Body-Coupled Communication for Body Sensor Networks

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ABSTRACT
Body sensor networks (BSNs) offer a wealth of opportunities for precise, accurate, continuous, and non-invasive sensing of physiological phenomena, but their unique operating environment, the body-area, poses unique technical challenges. Popular communications solutions that utilize 2.4 GHz radio transmission suffer from significant and highly variable path loss in this setting. To compensate for such loss, radio transceivers often transmit at power levels at or above 1 mW – a reality that limits battery life. We propose the use of body-coupled communication to address this issue, as it presents several distinct advantages over existing solutions, namely: reduced power consumption, minimal interference, and increased privacy. In this paper, we demonstrate a 23 MHz body-coupled channel that supports reliable data transfer with an average received power of 30 dBm over a 2.4 GHz radio frequency link. This scheme reduces power needed for transmission and increases battery life by up to 100%, while maintaining a favorable environment for application-specific quality of service requirements. Finally, we propose a system-level hardware architecture and explore its implications on BSN infrastructure.

Categories and Subject Descriptors
B.4.1 [**Data Communications Devices**]: Transmitters

General Terms
Design, Experimentation, Human Factors

Keywords
Body-coupled communication, body sensor network, low power, privacy

1. INTRODUCTION
Device miniaturization, advancements in energy storage and sensing technology, and the recent availability of interoperable wireless transceivers have popularized the field of wireless sensor networks (WSNs). Applications of wearable computing and medical monitoring have extended the WSN domain to the body-area. Consequently, BSNs are becoming increasingly relevant. One significant driver facilitating adoption of BSNs outside of the laboratory environment is the creation of healthcare technologies offering accurate, precise, continuous, and most importantly, non-invasive and naturalistic monitoring of physiological, physical, and environmental parameters [1]. As evidence of this push, our previous efforts [2], along with the efforts of others [3-4], have demonstrated the clinical efficacy of various BSN platforms in medical applications.

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However, significant challenges face those engineering BSNs. Systems must operate within a highly dynamic body-area environment, balance power and performance requirements, and ensure secure and reliable operation. These challenges are further complicated by strict size and price constraints [3].

To date, efforts to network the body have predominantly utilized the same communication technology found in larger WSN applications: 2.4 GHz ZigBee or Bluetooth radio transceivers. Such microwave transmission near the human body (Figure 1) however, suffers significant and highly variable path loss (Figure 5). Therefore, achieving sufficiently reliable communication necessitates an increase in transmission power, thus reducing the battery life of the energy-constrained nodes. In addition, there are considerable interference issues in the ISM-band due to channel contention from competing technologies (e.g. 802.11 b/g, etc.) and from the environment that further degrade link quality. Compensation for interference often requires increased transmission power. The resulting enlargement of the communication radius creates opportunities for malicious agents to listen to the channel, compromise system security, and breach patient privacy. In summary, existing BSN solutions do not adequately address all of the challenges associated with body sensor networking for medical applications, especially for power efficiency, interference, and privacy.

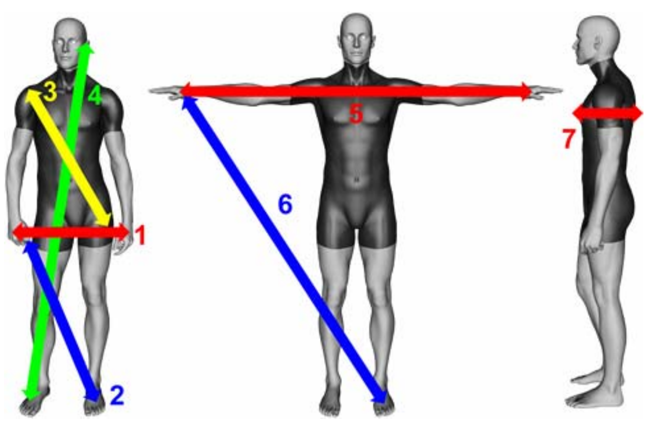

Figure 1. Test set for body transmission paths power

To alleviate the aforementioned shortcomings, we propose a body-coupled wireless communication solution. This physical link medium uses the human body as a communication channel, thus requiring all transmitting and receiving nodes to directly contact the skin. Unlike existing BSNs, the effects due to external interference and body-induced attenuation are reduced considerably. Furthermore, coupling the energy into the body instead of the air increases both transmission energy efficiency and privacy.

We have proposed a body-area communications solution that is capable of low-power communication across the body. Moreover, our solution is largely compatible with current BSN infrastructure. We present the feasibility, empirical results, and impact of our body-coupled communication for medically-oriented BSN applications.

