Analysis of Body Sensor Network Using Human Body as the Channel

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ABSTRACT
A body sensor network using human body as a communication medium is analyzed and designed to achieve both power- and energy-efficiency. An analysis of the body channel network on frequency, distance, transmitting power and received power is performed. The analysis reveals the star topology consumes less energy than the ad-hoc topology for body channel network. Based on the analysis results, the packet structure for body channel network, with variable payload size that minimizes energy consumption, is designed.

Categories and Subject Descriptors
A.1 [**General Literature**]: Introductory and Survey; C.2.0 [**Computer Systems Organization]:** Computer-communication Networks – *General*

General Terms
Measurement, Design, Experimentation

Keywords
Body sensor network, body channel communication, body channel network, star topology

1. INTRODUCTION
Recently, there have been active researches on the body channel communication (BCC), using human body as a communication medium [2], [7]–[13]. Since BCC operates as near-field coupling, the transmitting signal is limited to near body area and do not interfere with external RF devices. In addition, since the communication frequency can be lowered without increasing the antenna size, the transmitter power can be reduced much more compared to the Bluetooth or ZigBee radios [13]. These works showed good insights in understanding BCC, and opened the door for prospective applications of BCC such as healthcare systems, biomedical applications and multimedia systems [3], [8]–[12].

Unfortunately, no study has been reported yet how to form an energy-efficient network with BCC. To implement body sensor network applications, energy efficiency is the key issue due to the battery limitations of the wearable/implantable sensor nodes.

Figure 1 shows the concept of using BCC to form a body channel network (BCN). A base station controls the network and collects bio signal data from all sensor nodes. The test system is shown (a base station) with temperature, blood volume pulse (BVP) and other sensor nodes worn on a dummy.

In this paper, a BCN for healthcare system is analyzed in terms of frequency, distance, transmitting power and received power. Furthermore, an energy-efficient network protocol using BCC is designed and analyzed. In section 2, the body channel characteristics and the path loss equation are shown. Section 3 analyzes the BCN in distance, frequency and transmitting/received power. Topology comparison between simple star and simple ad-hoc is also described. In section 4, an energy-efficient packet structure for the BCN is designed and analyzed. Finally, section 5 concludes the paper.

2. BODY CHANNEL CHARACTERISTICS
2.1 The Body Channel
Zimmerman's model [13] describes the near-field coupling around the human body as a current loop formed by the transmitter electrode, the body channel, the receiver electrode and the capacitive coupled return path. In his model, the human body was assumed as a perfect conductor, and the body was approximated into a single node. This mechanism fits well for low communication frequencies where the impedance of the human body is small enough compared to that of the return path; however, as the communication frequency increases, effective impedance due to coupling capacitance of the return path becomes smaller and now the body impedance becomes significant so that it is no longer ignorable [2]. In addition, as the transmission distance increases, both the coupling capacitance of the external ground and the impedance of the body channel also increase, causing significant signal loss at the receiver. Hence, it is important to derive the relation between the received power, the communication frequency, the transmission distance, and the transmitting power, to fully understand the characteristics of the body channel communication; the relation can be set up by analyzing the path loss of the body channel as a function of distance, transmitting power, received power, and frequency.
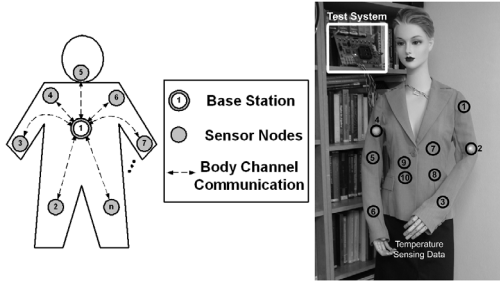
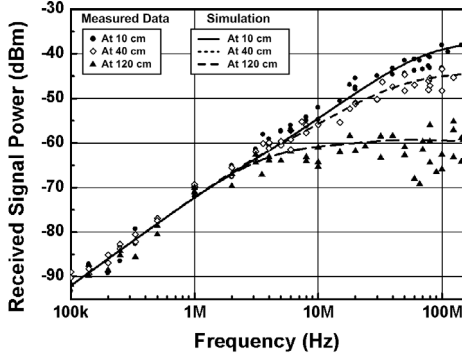Figure 1: BCN concept (left) and the test system (right)

