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Low Power Digital Communication in Implantable Devices Using Volume Conduction of Biological Tissues

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Abstract—**This work investigates the data communication problem of implantable devices using fundamental theories in communications. We utilize the volume conduction property of biological tissues to establish a digital communications link. Data obtained through animal experiments are used to analyze the time and frequency response of the volume conduction channel as well as to characterize the biological signals and noises present in the system. A low power bandwidth efficient channel-coded modulation scheme is proposed to conserve battery power and reduce the health risks associated.**

I. INTRODUCTION

IN recent years, implanted device has been developed and used in many applications [1,2]. As a man-made diagnostic, prosthetic, or therapeutic device, an intelligent medical implant allows continuous monitoring of the physiological or pathological state of a patient, releases drugs in a correct time, and provides vital functions of certain organs that are lost due to injuries or diseases. For these application areas, investigation on the data communication problem for implantable devices represents one of the most important tasks in developing future technology-based medicine.

Currently, there exist several methods to establish a communication channel for implantable devises. The most common method is Radio Frequency (RF) telemetry. RF technology has been successfully utilized for transmitting the biological signals [2]. However, biological systems consist of ionic fluids which are highly conductive. Thus, it is difficult to establish an effective RF communication link across biological tissues because of the shielding effect of the human body. This effect is similar to the case of transmitting a radio wave from an electrically shielded location. Optical transcutaneous telemetry is another popular method in sending data across the skin. It produces good performance when the communication distance is short and the skin is semitransparent. There are other data transmission methods, such as those based on ultrasound waves [3] and magnetic fields [4]. However, ultrasound signal attenuates rapidly through the bones and air while the magnetic field suffers from severe tissue absorption as is the RF case.

Recently, it has been noticed there exists a valuable natural resource within the human body that can be used to establish a data communication channel. Body tissue is made of various materials that conduct electrical current carrying information. This transmission is called *volume conduction*. Electrostatic laws of physics indicate that a current source within a volume conductor results in an electrical potential distribution within and on the surface of the conductor [5]. Our previous study has shown that our volume conduction system is a highly power-efficient communication system with the use of specially designed antenna [6].

This paper investigates the performance of spectrum-efficient coded-modulation scheme for volume conduction channel using information and coding theoretic analysis tools, and to determine the amount of power saving through coded modulation. We characterize the volume conduction channel and develop a suitable channel model in section II. The mutual information-theoretic capacity is used to investigate an ultimate power saving in section III. Simulation results show the performance of this system.

II. SYSTEM MODEL

Data communications between internal and external human body through volume conduction has been proved workable and efficient [7]. Fig. 1 shows a data communication application through the human body with an embedded transmitter antenna and two receiving skin-surface electrodes. If this communication system is improperly designed with high power consumption, the internal battery of the implant will be used up quickly and the current radiation during wireless communication and heat dissipation from the implanted device may affect or even hurt the surrounding tissues in the human body. Understanding this natural communication channel for low-power consumption devices and developing related methods are interesting and challenging problems in not only biomedicine, but also communications. While some research has been done in this decade [1, 7], most of the work uses analog signal to carry on biological data. In this paper, we proposed an optimal digital communication system based on the natural volume conduction channel.

A. Characterization of the Channel

From preliminary studies on biological signals such as the electrocardiogram (ECG) and electroencephalogram (EEG), it has been found that these biological signals can be modeled

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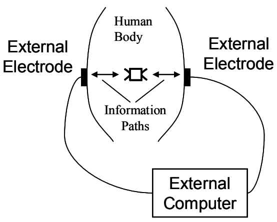

Fig. 1. Communication through the human body based on the volume conduction property of the biological tissue with an implanted device and two external electrodes.

as a 1/*f* process. As such, for data communication systems the background biological signals can work as interference and degrade the quality of desired communication, especially at frequencies less than 1KHz (most biological interferences are below 100Hz). For power efficiency, a properly designed data communication system should avoid the use of these frequencies.

As the frequency increases over 1KHz, the noise condition improves drastically because biological tissues do not usually produce oscillatory signals with an extremely high frequency. First, in these frequencies, we may safely assume that the power-spectral-density (PSD) of the biological noise is under the floor of the additive white Gaussian noise (AWGN). Second, the conductive fluids within the human body effectively shield the electromagnetic emission from the outside of the body, creating a desirable environment for communication and making the design of a low-power, reliable communication channel possible. As the frequency increases further approaching tens of KHz, on the other hand, the tissue absorption of high-frequency signal increases. In addition, the dielectric properties of tissue (mainly capacitance) become significant which result in phase shifts in signals and reduction in tissue impedance. While more precise channel measurements are needed, our preliminary results indicate a good channel gain is obtainable up to 10 KHz.

