BER Performance of Implant-to-Air High-Speed UWB Data Communications for Neural Recording Systems

H. Bahrami, *Student Member, IEEE,* S. A. Mirbozorgi, *Student Member, IEEE,* L. A. Rusch, *Fellow, IEEE* and B. Gosselin, *Member, IEEE*

Abstract— **Implant-to-air ultra-wideband communication systems are interesting for neural recording systems due to their low power consumption and high data-rates. In this paper we investigate the performance of an implant-to-air wireless link using a realistic model of the biological channel for neural recording systems. We propose an optimized fifth-derivative Gaussian pulse as a transmitted waveform for different modulations: binary phase shift keying (BPSK), on-off keying (OOK) and differential phase shift keying (DPSK). Monitoring of neural responses with high resolution in the brain requires a high data rate link as the number of electrodes is increased. Each electrode needs a data rate around 800 kb/s to support its neural channel. As we target more than 512 electrodes, we require a data link higher than 400 Mbps.**

I. INTRODUCTION

Implantable wireless transmitters are an essential part of implanted neural recording systems used for treatment and research on neurological impairments [1-5]. As shown in Fig. 1, such applications require a wireless link between an implanted device and an external receiver. Ultra-wideband (UWB) is one of the promising technologies for short range and low power communications such as the implanted neural recording systems [2-5]. Full knowledge of the wireless channel is essential for efficient modulation and demodulation [6]. To date, the properties of the human head as a wireless propagation media in the UWB frequency band have been poorly considered [7]. Designing a reliable wireless data link in the presence of lossy tissues featuring frequency dependent dielectric properties is a challenging task. Recently, we calculated the frequency response of the channel for the human head in the UWB band (3.1-10.6 GHz) [8]. We introduced a methodology for designing a reliable wireless link for neural recording system using tissue modeling and designed antennas for this purpose. Simulations were carried out with High Frequency Structural Simulator (HFSS), exploiting an inhomogeneous layered model with different dielectric constants to capture the effect of surrounding tissues.

By using the previous results (the simulated frequency response of the channel) [8], we are able to investigate the maximum achievable data rates of the wireless link with acceptable bit error rate (BER). In wireless communications, BER performance is limited by several factors including inter-symbol interference (ISI), maximum allowable transmitted power, path-loss, etc. When ISI is not present, the only constraint on achieving higher bit-rates, for a specific BER, is the signal-to-noise ratio; any bit-rate is achievable by increasing the energy per bit [6]. Recently, data transmission performance at 80 Mbps was investigated for wireless implant-to-air data communication for gastro applications [9]. In their work, a multiband orthogonal frequency division modulation (MB-OFDM) was used which consume more power than impulse-radio UWB. We estimate that data rates above 80 Mbps can be achieved for neural recording systems for the following reasons.

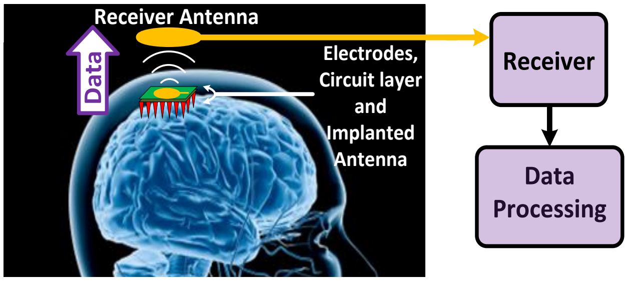

Fig. 1. An overview of an implanted neural recording system.

1) For gastro application, the distance between the TX and RX antennas is 33 mm. The worst case separation for neural recordings is 10 mm. Smaller separations leads to less signal attenuation.
2) In [9] the transmission powers were chosen to respect the FCC limitations assuming antennas is in free-space. An antenna placed inside the body experiences an insertion loss caused by biological tissues between the implanted antenna and the air. The transmitter could therefore transmit more power to compensate the insertion loss of the biological tissues while still respecting FCC limitations.
3) Antennas in [9] are designed for free-space, resulting in much greater channel insertion loss.
4) Higher bit rates can be obtained by using more bandwidth than the 528 MHz used in [9].