Figure 2: Measured received signal power vs. frequency

2.2 Path Loss

To measure the body channel path loss, we designed the transmitter boards in our previous work [2]. A circular electrode having 1.5 cm diameter was used to interface electrical power to the skin. Figure 2 shows the measured received signal power through the body channel with the frequency sweeping from 100 kHz to 120 MHz while the transmitting power is fixed to 3 dBm [2]. The body channel shows band-pass-like characteristics with 120 MHz bandwidth. When the frequency is increased over 120 MHz, the radiation effect cannot be ignored and the Federal Communications Commission (FCC) regulation limits using this band [2], [4]. From the measured data, the following relationship between the transmitting power and the received signal power is obtained [2]:

$$P_r = P_t \cdot \frac{\alpha(Kf)^2\left(1 + \frac{f}{2f_0}\right)^2}{\left(1 + \frac{f}{f_0}\right)^p} \qquad (1)$$

where $\alpha = 0.0024$, $f_0 = \frac{10 \times 10^6}{d}$, $p = \begin{cases} 4, & d > 0.8 \\ 3, & else \end{cases}$ and

$K = 3 \times 10^{-9}$. Here, P_r is the received power, P_t is the transmitting power, f is the frequency, and d is the distance. From equation (1), we derive the body channel path loss, given by equation (2):

$$\begin{aligned} G_{dB} &= 10\log_{10}\left(\frac{P_t}{P_r}\right) \\ &= p \cdot 10\log_{10}\left(1 + \frac{f}{f_0}\right) - 20\log_{10}\left(Kf\left(1 + \frac{f}{2f_0}\right)\right) + 26.2 \\ &= p \cdot 10\log_{10}\left(1 + \frac{30d}{\lambda}\right) - 20\log_{10}\left(\frac{0.900}{\lambda}\left(1 + \frac{15d}{\lambda}\right)\right) + 26.2 \qquad (2) \end{aligned}$$
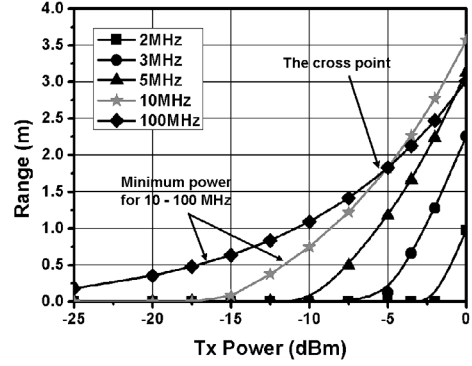

Figure 3: Maximum transmission range versus Tx power

where λ stands for the wave length in meters.

In the following sections, we assume the received power threshold to be -70 dBm. This is because our measurement results described in section 2 reveal that transmission range of 1.5 m, which is a typical maximum distance of two different nodes in the body channel, results in 70 dBm of channel loss.

3. ANALYSIS OF BODY CHANNEL NETWORK

3.1 Transmitting Power

Figure 3 shows the maximum transmission range versus transmitting power for various frequencies, plotted using equation (2). From the graph, at 2 MHz, transmitting power should be at least -2.5 dBm for successful transmission on the body. As the frequency increases, the minimum required transmitting power for the same transmission distance drops; it is observed that frequency band between 10 MHz to 100 MHz minimizes the power. At 100 MHz, -17.5 dBm is enough for distance of 0.5 m. Nonetheless, because the body channel path loss increases at frequencies over 100 MHz as described in section 2, the cross point exists between 10 MHz and 100 MHz curve, around -5 dBm of transmitting power.

3.2 Frequency

Returning to equation (2), the maximum transmission range vs. frequency for various transmitting powers is analyzed. As figure 4 shows, if the transmitting power is 0 dBm, then the frequency should be higher than 1.6 MHz, or the transmitter signal cannot be
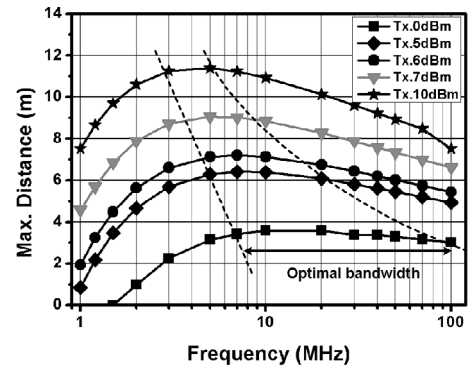

Figure 4: Maximum transmission distance versus frequency

successfully recovered at the receiver.