We have performed animal experiments in which we transmitted sinusoidal signals from the torso region within laboratory pigs. The signals utilized in our experiments include four sinusoids of frequencies at 150Hz, 1KHz, 2.5KHz, and 5KHz, and a linear chirp with a sweep rate of 10KHz/sec. In our experiments, we measured sensitivity defined as the threshold value of the transmitted current above which the received signal can be visually observed. We found that, below 10KHz, 1) the attenuation of transmitted signal is virtually independent of modulation frequency (the channel gain is frequency non-selective); 2) most noises recorded are of low frequencies below 1 KHz, and 3) the attenuation of transmitted signal is proportional to the square of the distance between the transmitter and the receiver.

From our experimental results, therefore, we conclude that the characteristic function of the volume conduction channel is both frequency non-selective and linear phase over the frequency range of interests, say from 1KHz to 10KHz. In addition, over these frequencies, the effect of biological 1/*f* noise is considered negligible. The channel is thus modeled as the additive white Gaussian noise (AWGN) channel over these frequencies.

In our volume conduction system, we have an X-shaped electrode implanted, working as a transmitter antenna, and multiple external electrodes as receiver antennas attached on the skin. Obviously, we can model the volume conduction channel as a single-input single-output linear phase delay channel.

B. Evolution from Analog System to Digital System

Our first generation communications system on volume conduction channel was an analog system [6, 7]. The analog biological signal was modulated on to a carrier signal and transmitted. At the receiver, the signal is downshifted (in frequency) to obtain the signal in the baseband. It is well known that the digital system provides better system performance and more flexibility than the analog system does. In this section, we investigate the benefit of utilizing the digital transmitter and receiver system, especially in conjunction with the use of forward error correcting codes.

In a digital system, the biological signal is first quantized. The number of quantization levels is denoted as M; $K_q = \log_2(M)$ is the number of quantization bits per sample. Based on the quantization level, the fidelity of the system can be determined. As mentioned in Section II, the frequency of the biological signal (or noise) is less than 1KHz. Thus, the bandwidth of the anti-aliasing filter is chosen at 1KHz; hence the sampling frequency f_s is at 2.2 KHz [samples/sec].

From the above setting, the source rate R_s is given by

$$R_s = K_q \times f_s \text{ [bits/sec].} \tag{1}$$

The source bits are transmitted through the channel and the biological signal can be reconstructed at the receiver. The quality of this reconstructed signal can be represented as the peak signal to noise ratio which can be analyzed theoretically as the function of both the quantization level M and the bit error probability P_e of the channel [8],

$$SNR_Q = \frac{3M^2}{1+4(M^2-1)P_e}. \tag{2}$$

In order to have a certain level of quality satisfied on the reconstructed signal, the channel transmission rate R_t must be selected to be greater than the source rate R_s. The overall transmission rate is determined by the channel code rate and the size of the digital constellation:

$$R_t = B_c \times \log_2(J) \times R_c, \tag{3}$$

where B_c is the channel's transmission bandwidth (e.g. 9KHz), J is the size of the digital constellation, and R_c is the rate of the channel code.

Under a certain bit error probability P_e, the output SNR_Q is proportional to the steps M. Since M is limited by the channel bandwidth (by the relationship $R_s \le R_t$), the output SNR_Q is also limited by the channel bandwidth.

III. SAVING TRANSMISSION POWER BY CHANNEL CODING

Shannon's coding theorem states that the mutual information-theoretic capacity of a given channel is the

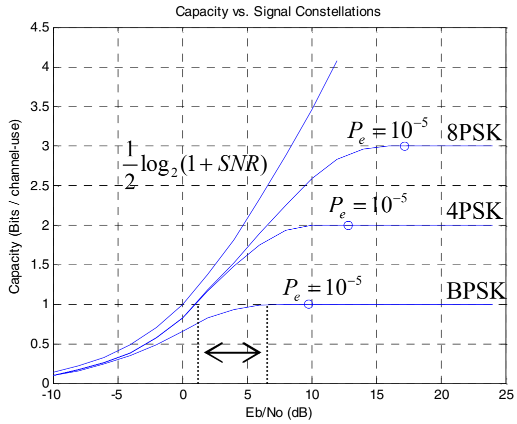

Fig. 2 Capacities versus Different Signal Constellations.

ultimate limit on the reliable information transmission-rate that can be supported by an arbitrarily small probability of error. In the volume conduction channel case, we want to find the maximum amount of power saving while maintaining a fixed level of data transmission rate. The amount of power saving obtained by doing so is called the *coding gain*. In order to investigate an optimal coded modulation scheme at a fixed rate and find the potential saving in transmittal power, we first investigate the mutual information theoretic capacities of the modulated volume conduction channel.