Based on these features, we are able to push data rate above 500 Mb/s. The choice of modulation scheme depends on the required BER and the data rate, power consumption and complexity of the system. There is a trade-off between complexity and power consumption. Based on the modulation schemes, the architectures are divided into two categories, which are coherent and incoherent architectures. Coherent detection requires more complex circuitry which

This work was supported in part by the Natural Sciences and Engineering Research Council of Canada, by the hSITE Strategic Network and by the Regroupement Stratégique en Microélectronique du Québec.
H. Bahrami, S. A. Mirbozorgi , L. A. Rusch and B. Gosselin are with the Dept. of Electrical and Computer Eng., Université Laval, Quebec, QC, Canada, G1V0A6 (email: hadi.bahrami-abarghouei.1@ulaval.ca).

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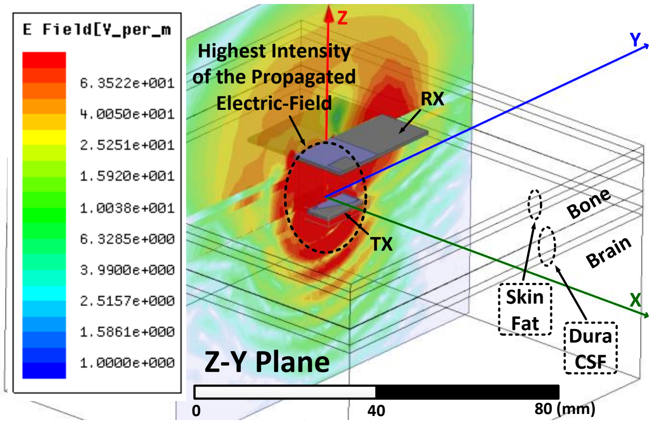


Fig. 2. Radiated E-field while TX and RX antennas are communicating through the biological tissues in Z-Y plane in HFSS.

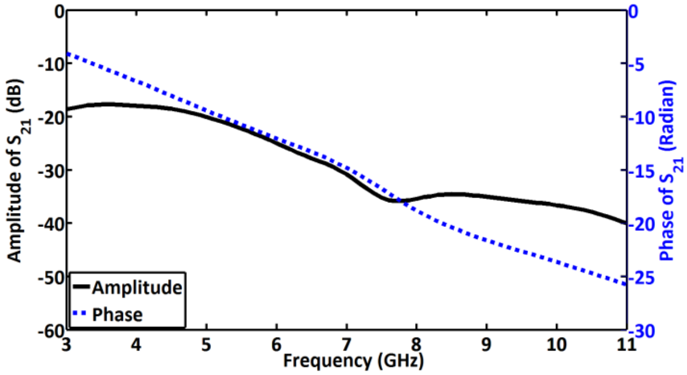


Fig. 3. Simulated amplitude and phase of frequency response of the implant to air wireless link of the head.

results in higher power consumption; incoherent detection is less complex, which results in lower power consumption, but worse BER performance. DPSK has the low complexity of incoherent detection, but vis-a-vis BPSK, has only a 1 dB power penalty compared to the 3 dB power penalty of OOK for an additive white Gaussian noise channel [6].

The primary purpose of this work is optimization of the transmitted pulse and investigation of BER performance of BPSK (coherent), DPSK (incoherent) and OOK (incoherent) modulations. Data rates of 0.5, 1 and 2 Gbps are studied for the neural recording system. In section II, we present the previously reported frequency response of the channel and our strategy for optimizing the transmitted pulse. In section III we study BPSK, OOK and DPSK modulations for different high speed data rates and compare their BER performance. Finally in section IV conclusions are drawn.