In the figure, the maximum range has peak points, around 3 to 100 MHz, depending on transmitting power. Within the optimal bandwidth, the transmission range is maximized for given transmitting power. The range of over 2 m is not realistic considering the size of human body; however, the relation is meaningful in calculating the power-efficient frequency range. From the graph, the optimized frequency band to maximize the transmitting distance is between 10 MHz to 100 MHz.

From equation (1), we can derive the frequency versus transmitting power for various distances, as in equation (3):

$$P_t = P_r \cdot \frac{\left(1 + \frac{f \cdot d}{10^7}\right)^p}{\alpha (Kf)^2 \left(1 + \frac{f \cdot d}{2 \cdot 10^7}\right)^2} \qquad (3)$$

where K, p, and α are the same as given in equation (1). The equation (3) predicts that the minimum transmitting power drops sharply with frequency. This is due to the reduced channel loss in higher frequency. However, with frequencies above 100 MHz, the human body operates as an antenna, and the radiation effect begins to dominate [2].

3.3 Topology Comparison

Two basic topologies, a star and an ad-hoc can be used in body channel network, as shown in figure 5. Each topology is assumed to have 8 sensor (leaf) nodes placed around the body, and a base station placed in the center. In the star topology, each node is controlled by centralized coordinator, the base station, and communicates with the base station directly [6]. On the other hand, in ad-hoc topology, many identical nodes exist, and some of them will work as the message router. For simplicity, we assume the "router" nodes are positioned between the leaf nodes and the base station, as shown in figure 5. Considering the size of human body using BCC, the transmission range is limited to 2 m; most of the sensors will be within this range from the base station.

To perform energy simulation, the network simulator GloMoSim [5] is used. Body channel path loss model of equation (2) is imported as a channel model. Range between the sensor (leaf) nodes and the base station is varied from 0.1 m to 2.0 m. Each node is set to send a constant bit stream (CBR) of 32-byte, every 0.1 to 0.4 seconds with total simulation time range to be 60 minutes. The CBR was chosen because it is most similar to the data type often used in the healthcare system, with data rate of 80 bps to 600 kbps [1]. Transmitter power is set to 10 dBm, and the receiver threshold is -70 dBm. Packet loss probability is limited to 0.061%, and all nodes are assumed to be stationary. GloMoSim then extracts energy consumption for each node. Figure 6 shows the comparison between star and ad-hoc topologies in the view of aggregated energy consumption of all nodes. As shown in the graph, for the given distance between the base station and the sensor node, the star topology consumes about half of the energy consumed by the ad-hoc topology in the frequency region of 1 MHz to 110 MHz.

Typically, the ad-hoc topology has more nodes than the star topology does for the same number of the "leaf" sensor nodes. If we only consider the transmitting energy, ad-hoc topology may be the better option depending on the frequency range; however, as
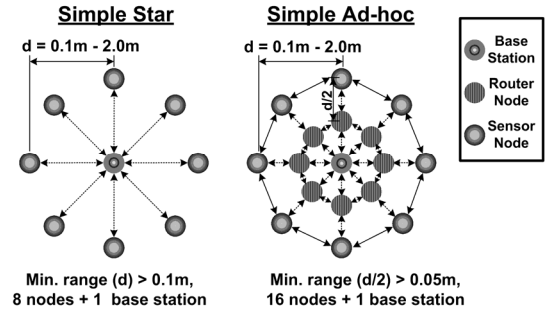

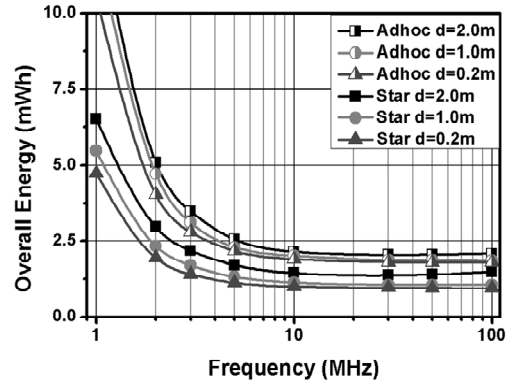Figure 5: Star topology vs. ad-hoc topology

Figure 6: Star and ad-hoc energy comparison

the receiver circuitry energy is roughly proportional to the number of all nodes, the overall system energy consumption is far less in star topology.

