Energy-efficient Adaptive Modulation in Wireless Communication for Implanted Medical Devices

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***Abstract*— In contrast to conventional wireless communication which takes place over the air, Radio Frequency (RF) communication through the human body poses unique challenges. Studies on RF propagation through human body indicate that the heterogeneous body tissues with different dielectric properties constitute a complicated and lossy environment for signal propagation. This environment also varies with different implant positions, individuals, body shapes and postures. As a result, there is a large variation in the path loss value of the in-body communication channel. In this paper, we first examine the energy efficiency of different digital modulation schemes in a basic wireless implant system. We point out that using a fixed type of modulation does not help to achieve the best energy efficiency in the implant system that has varying channel conditions. We then propose an adaptive communication system model which is suitable for wireless medical implant. Simulations results show that adopting adaptive modulation can provide a considerable amount of energy saving.**

I. INTRODUCTION

Medical implants are miniature devices that can be placed inside the human body for various monitoring, diagnostic and therapeutic purposes. As technologies advance, wireless communication capabilities have been integrated into medical implants. Especially, the advent of far-field RF communication links has eliminated the inconvenience caused by the traditional inductive coupling method which has the drawbacks of low speed, very limited communication range and the difficulty in use. Nowadays, emerging wireless medical implant applications include brain computer interfaces, glucose monitors and capsule endoscopy [1], [2]. It is widely agreed that low power consumption is one of the most challenging issues in a wireless implant system for various reasons. First, for devices that are powered by batteries, frequent battery replacement is not feasible and hence energy saving mechanisms have to be employed in order to extend the device lifetime. Secondly, considering the physical size and weight of the implant device, lowering the demand on power consumption helps in reducing the battery size and the overall size and weight. Moreover, low power consumption is also desirable for safety considerations [3].

To achieve the goal of maximising device lifetime and minimising device size, a considerable amount of work has been carried out on innovative hardware design of the medical implant [4]. However, energy-efficient and reliable communication waveforms which are also key to the performance of a medical implant system have not been thoroughly investigated. According to [5], in a typical wireless sensor, the majority of the power is consumed by the radio unit for data communication. Therefore, we first study the energy efficiency of different digital modulation schemes in a wireless implant system by using a metric known as *energy per information bit*. It shows the energy required for transmitting one information bit to the receiver with a target Bit Error Rate (BER). Based on the results obtained, we then propose a system model that uses adaptive modulation to achieve the best energy efficiency in a human body channel.

The rest of the paper is organised as follows. Section II describes the communication scenario, the channel model and the energy efficiency metric used in the system. Section III compares the energy consumption of several popular modulation schemes and points out the motivation and necessity for using adaptive modulation techniques. Section IV describes the proposed communication system model which aims to achieve the best energy efficiency. Section V shows the possible energy savings in the proposed adaptive system. Section VI summarises the paper.

II. SYSTEM MODEL

A. Communication Scenario

We consider a simple point-to-point scenario where an implanted device has to communicate with an external Base Station (BS) in the 402 MHz to 405 MHz Medical Device Radiocommunication Service (MedRadio) band, which was originally known as the Medical Implant Communication Service (MICS) band. The communication is bidirectional and the link from the implant to the BS is defined as an uplink while that from the BS to the implant is a downlink. The communication session is always initiated by the BS and the implanted device can only start to transmit after an instruction from the BS is received.

B. Channel Model

We assume the communication channel consists of two parts in our system, i.e. the in-body channel (from the implant to the body surface) and the out-body channel (from the body surface to the external BS). Characteristics of radiation from a source inside the human body have been studied extensively via software simulation [6]–[8]. It is found that the heterogeneous human body tissues with varying dielectric properties constitute a lossy environment

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for the signal propagation. In this paper, we adopt the in-body channel model developed by Sayrafian-Pour *et al.* [9]. As shown in Equation 1, the path loss in dB is a function of the separation distance d between the implant and a receiver at the body surface,

$$PL(d) = PL(d_0) + 10n \log_{10}(d/d_0) + S, d \geq d_0 \quad (1)$$

where d_0 is the reference distance (i.e. 50 mm), n is the path loss exponent and S is the random variable representing the scatter caused by different tissues around the implant as well as the antenna gains in different directions. S is found to have a normal distribution with zero mean and standard deviation σ_s. Two scenarios for the implant to body surface communication are defined for this channel model and values of the corresponding parameters are summarised in Table I. In both cases, S has a large variance, which means that even for the same separation distance between the transmitter and the receiver, the path loss can change greatly.