II. WIRELESS CHANNEL MODELING AND PULSE SHAPING

A. Frequency Response of the Wireless Channel

The frequency response of the channel is defined as

$$H(\omega) = A(\omega)e^{j\theta(\omega)} \tag{1}$$

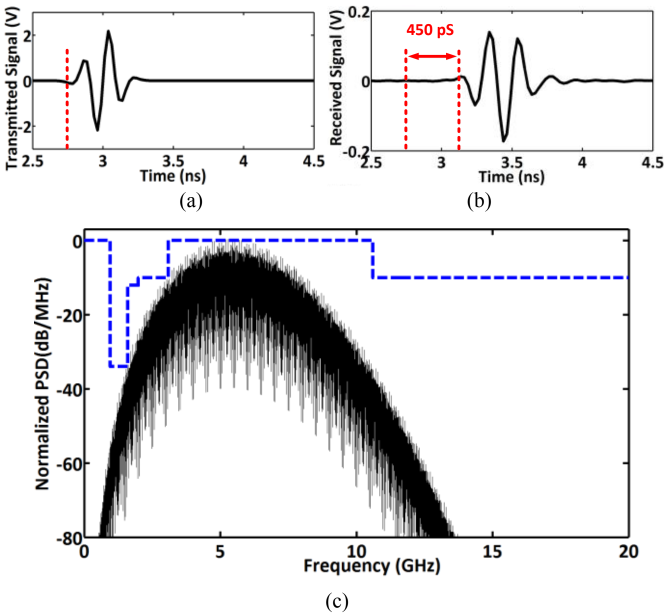
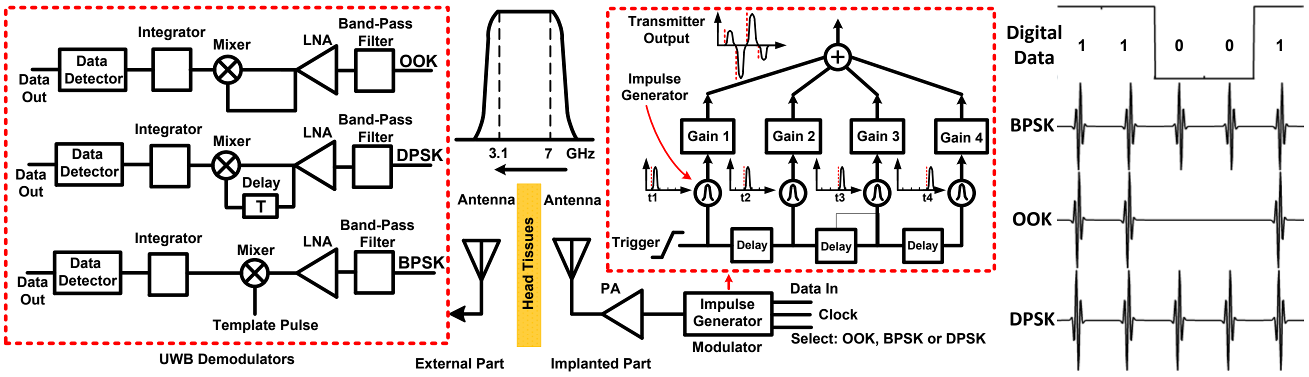


Fig. 4. The optimized 5th derivatives of Gaussian (a) the transmitted pulse (b) recieved pulse (c) normilazed PSD of the optimized pulse.

where A(ω) and $\theta(\omega)$ are the amplitude and the phase of frequency response of the wireless channel [6]. In our previous work, a multi-layer model of the head tissues was presented for modeling the wireless channel. We used a commercial finite element method solver (HFSS software) to capture head tissue as a sequence of dielectric layers. The antennas (TX and RX antennas) were designed by considering the impact of the surrounding tissues [8]. Fig. 2 shows the behaviour of the propagated electric-field between the antennas (TX and RX). The highest electric-field intensity is localized close to the antennas, leading to higher coupling between the antennas (higher received signal-to-noise (SNR)). We characterized the frequency response of the channel (S_{21}), amplitude and phase, which are plotted in Fig. 3. It shows 1) the insertion loss of the channel increases with frequency and 2) the phase of the channel is almost linear. A channel is considered non-distorting within the signal bandwidth when the amplitude response is constant and the phase response is linear. Operation at low enough frequency will preclude distortion; while including higher frequencies may produce inter-symbol interference, which can lead to the system error performance deterioration. From Fig. 3, distortion in this system is introduced in the amplitude. We expect lower loss in the channel at lower frequency; operation in those frequencies improves the BER performance of the system.