4. PACKET DESIGN FOR BODY CHANNEL NETWORK

4.1 Data Packet Structure

Figure 7 depicts the proposed physical protocol data unit of the body channel communication. The packet consists of four components: a 20-bit sync header, a 32-bit PHY header, a 16-bit footer and a variable length (0-bit to 4080-bit) payload. The sync header is split into a 4-bit preamble and a 16-bit sync ID code. The preamble field utilizes bit synchronization. The 16-bit sync ID code is reserved for scalability and for the possible future usage, e.g. in case of using other MAC layer protocols such as CDMA. The PHY header contains information on the length of the payload, and the identification for each sensor node. It is made up of a 16-bit length code, an 8-bit ID, and an 8-bit header. The length code defines the length of the payload, which varies from 0-bit to 4080-bit, with LSB 8-bit reserved. The bit width of the payload is the multiples of 16 to match the 16-bit bus in the transmitter and the receiver. The 16-bit bus is assumed because most of the biomedical signals require up to 16-bit resolution [1]. The 8-bit ID code stands for each sensor node ID, and it can
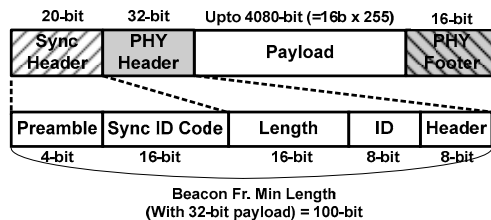

Figure 7: PHY protocol data unit structure

distinguish up to $2^8 = 256$ different sensor nodes. The 16-bit footer is used for CRC-16 code, checking data validity of the packet.

4.2 Energy Analysis

With 4080-bit payload, the packet length is 4148-bit. The maximum payload size is limited to 4080-bit so as to minimize the energy consumption. The energy consumption is analyzed for variable packet sizes by using GloMoSim [5], and the simulation environment is set similar to that of the topology comparison case, described in section 3. The packet size is varied from 32-byte to 12,500-byte, and the total energy consumption of the base station and the sensor node is compared for various frequencies. Because only energy is concerned, the total data size is fixed to 256-kilobyte in this case; therefore, the longer the packet length, the smaller the total number of packets to be sent.

The energy consumption of every nodes for given packet size, with the total amount of data size fixed, is plotted in figure 8. The graph shows the energy consumption drops quickly as the packet size increases, regardless of the frequency. This is because of the reduced transactions between sensor node and the base station for longer packets; each time the sensor node sends data, transmitter circuit is activated from sleep mode, which by itself consumes energy. For example, to send 256-kilobyte-data with packet size of 32-byte, the total number of packets is 8,000; for 1,280-byte, only 200 packets are required. However, as the packet size is increased over 4148-bit, the energy consumption settles around 1.02 mWh, 1.20 mWh, and 1.75 mWh within 3.4%, 8.3%, and 19.4% deviation, respectively. In addition, if the packet is too long, then the probability of error and computational power to process the packet are increased. Therefore, the maximum packet size is designed as around 4,000-bit. Biomedical signals have various data rates ranged from 80 bps (body temperature) to 600 kbps (EMG data), the latter having 7,500 times the formal data rate [1]. Therefore, we vary the payload length to minimize the energy consumption; we use shorter payload for ECG data than for EMG data. For example, when it comes to ECG sensors, each sensor node should send data with throughput of 15,000 bps [1]. Assuming the 10 Mbps transmission, and assuming each sensor node is scheduled to send data every 0.25s, we can calculate the optimum payload size to be 16×235 =3760-bit; with 4 packets, it can minimize the energy consumption.

5. CONCLUSIONS

The body sensor network using human body as a communication medium is analyzed in frequency, transmission range, node distance, transmitting power, received power, and energy consumption to form a power- and energy-efficient network. Analysis shows that the star topology consumes about half the energy of the ad-hoc topology for body channel network, and the optimum bandwidth for BCC is between 10 MHz to 100 MHz. Based on the analysis, the optimum data packet structure with payload size of 0-bit to 4080-bit is designed for the body channel network.

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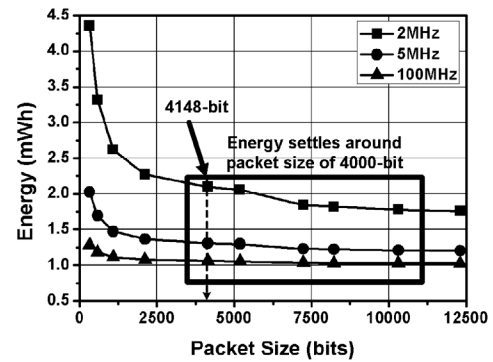

Figure 8: Energy consumption for various packet sizes when the total size of data to be sent fixed to 256-kilobyte

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