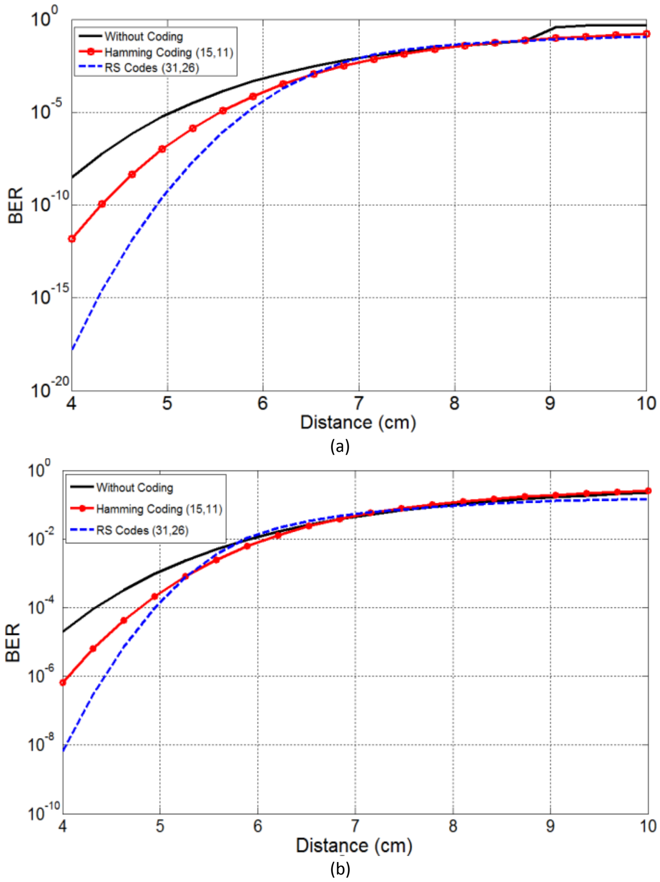

Figure 6. BER vs Transmission Distance, (a) Compares the achievable BER when the bio-mote implements BPSK alongside error coding Hamming, Reed-Solomon codes and without coding to communicate with reader. (b) Compares the achievable BER when the bio-mote implements ASK alongside error coding: Hamming ,Reed Solomon codes and without coding to communicate with the reader.

would need to resend an erroneous packet. While error detection is popular in communications using larger devices, it did not deem as a practical choice due the very limited power available at the mote.

III. CONCLUSION

This paper has analyzed the performance of a basic communication system for a microscale implantable device which can communicate to an external device using magnetic induction. Performance was analyzed in terms of BER and communication distance given the limited amount of available power achieved using the hybrid model proposed in this paper. It was found that magnetic-induction based systems hold a good promise for communication between micro- and nano-scale devices.

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