125Mbps Ultra-Wideband System Evaluation for Cortical Implant Devices

Yi Luo1, Chris Winstead1 and Patrick Chiang2

Abstract—This paper evaluates the performance of a 125Mbps Impulse Ratio Ultra-Wideband (IR-UWB) system for cortical implant devices by using low-fracQ coils. The proposed UWB cortical implant system diagram is depicted in Fig. 1. The system consists of two mutual-inductor coils which achieve data rates up to 2.5 Mb/s [2] [4]. More recently, a non-optimized inductive coupling coil with low-fracQ has been implicitly reported to the extent to which the low-fracQ coils affect the system performance. Ongoing investigations have shown that the low-fracQ coils are unsuitable for implantable devices since the parasitic capacitance around the coils is large due to the high conductivity of the body tissue [11]. One solution to this problem is lowering the coils’ quality factor (fracQ) by adding series or parallel resistors. Some researchers have argued that low-fracQ coils are unsuitable for implantable devices since the amplitude of the received signal will be reduced because of low fracQ value, thus degrading the signal-to-noise ratio (SNR) at the receiver [5], [11]. But to the author’s knowledge, it has not been explicitly reported the extent to which the low-fracQ coils affect the system performance.

In this paper, we evaluate the performance of a 125Mbps IR-UWB system, in which the wideband data pulses are transmitted in near-field domain using low-fracQ inductive coils. This IR-UWB system is modeled using measured parameters from a reported UWB transceiver implemented in 90nm-CMOS technology. The transfer functions between all the coils are analyzed to avoid tissue damage through heating effects [3].

Most cortical implant devices receive data through a mutual inductance channel, in which a coil is implanted inside the body. The implanted coil is coupled to an external coil placed against the skin. By stimulating the external coil, signals are induced in the implanted coil, which allows delivery of data to the implanted device. To date, most of the implantable devices use narrow-band modulations such as ASK, FSK or PSK, which achieve data rates up to 2.5 Mb/s [2] [4]. More recently, a data rate of 10.2 Mb/s was demonstrated using Pulse Harmonic Modulation (PHM) [5], which is also a narrow-band technique that exploits self-resonance of the coils used to create the inductive data channel.

II. SYSTEM ARCHITECTURE AND MODELING

The proposed UWB cortical implant system diagram is depicted in Fig. 1. The system consists of two mutual-inductor...
interfaces: one pair to deliver power into the implanted device ($L_1$: $L_2$), and a second pair to deliver data ($L_3$: $L_4$). These pairs of coils can be made approximately independent of each other, so that the data channel is isolated from the power channel. In practice, there is likely to be a small mutual inductance between all four coils, leading to potential interference. We therefore account for all mutual inductances in this analysis.

The transmitted data is encoded by a convolutional encoder with rate 1/2, i.e. the encoder adds one parity-check bit for each data bit. The encoded data sequence is modulated using On-Off Keying (OOK). The driver injects a train of OOK-modulated UWB pulses into the transmit coil ($L_3$). The transmitted pulse chain $V_{od}$ passes through the inductive coil link, stimulating an output signal $V_{od}$ on the terminals of $L_4$. A power interference contribution, $V_{op}$, also appears at $L_4$ and is superimposed on $V_{od}$. After being received by the UWB receiver, the data is processed by the convolutional decoder, and the original data bits are recovered.

A. Transmitter Model

The transmitter consists of a convolutional encoder and a UWB pulse generator. For this work, we chose a low-complexity $R = 1/2$ convolutional encoder with generator polynomial $G(x) = [1 + x^3, 1 + x + x^2]$. After encoding, the data is modulated as a train of Gaussian-derivative pulses. We use the Scholtz's monocycle pulse in this evaluation [12] with a 1ns pulse width, as shown in Fig. 2(a) (the amplitude has been normalized to 1V).

B. Inductive Coil Link

The lumped model for the inductive coil link is also illustrated in Fig. 1. The coupling coefficients $k_{ij}$ between coils $L_i$ and $L_j$ are reported in Table I. The central frequency of the data coil is $f_d = 4$GHz (or close to it). The carrier frequency of the power coil $f_p$ is typically in the range of 1–10MHz [6]. In this work, we assume $f_p = 1$MHz.

1) Coil Parameters: We use two pairs of coils to transmit power and data separately, since if only one pair of coil is used for both power and data transmission at the same time, it requires extremely wide bandwidth in order to transmit the UWB signals and hence result in a much lower $Q$ value, leading to the severe reduction of power efficiency.