TABLE I
PARAMETERS FOR THE STATISTICAL PATH LOSS MODEL

Scenario	$PL(d_0)$(dB)	n	σ_s(dB)
Deep tissue implant to body surface	47.14	4.26	7.85
Near surface implant to body surface	49.81	4.22	6.81

C. Energy Consumption Metric

We use the energy metric known as energy consumption per information bit E_b to characterise the energy consumption of different modulation schemes. E_b is defined as the ratio of active mode power consumption P_{ac} to bit rate R.

$$E_b = \frac{P_{ac}}{R} \quad (2)$$

P_{ac} consists of three parts: the transmitted signal power, P_{Tx}, the circuit power, P_c, and the power consumed by the Power Amplifier (PA), P_{PA}. The PA is separated from the circuit model because its power consumption is highly related to the transmitted signal power and the relationship can be described as $P_{PA} = \alpha P_{Tx}$ [10]. The value of α is given by $\alpha = \xi/\eta - 1$ with η the drain efficiency of the PA and ξ the Peak-to-Average Ratio (PAR) of the transmitted signal. Hence

$$\begin{aligned} P_{ac} &= (1+\alpha)P_{Tx} + P_c \\ &= \frac{\xi}{\eta}P_{Tx} + P_c \end{aligned} \quad (3)$$

To calculate the circuit power consumption, the general analog transceiver model shown in Figure 1 is adopted. Since the implant is more energy-constrained than the BS, only the transmitter circuit of the implant is considered. Therefore P_c consists of the power consumption of the mixer P_{mix}, the frequency synthesiser P_{syn}, the active filter at the transmitter P_{fil}^{Tx} and the Digital-to-Analog Converter (DAC) P_{DAC}. The circuit power calculation models for different modulation schemes are presented in Table II.

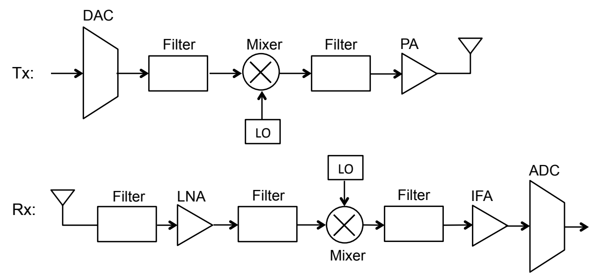

Fig. 1. Block diagram of an analog transceiver, adapted from [10].

TABLE II
CIRCUIT POWER MODELS FOR DIFFERENT MODULATIONS

Modulation	Implant Circuit Power
MQAM	P_{mix} + P_{syn} + P_{fil}^{Tx} + P_{DAC}
MPSK	same as MQAM
MFSK	P_{syn} + P_{fil}^{Tx}

III. ENERGY CONSUMPTION ANALYSIS

A. Mathematical Analysis

To simplify the analysis, we assume the system is uncoded. Let P_{Rx} denote the received signal power at the BS, then the transmitted signal power at the implant is

$$P_{Tx} = P_{Rx} G M_l \quad (4)$$

where G is the total power gain factor of the wireless channel and M_l is the link margin. Now let N_0 and N_f denote the noise power spectral density and the receiver noise figure respectively, the Signal-to-Noise Ratio (SNR) per bit γ_b at the BS is defined as

$$\gamma_b = \frac{P_{Rx}}{R N_0 N_f} \quad (5)$$

Hence

$$P_{Rx} = \gamma_b R N_0 N_f \quad (6)$$

According to Equation (2) to (6), the final expression of E_b becomes

$$E_b = \frac{\xi}{\eta}\gamma_b N_0 N_f G M_l + \frac{P_c}{R} \quad (7)$$

B. Numerical Evaluation

We choose five commonly used modulations schemes, including both low-order and high-order modulations, for the numerical evaluation. The numerical values used for the parameters are summarised in Table III and the results are shown in Figure 2. The horizontal axis represents the total loss between the implant and the external BS and this loss could be caused by human body attenuation, free space attenuation or a combination of both. The vertical axis is the energy consumption per information bit in terms of decibels relative to a millijoule, i.e. $\log_{10}(E_b/0.001)$ dB mJ. It can be observed that when the total loss is small, QAM is more energy efficient than the other modulations. This is because the circuit power consumption is more dominant compared with the transmitted signal power in this path loss range. Therefore modulation schemes that allow higher data rate are more advantageous since the circuit is being used for a shorter time. As the total loss increases and the transmitted signal power starts to dominate the total energy consumption, low-order modulations such as QPSK and QFSK become better choices in terms of energy efficiency.The second plot in Figure 2 is obtained by further applying a maximum transmit power to the calculation and the value of -2 dBm provided by [11] is applied to the implant.