2. BACKGROUND

For efficient body-coupled communication, an electrical signal must be coupled to the skin with careful consideration of the body's characteristics. To our knowledge, a comprehensive study of the body's impedance characteristics over a broad range of frequencies has not been performed. Instead, many efforts have empirically studied signal transduction into the body [5-8]. Galvanic transfer (i.e. electrodes attached to the skin) is generally accepted as the most efficient coupling method [5], but this approach raises concerns related to potentially adverse but yet undiscovered health risk. An alternative solution insulates the electrical system from the human body by imparting electromagnetic fields via capacitive coupling instead of direct ohmic contact.

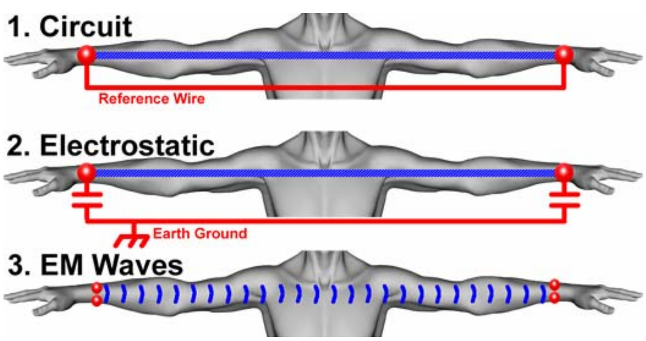

Figure 2. Body-area transmission methods

Beyond selecting the body-coupling method, it's important to understand and design for the physical means of communication across the body. In principal, there are three approaches to this problem (Figure 2) [7]. First, a circuit can be implemented that passes current through the body directly, with the resulting signal captured at an output node. In this implementation, the input transmitter and receiver nodes must share a common reference connected by a wire, which is not desirable for wearability. Second, electrostatic coupling allows for current transfer through the body, but the common reference that the transmitter and receiver nodes share is "earth ground" to which they are both capacitively coupled. Originally explored by Zimmerman [8], this means of communication is highly sensitive to its operating environment, an undesirable characteristic when designing robust and reliable systems.

The third method treats the body transmission channel as a waveguide, allowing for electromagnetic signaling between polarized contacts of a transmitter and receiver. With the selection of an appropriate carrier frequency and modulation scheme, high data-rate communication can exist between two nodes coupled to the body with no external connections and virtually no dependence on the external environment [7]. It is generally assumed that lower frequencies are most easily passed through the body due to the body's absorption characteristics, so a low frequency carrier is preferred [8]. Unfortunately, it is difficult to model the extent to which the body will act as a traditional waveguide when the carrier wavelength is larger than the span of the human body. While our description of the waveguide does not capture all of the physical characteristics of the medium, it makes a compelling case for its use in wearable BSN applications.

Body-coupled communication offers transmission power advantages over microwave communication by reducing the amount of wasted radiated power beyond the body-area. This principle also creates opportunities for higher spatial reuse in and between BSNs and for better assurance of privacy.

3. SYSTEM ARCHITECTURE

Wireless sensor network platforms, including BSNs, typically implement commercial off-the-shelf (COTS) products to provide the radio physical layer necessary for signal transmission and reception. Many commercial RF transceivers, such as the Chipcon 2500, support flexible modulation schemes, coding, and even control over transmission power. Consequently, higher level software layers can build upon this functionality to implement MAC, network, and application layer protocols. Thus, the decision to choose a particular modulation or channel coding scheme rests on the channel model and the desired quality of service (QoS) metric. If we view the body-coupled channel as the link medium, and work from a physical model, we can share a majority of physical layer architecture with existing RF solutions, only selecting appropriate modulation, coding, and transmission power. Such a decision enables legacy systems to easily migrate to a body-coupled communication scheme, perhaps without a designer's comprehensive understanding of the physical layer support or the link medium properties.

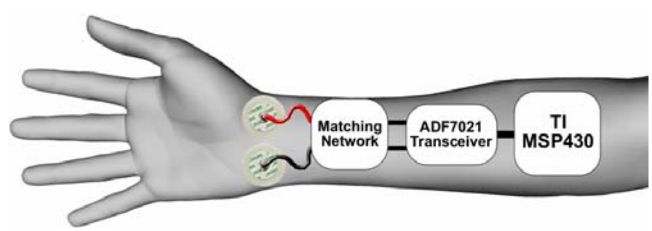

Figure 3. Body-coupled system architecture

An example implementation (Figure 3) could involve the use of a narrow-band, general-purpose, sub-GHz, low-power, CMOS transceiver chip, such as the Analog Devices ADF7021. Building upon an MSP430, the microcontroller found in many popular WSN platforms, the ADF7021 provides support for a variety of *m-ary* modulation schemes down to our desired operating frequencies (i.e. 10-30 MHz). Additionally, the chip provides a phase lock loop (PLL) and all supporting circuitry required for wireless communication. This design is generalizable to an RF or body-coupled solution with the selection of a transducer.