B. Pulse Shaping

UWB impulse radio (UWB-IR) transmits information through short nanoseconds baseband pulses without employing a carrier, leading to advantages such as low complexity, low power consumption and ranging capability [10, 11]. A filtered pulse could be used to comply with the FCC emission mask [11]. The derivative of a Gaussian pulse is more efficient as it does not require additional pulse shaping circuits that makes the circuit bulkier. Among



(a) (b)

Fig. 5. The system level design of BPSK, OOK and DPSK modulations (a) block diagrams (b) the modulated waveforms.

different pulse shapes, the Gaussian pulse and its derivatives have a desirable compromise in frequency and time-bandwidth [11]. Gaussian derivatives are widely used in the UWB transmitters; their center frequency is increased when taking an additional derivative and their spectrum bandwidth is optimized by tuning the pulse time duration [11].

To achieve our targeted goal, the spectrum of the transmitted pulse should be modified 1) to comply with the emission FCC mask and 2) to be localized in the 3.1-7 GHz frequency range (because of the high insertion loss in 7-10 GHz shown in Fig. 4-c). In this paper, to reach the desired pulse, the time duration of the 5th derivatives of Gaussian pulse is optimized and shown in Fig. 4-a. The achieved pulse duration is around 400 ps, compatible with high data rates such as 2 Gbps. To investigate the behaviour of the channel, the optimized pulse (Fig. 4-a) transmission through the biological tissues is simulated. The received pulse is shown in Fig. 4-b; the optimized pulse is attenuated and distorted by the tissues.

III. SYSTEM LEVEL DESIGN

In wireless neural recording applications, the number of electrodes is increased to enhance understanding of the targeted part of the brain. A reliable high speed link is needed. The carrier-less impulse UWB transmitter is an excellent choice for implant applications because the transmitter does not need an up conversion mixer and power amplifier as in a traditional RF system; these are typically power hunger in CMOS implementation [2-5]. For the implantable transmitter, the following specifications should be respected: 1) simple structure with low power consumption, 2) small size and 3) high data rate. BPSK, OOK and DPSK modulations are of interest in this work because of their 1) simple transmitter structure, 2) low power consumption and 3) desired BER performance. For implementing the pulse shape with CMOS technology, a band pass filter as pulse shaper has been conventionally used in implanted transmitters for neural recording system [3-4]. However, in [5], edge combining is used for 24 Mbps. This method is a simple way to implement the optimized very short pulse without a band pass filter, while consuming low power [11]. In this work, to achieve the aforementioned features, we use edge combining as shown in Fig. 5-a. Fig. 5-a shows the block diagram of the wireless system for the three modulations used for the BER simulations. Fig. 5-b shows the waveform modulated with random digital data.

A. BPSK Modulation

Phase-Shift Keying (PSK) is a modulation scheme in which the phase of a signal is varied in order to transmit information. In binary phase shift keying (BPSK) the phase of the signal is varied by 180 degrees with the polarity of the data. BPSK is detected by using a matched filter or the equivalent correlation receiver. To detect the received signal coherently a template pulse is needed for the correlation receiver as shown in Fig. 5-a. To generate the optimal template, the frequency response of the channel must be known [6].