TABLE III
NUMERICAL VALUES OF THE PARAMETERS USED IN THE ANALYSIS

Symbol	Value	Symbol	Value
BER	10^{-5}	ξ	1 (MPSK) [12]
f_c	403.5 MHz		$3(\sqrt{M}-1)/(\sqrt{M}+1)$ (MQAM) [10]
B	300 kHz		1 (MFSK) [10]
N_f	4 dB [11]	η	0.35 (MPSK) [12]
N_0	-174 dBm/Hz		0.35 (MQAM) [10]
P_{DAC}	15 mW [10]		1 (MFSK) [10]
P_{fil}^{Tx}	2.5 mW [13]	γ_b	17.7 dB (64QAM)
P_{mix}	3 mW [13]		13.4 dB (16QAM)
P_{syn}	10 mW [13]		9.5 dB (QPSK)
			9.5 dB (BPSK)
			10.6 dB (QFSK)

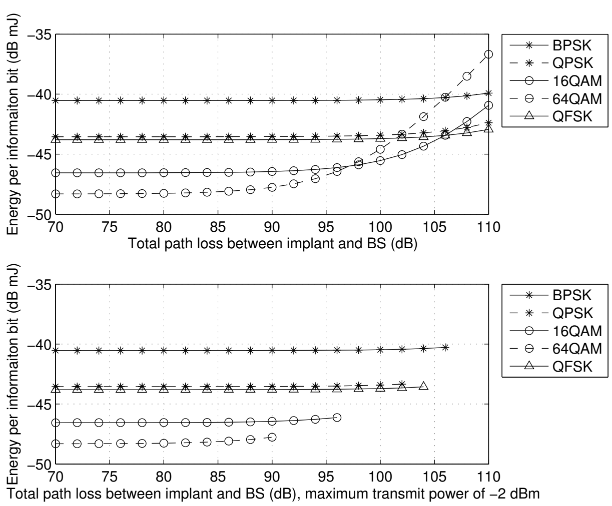

Fig. 2. Comparison of energy per bit for different modulations.

IV. PROPOSED ADAPTIVE SYSTEM

Based on the above analysis, we propose an adaptive modulation system for wireless implant communication. As shown by the block diagram in Figure 3, the BS is responsible for monitoring the wireless channel as well as controlling the communication session. When a communication session is required, the BS will send out a beacon signal to wake up the implant. The implant receives the signal, estimates the total loss between the BS transmitter and the receiver. Next based on the path loss value, the Modulation Switching & Power Control Unit of the implant receiver will choose the most energy efficient modulation to use for the transmission. Here we assume the implant has a perfect knowledge of the BS transmit power and the received SNR value.

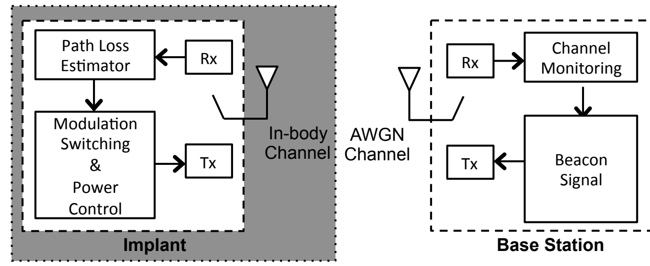

Fig. 3. Block diagram of the proposed adaptive system.

The modulations we consider for the adaptive scheme are summarised in Table IV. The total loss region for each modulation is obtained from Figure 2. Also the *maximum transmit power* allowed for each transmission mode is -2 dBm and there is no transmission when the path loss is above 103.5 dB.

TABLE IV
PARAMETERS FOR THE ADAPTIVE SYSTEM

	Mode 1	Mode 2	Mode 3	Mode 4
Modulation Scheme	64QAM	16QAM	QPSK	BPSK
Total Loss Range (dB)	$(0, 87.5)$	[87.5,93.5)	[93.5,100.5)	[100.5,103.5)
R (kbps)	1800	1200	600	300

V. NUMERICAL EVALUATION

To show the energy savings achieved by using adaptive modulation in the proposed system, we consider two scenarios, i.e. near surface implant and deep tissue implant scenario. In each case, the energy consumption caused by using the adaptive modulation scheme is compared with that caused by using fixed BPSK and QFSK modulation.