A. Channel Capacity for a Digital System

From the discussion given in section II, the input/output relationship can be mathematically given as a discrete-time *memoryless* channel. In each time epoch of a fixed period, a signal X from a J-ary phase-shift keying (PSK) alphabet $\{x_0, x_1, \cdots, x_{J-1}\}$ is transmitted. The output of the AWGN channel is denoted as Y. The effect of the input symbol going through the AWGN channel can be described by the Gaussian transition probability density function, $P(Y = y \mid X = x_i) = P(y \mid x_i)$.

Then, the mutual information theoretic capacity of the channel is defined as

$$C = \max_{P(x_j)} I(X;Y) = \max_{P(x_j)} \sum_{j=0}^{J-1} \int P(x_j)P(y \mid x_j)\log\frac{P(y \mid x_j)}{P(y)}dy . \qquad (4)$$

For a finite size alphabet $\mathcal{X} = \{x_0, x_1, \cdots, x_{J-1}\}$ the maximum mutual information is achieved when the distribution of input signals is uniform under the constraints $P(x_j) \geq 0$ and $\sum_{j=0}^{J-1} P(x_j) = 1$. The unit of the capacity C is bits-per channel use (one channel use is defined as a single transmission and reception of a J-ary channel symbol). Fig. 2 shows the evaluation of the channel capacity (bit rate per channel use) as the function of E_b/N_0 for different signal constellations which are BPSK, 4PSK and 8PSK. This capacity result can be contrasted with the theoretical bit error probability for uncoded PSK modulation over the AWGN channel. For example, for binary PSK, it is given by

$$P_e = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) := \frac{1}{\sqrt{2\pi}} \int_{\sqrt{2E_b/N_0}}^{\infty} e^{\frac{-t^2}{2}} dt , \qquad (5)$$

where $Q(\bullet)$ denotes the Gaussain Q-function.

One thing that should be noticeable from Fig.2 is that when these constellations are used in combination with a channel coding scheme (reduction in the overall transmission rate), the required SNR can be dramatically reduced. See an example below.

B. Coded Modulation Schemes

A channel encoding and decoding scheme can be designed in practice which approaches the capacity limit very closely. We propose to use the low-density parity-check (LDPC) codes in our channel coding block for their superior error correction capability. In addition, the signal processing complexity of the decoder grows only linearly with the block length increased [9].

Now, as an example, we suppose to fix the transmission rate ($\log_2(J) \times R_c$) at 1 bit/channel-use and find the most suitable coded modulation option at this rate using the mutual information-theoretic results obtained in Fig. 2. An optional system should be compared with the uncoded BPSK modulation for they both transmit at 1 bit/channel-use. We note that from Fig. 2, the required E_b/N_0 for uncoded BPSK is around 6 dB (at this point and beyond the capacity becomes 1). On the other hand, suppose an option of using 4PSK constellation with a code rate of 1/2. The 4PSK curve in Fig. 2 indicates that such an option can be achieved at the required E_b/N_0 of around 2dB only. Thus, there is about 5dB SNR benefit using this scheme compared to the uncoded BPSK. Going further, however, on an optional system with 8PSK and a channel code rate 1/3, we note that, the E_b/N_0 gain is only marginal.

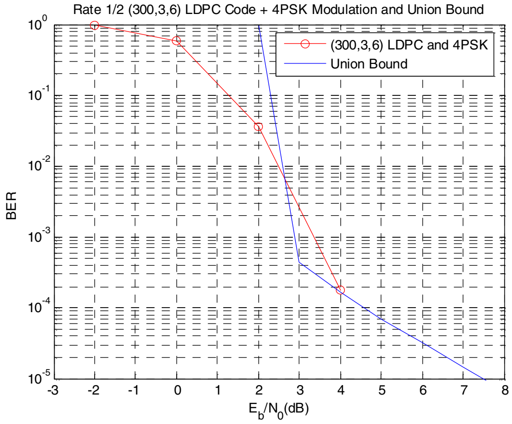

Fig. 3 Bit Error Probability Performance and Union Bound of Coded 4PSK.

C. Simulations and Union Bounds

In this part, we provide the system simulation results which are contrasted with the theoretical union bounds. The simulation results are obtained through Monte Carlo computer evaluations. As mentioned, we propose to use the

LDPC coded modulation scheme. Details on the encoding and decoding operations of this coded modulation scheme can be obtained in [10]. Fig. 3 is the simulation result for bit error probability versus E_b/N_0, using a regular rate 1/2 LDPC code of block length 300 with 4PSK modulation for 1 bit/channel-use. The bit-error probability at 10^{-4} for uncoded BPSK system, using (5), is 8.4dB. The bit-error probability at 10^{-4} for coded modulation is obtained at 4dB. Therefore, we note that about 4.4 dB saving (as compared to the ultimate 5dB gain) is achievable with block length of the code more than 300.