B. OOK Modulation

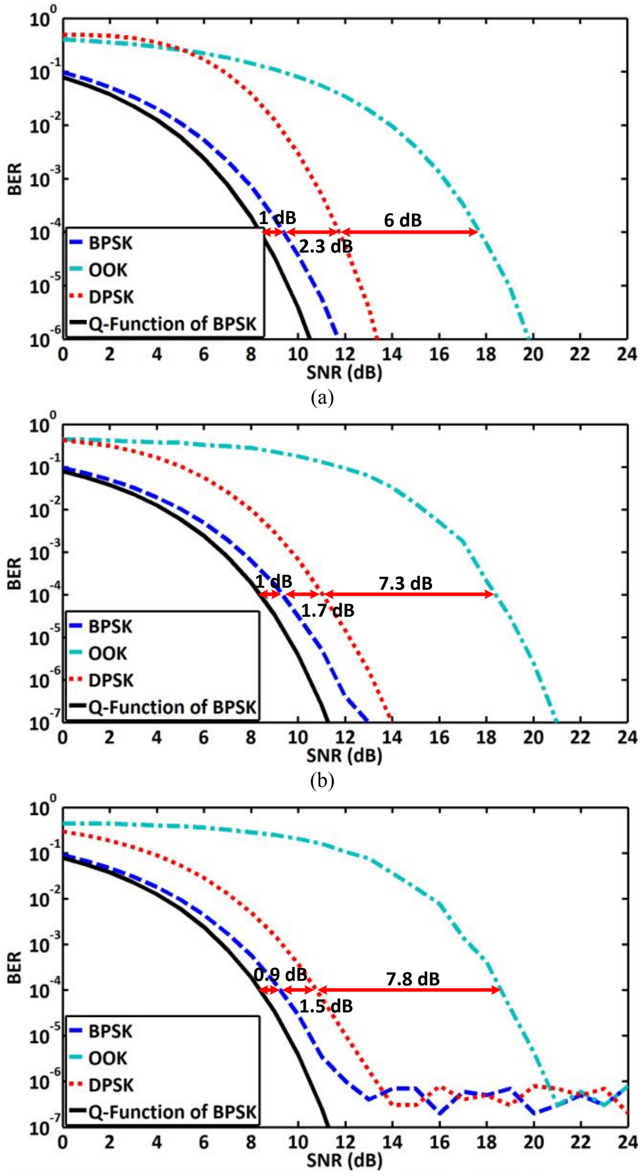
On-Off Keying (OOK) is the simplest form of amplitude-shift keying modulation. The presence of a waveform for a specific duration represents a binary one, while its absence for the same duration represents a binary zero [6]. For detection, the received signal is multiplied by itself, integrated and detected as shown in Fig. 5-a.

C. DPSK Modulation

DPSK modulation is based on changes in phase from symbol to symbol. Because the data are detected by correlation with a delayed version of the received waveform, the data must first be encoded in a differential fashion [6]. The detection is achieved by self-homodyne detection (i.e. correlation with a delayed version of the received signal), followed by integrating and detecting blocks as shown in Fig. 5-a.

D. BER Performance

BER performance is presented in Fig. 6 for BPSK, OOK and DPSK modulations at different data rates (500 Mbps, 1 Gbps and 2 Gbps). All simulations are done in MATLAB using the results from HFSS (Fig. 3) as the channel frequency response. The BERs are calculated using Monte Carlo simulation with 1 million random bits and 10 iterations. The simulations of the BER performance are based on system levels that are presented in Fig. 5-a; Fig. 5-b shows the



(a)

(b)

(c)

Fig. 6. The BER perfomances of three modulations with different data rates. The red arrows are loss of modulations relative to eachother (a) 500 Mb/s (b) 1Gb/s (c) 2Gb/s .

modulated waveforms that are passed through the biological model for different modulations. In Fig. 6, we see as expected the best BER performance is obtained by BPSK. When the data rate is increased, the BER performance is reduced for OOK modulation. BPSK and DPSK modulations have very similar performance (comparing lower data rate results). As shown in Fig. 6-c, a floor appears in the BER performance at around 10^{-6} in 2 Gbps caused by ISI. Increasing the data rate above 2 Gbps leads to greater ISI and worse BER performance. In this case, increasing SNR cannot improve BER performance; however equalization techniques can be used to solve this issue at rates above 2 Gbps.

IV. CONCLUSION

Designing a reliable wireless data link in the presence of lossy tissues with frequency dependent dielectric properties is a challenging task. In this paper we have investigated BER performance of different modulations of BPSK, OOK and DPSK when the optimized 5th derivatives of Gaussian pulse are used as the transmitted waveform. Finally, we have shown the BER performances of the implanted system for BPSK, OOK and DPSK modulations with different data rates. Our results show the BER performance of 10^{-4} could be achieved for data rate around 2 Gbps when the receiver received an acceptable SNR. As our HFSS simulation predicts overall linear phase from the channel, we anticipate good improvement in receiver efficiency for data rate 2 Gbps when using an equalizer.

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