4. EVALUATION

4.1 Test Procedure

An RF function generator and frequency spectrum analyzer were connected to carbon-conducting electrodes adhered to the skin at two different locations on the body. Five tests were conducted with five subjects; two male and two female subjects with ages ranging from 20 to 27 (subjects 1-4) and one male subject at 54 years of age (subject 5). As shown in Figures 2 and 3, each subject wore a set of two electrodes spaced 3 cm apart on the bottom of each wrist – one set connected to the two terminals of a RF generator and the others to the spectrum analyzer. The transmit power on the RF generator was set to -12dBm and frequency was varied from 1-50 MHz in steps of 500 kHz. This procedure creates a fine degree of granularity for the study of frequency selection. It was hypothesized that the human body has common resonant frequencies where the transmission power efficiency would be higher regardless of the subject. Finally, with a transmit power of -12 dBm and a carrier frequency chosen from the previous experiment, electrodes were placed at 7 points on the body, shown in Figure 1, and the received power was documented for each location and compared to that of 2.4 GHz transceivers.

4.2 Results

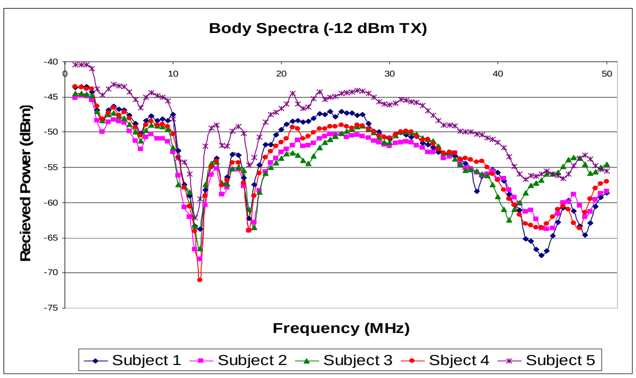

Figure 4. Body-coupled test results

The results from the frequency sweep tests are illustrated in Figure 4. The body seems to exhibit similar frequency characteristics across subjects allowing for a reliable selection of a single carrier frequency independent of the user. It is interesting to note that the subject at 54 years of age exhibited the same frequency pattern but with consistently higher received power. The reason for this observation is unknown but will be explored in a later, more extensive experiment. Both 13.56 MHz and 23 MHz carrier frequencies were selected for further testing. 13.56 MHz was selected since it is an FCC regulated band designated for medical and near-field applications, and 23 MHz was chosen because it represents a peak in transmission efficiency for the average subject. Subject 1 was representative of the average in the Figure 4 results and was therefore selected to perform further testing on received power for different electrode placements on the body described in Figure 1. The results of these tests are shown in Figure 5.

This data shows that even without matching electrodes to body impedance, intra-body communication can appreciably outperform a 2.4 GHz radio solution in cross-body transmission.

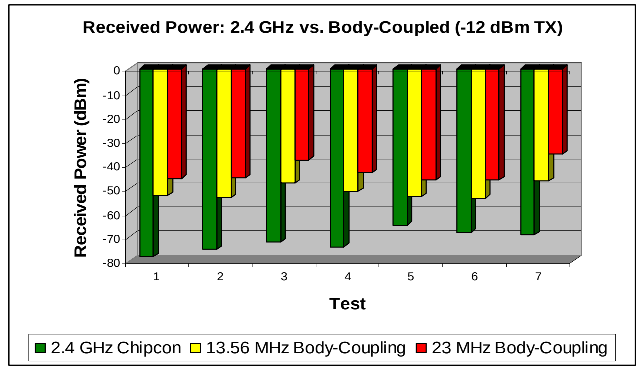

Figure 5. Body-coupled vs. 2.4 GHz received power

Traditional quarter-wave antennas at 10-30 MHz would be 2.5-7.5 meters long making them impractical for BSN implementation, but our results suggest that reliable communication is possible using small scale transducers when coupled to the human skin. If we assume a modulation scheme such as binary FSK, an estimation of the received power required to send a specified data-rate across the channel is given by the following two equations [9]:

$$P_p = 1 - \left(1 - P_e\right)^N \quad (1)$$

$$Pe = \frac{1}{2} e^{-\frac{E_b}{2 \cdot N0}} = \frac{1}{2} e^{-\frac{P_r}{2 \cdot N0 \cdot Rb}} \quad (2)$$