A. Near surface implant to an external BS

We assume the BS is located 2 m away from the body surface and the separation between the implant and the body surface is a random variable that is uniformly distributed over the range of 50 to 60 mm. The reason of using a variable rather than a constant value to represent the implant depth is to include the variation that could possibly be caused by the layers of clothes or the change of the patient's body shape. We run the test 1000 times and one bit is transmitted in each round. Due to the randomness of the implant depth and the scattering of the in-body channel, the total loss between the implant and the BS changes from test to test. As illustrated in Figure 4, the horizontal axis represents the test rounds while the vertical axis is the accumulated energy consumption after each test round. In all three schemes, the accumulated energy increases as the number of transmissions grows up and this increase should be upper bounded by the available power of the implant battery. We can see that the adaptive scheme results in the least energy consumption while BPSK consumes the most. Althougth QFSK requires a larger value of γ_b to achieve the target BER, it is more energy-efficient than BPSK as the circuit power dominates the total power consumption.

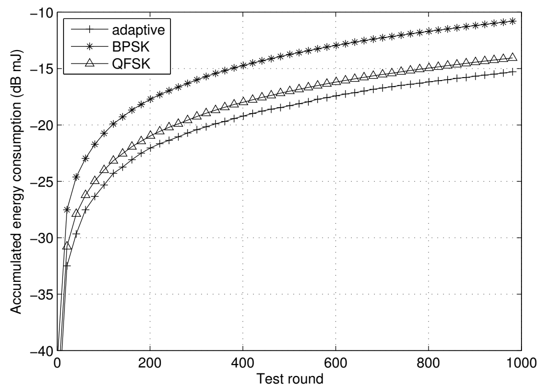

Fig. 4. Energy consumption of the adaptive and fixed modulation scheme for a near surface implant scenario.

B. *Deep tissue implant to body surface receiver*

For this scenario, we assume the BS controller is attached to the patient's body surface and we test the deep tissue implant for a separation range of 100 to 300 mm [13]. At each separation value, we run the test 1000 times and find the average energy consumption for that point. The result is displayed in Figure 5. The horizontal axis represents the separation distance between the deep tissue implant and the body surface BS while the vertical axis shows the average energy per bit at each separation value. The value shown by each marker is the result of averaging 1000 results. We can see that the energy consumption per bit of the adaptive scheme is significantly smaller than that of the fixed modulation and the increasing trend is results from the change of transmission mode from high-order modulation to low-order modulation as the path loss increases. The result for BPSK and QFSK is in line with the one shown in Figure 2.

VI. COMMENTS & CONCLUSION

To summarise, we first show that a fixed modulation scheme can not guarantee the best energy efficiency in a wireless implant system which has large variations in the channel path loss value. We then propose an adaptive system based on the analysis. We consider two scenarios where the adaptive technique can be applied. For both the near surface implant and deep tissue implant scenario, the simulation results indicate that a considerable amount of energy can be saved by using the proposed adaptive scheme.

Moreover, in this paper our focus is on the possible energy savings that can be obtained in the proposed system

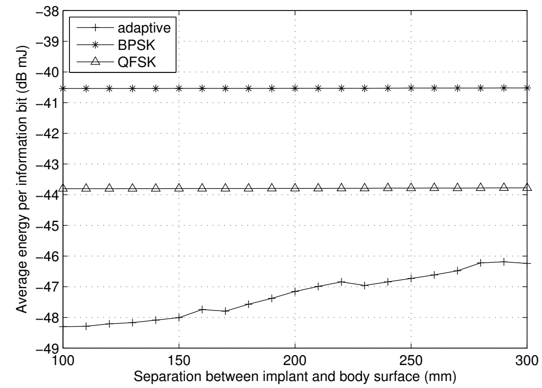

Fig. 5. Energy consumption of the adaptive and fixed modulation scheme for a deep tissue implant scenario.

and hence we assume the implant receiver has a perfect knowledge of the SNR value. However, the situation is more complicated in reality. Our further studies will incorporate energy-efficient SNR estimation techniques to the adaptive system.

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