The union bound is a convenient performance evaluation measure assuming maximum likelihood detection of the codeword. Its basic form is the summation of every pairwise error probability (PEP) $\beta_j = P_e(x_0 \rightarrow x_j)$ for $j = 0,1,\cdots J-1$. Refering to the detailed analysis in [10], the union bound P_e on bit error probability can be obtained by

$$P_e \le \sum_{h=1}^{N} \frac{h}{N} A_h \binom{N}{h}^{-1} \phi(h), \qquad (6)$$

where N is the codeword length, h is the Hamming distance, A_h is distance spectrum and $\phi(h)$ is a utility variable related to the PEP β_j.

IV. TRANSMISSION POWER CALCULATION

Low power consumption and high data rates are our primary concerns in this research. Transmitting signals at a lower power allows longer battery life as well as reduces a potential health risk involving signal generation inside the human body. In section III part B, we have indicated that it is power-efficient to use the rate 1/2 LDPC code with 4PSK modulation. On this option, we have about 4.4 ~ 5dB gain on transmittal power over uncoded modulations.

Sensitivities and transmission power versus different distances are given in Table 1, with a 1KHz sinusoidal signal transmitting within torso. The measurement distance between transmitting antenna and receiving electrodes are listed in column 1. The measured sensitivity values are given in column 2. The transmittal powers without coding method are obtained from the sensitivity currents and given in column 3. The theoretical transmittal powers with channel coding method are calculated and given in column 4.

TABLE 1
COMPARISON OF TRANSMISSION POWER WITHOUT/WITH CHANNEL CODING PLUG IN

Distance	Sensitivity	Transmission Power without coding	Transmission Power with coding
12cm	24.75 μA	0.252 μW	0.0797 μW
10cm	17.19 μA	0.122 μW	0.0386 μW
8cm	11.00 μA	0.0498 μW	0.0157 μW
6cm	6.19 μA	0.0158 μW	0.0050 μW

V. CONCLUSION

We have addressed a natural communication channel which utilizes the volume conduction properties of biological tissue, and characterized it into a frequency non-selective channel through animal experiments. Based on the properties of this volume conduction channel, a digital channel coding scheme has been proposed. We identified a coded modulation method with which the data can be transmitted at a lower power from inside the human body without sacrificing the overall transmission rate and probability of making errors. On the other hand, the use of digital system requires the inclusion of a A/D conversion block and the channel encoder in the internal system each of which consumes a certain level of operational power. For a fair comparison they should have been included in the overall system comparison. The effect of these is expected to be significant when the transmittal power is as small as the processing power for these additional system components. Then, the problem becomes optimal trade-off between the processing power and the transmittal power. We will investigate this line of research in future work.

REFERENCES

[1] J. Kim, and Y. Rahmat-Samii, “Implanted antennas inside a human body: simulations, designs, and characterizations,” *IEEE Transl. Microwave Theory and Tech.,* vol. 52, Aug. 2004, pp. 1934–1943.

[2] R.S. Mackay, *Bio-medical telemetry; sensing and transmitting biological information from animals and man*, Wiley, 2nd Ed., New York, 1993.

[3] D.W. Ferrel, D.R. Nelson, T.C. Sciarrotta, E.A. Standora and H.C. Carter, “A multichannel ultrasonic biotelemetry system for monitoring marine animal behavior at sea,” *ISA Trans.* Vol. 13, pp. 120-131, 1974.

[4] I.P. Ivanov, “Pulse ratio modulation in magnetic recorders,” *Biomed Sci Instrum*., vol. 8, pp. 44-47, 1971.

[5] R. Plonsey, *Bioelectric Phenomena*, McGraw-Hill Book Co., N.Y., pp. 205, 1969.

[6] B.L. Wessel, P. Roche, M. Sun, and R. J. Sclabassi, “Optimization of an implantable volume conduction antenna,” *IEEE Proc. of Engi. in Medicine and Biology Society*, vol. 2, pp. 4111 – 4114, 2004.

[7] M. Sun, Q. Liu, W, Liang, B. L. Wessel, P.A. Roche, M. Mickle, and R.J. Sclabassi, “Application of the reciprocity theorem to volume conduction based data communication systems between implantable devices and computers,” *IEEE Proc. of the 25th Engi. in Medicine and Biology Society*, vol. 4, pp. 3352 – 3355, Sept. 2003.

[8] Leon W. Couch, *Digital and analog communication systems*, Prentice Hall, 6th Ed., New Jersey, 2001.

[9] R.Gallager, “Low-density parity-check codes,” *IEEE Trans. on Information Theory*, vol. 8, pp. 21-28, Jan. 1962.

[10] Heung-No Lee and J. Zhang, "Combinatorial Union Bounds on the Concatenation of the LDPC codes and the space-time block codes," Submitted to IEEE Trans. Info. Theory, August 2005..