where P_p is the packet error rate, N is the number of bits/packet, P_e is the bit error rate, P_r is the received power, $N_0/2$ is the noise spectral density related to the equivalent noise temperature (T_{sys}) or noise floor, and R_b is the data-rate in bps. If we further assume a packet error rate of 1%, 1000 bits/packet and a data throughput of 250kbps — figures the ZigBee protocol specifies at -92dBm received power [4,10] (-24 dBm transmit power across the human body according to Figure 5) — along with $N_0=1.38\times10^{-19}$ Watts/Hz (T_{sys}=10,000K), we require a received power of at least -91.2 dBm. As shown in Figure 5, most values for received power lie over 40 dB above this value, so a body-coupled scheme could theoretically transmit at around -52 dBm and still allow the same throughput as ZigBee (250 kbps with 1% packet loss at -24 dBm transmit power). With 28 dBm less transmission power we can achieve three orders of magnitude improvement in efficiency. Transmit powers greater than -52 dBm would facilitate higher data rates enabling applications previously not possible for BSNs.

5. DISCUSSION

5.1 Impacts

5.1.1 Low-Power Communication

Ultra low-power communication has been the elusive goal of WSN research for some time. The direct benefit of low-power communication is the increased run duration (i.e., battery life) of a WSN node. In a typical body-area setting, run duration is extremely short due to packaging constraints that keep battery sizes/capacities to a minimum. To put things in perspective, starting at 0dBm transmit power, a decrease of 10 dB can equate to a nearly 12 mA reduction in current consumption when using the Analog Devices transceiver IC listed above. Since low power microcontrollers generally found in BSNs (e.g. the TI MSP430) consume much less power than the wireless transceivers, savings in wireless transmit power have a large impact on system power consumption. Therefore, if we assume an average sensor node current consumption of 20 mA mostly from the radio, using body-coupled communication alone would double the node's battery life. Even for smaller energy stores (i.e., <500 maH), this 100% increase in battery life will allow for roughly 24 hours of extra run time, which makes BSNs practical for a larger number of applications.

5.1.2 Security

Security is a great concern in many BSN applications, especially where the wearer's medical data is being collected and transmitted. For this reason, much research has been performed to create efficient, yet robust, communication schemes that prevent malicious attacks on the system. Body-coupled communication has inherent security without any coding or encryption overhead, since little to no signal would be radiated to the outside world. An attacker would most likely have to be in contact with the subject, making a successful attempt at gathering BSN information very unlikely without the subject's knowledge.

5.1.3 Interference

The body-coupled communication feature of having little to no radiated signal is attractive not only from a security standpoint, but also from a channel reuse perspective. In dense BSN deployments, each of the nodes shares the same portion of the RF spectrum as its physically neighboring nodes. These neighbors can be on the same person or on different people. When considering a hospital application involving numerous patients, each equipped with multiple physiological monitors, the channels in that region of the spectrum can quickly reach full capacity and adversely affect network performance. Therefore, body-coupled communication encourages spatial reuse of the spectra by keeping radiated power low, and could therefore allow a hospital to support BSN operation for all patients in a reliable fashion.

5.2 Future Work

5.2.1 Body Contact Design and Implementation

The human body can vary dramatically across subjects, contact placement, and frequencies, so with further understanding of these characteristics, a contact could be designed to maximize the transmission efficiency through the human body across all subjects. More research is needed to understand the physics of body-coupling (e.g. body impedance, transducer placement, etc.). In addition, the construction of devices that can couple signals safely and non-invasively would be worthwhile so that a subject could wear a simple BSN node with little change in their daily lives, thus promoting easier technology adoption.

5.2.2 Energy Scavenging

By combining a variety of techniques to reduce BSN power consumption, energy scavenging becomes a more viable option for nodes needing extended run duration. Because BSNs are often situated on constantly moving human bodies, kinetic MEMS energy scavengers have the potential to deliver up to 800 uW/cm^3 - a viable source of supplementary energy [11]. This energy could dually trigger the node to wake from sleeping states and also charge capacitors and/or batteries. BSN energy scavenging could also enable nearly limitless run-time if node power were reduced below the average output of the energy scavenging technology using body-coupled communication.

6. CONCLUSION

This paper explored the use of body-coupling techniques to communicate in a BSN. Results demonstrate an average 30 dB gain for received power in a body-coupled receiver, as compared to a 2.4 GHz RF receiver, for a 23 MHz, -12 dBm signal transmission. Body-coupled communication not only reduces the power necessary to maintain a reliable communication link across different paths through the human body, but also creates opportunities for higher spatial/channel reuse and better awareness of security and privacy issues. With further work, body-coupled communication, in concert with other technologies, may enable long-term physiological monitoring in BSNs.

7. ACKNOWLEDGMENTS

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