Several papers have described coil design procedures for cortical implants [7], [13]–[16]. In this work, we adopted dimensions parameters reported by Jow [14] for power coils, and designed the data coils exclusively for UWB transmission. The $L/R/C$ values of coils and coupling coefficients are shown in Table I. $R_4$ is designed to be a large value in order to decrease the quality factor $Q$. By using a low-$Q$ design, we obtain a flat frequency response which minimizes inter-symbol interference (ISI) in the transmitted pulses.

It should be noted that the data coils presented here are not optimized, i.e. the undesired cross coupling coefficients ($k_{13}$, $k_{14}$, $k_{23}$ and $k_{24}$) are not minimized, thus the power interference is not minimized.

TABLE I: $L/R/C$ values and coupling coefficients of the inductive link coils.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>$L_1$</th>
<th>$L_2$</th>
<th>$L_3$</th>
<th>$L_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1$ (µH)</td>
<td>25.71</td>
<td>29.51</td>
<td>0.16</td>
<td>0.15</td>
</tr>
<tr>
<td>$C_1$</td>
<td>0.99nF</td>
<td>0.86nF</td>
<td>0.12/F</td>
<td>12.5/F</td>
</tr>
<tr>
<td>$R_1$ (Ω)</td>
<td>6.94</td>
<td>10.62</td>
<td>1.83</td>
<td>2000</td>
</tr>
</tbody>
</table>

* The dimensions are the same with the design in [14].

2) Transfer Function: We denote the signal path from $L_i$ to $L_j$ as $P(ij)$. The data signal paths from $V_{id}$ to $V_{od}$ include path $P(34)$, $P(314)$ and $P(324)$, with corresponding transfer functions $H_{34}$, $H_{314}$, $H_{324}$, and impulse responses $h_{34}$, $h_{314}$, $h_{324}$, respectively. The power signal paths from $V_{ip}$ to $V_{op}$ include path $P(14)$, $P(134)$ and $P(124)$, with corresponding transfer functions $H_{14}$, $H_{134}$, $H_{124}$, and impulse responses $h_{14}$, $h_{134}$, $h_{124}$, respectively. Since $L_{1,3}$ are loosely coupled (small $k$) with $L_2$ and the current in tank $L_4C_4$ is very small, we can neglect the effect of $L_4C_4$ loading on the tank $L_1C_1$ and $L_3C_3$ to simplify the equations [11]. The transfer functions in the S-domain are deduced as follows:

$$H_{ij}(s) = \frac{M_{ij}s}{D_i(s)\cdot D_j(s)}, \quad i = 1,3 \quad (1)$$
Fig. 2: (a) A transmitted pulse. (b) A received pulse by coil L4. (c) Bode diagram of $H_34$.

$$\frac{-M_2M_3C_3s^3}{D_3(s)D_2(s)D_4(s)}$$, $j = 1, 3$ (2)

$$\frac{-M_{13}M_{j4}R_2C_3s^3 + M_{11}M_{j4}s^2}{D_1(s)D_3(s)D_4(s)}$$, $(i,j) = (1,3)$ or $(3,1)$ (3)

where

$$D_1(s) = R_3L_1C_1s^2 + (R_3R_1C_1 + L_1)s + (R_1 + R_{31})$$
$$D_2(s) = L_2C_2s^2 + R_2C_2s + 1$$
$$D_3(s) = R_3L_3C_3s^2 + (R_3R_3C_3 + L_3)s + (R_3 + R_{33})$$
$$D_4(s) = L_4C_4s^2 + R_4C_4s + 1$$

Fig. 2(b) shows one received pulse at the input of the low-noise amplifier (LNA) when the transmitted pulse is in Fig. 2(a). Fig. 2(c) shows the bode plot of data transfer function $H_34$.

C. UWB Receiver

The extremely short pulses used for UWB modulation require very precise synchronization and fast switching times in both the Tx and Rx circuits. Hu et al. demonstrated a UWB architecture using pulse Injection-Locking (IL) to achieve phase synchronization [17]. This injection-locking UWB receiver (IL-UWB) eliminates the clock/data recovery (CDR) circuitry and multiplexer that are commonly used in UWB systems.

Furthermore, the ADC can run at the actual data rate so that the sampling requirements can be relaxed and the power consumption is significantly reduced. In Hu’s demonstration, the receiver consumed 90pJ/bit at a data rate of 125MHz.

1) Operation Principle: As depicted in Fig. 1, after the inductive link transmission, the received data $V_{od}$ is passed through the IL-UWB system. It is first amplified by a two-stage LNA, then is directly injected into an injection-locked VCO (IL-VCO), which provides sample timing for a 2-bit flash ADC.

2) Jitter and Noise: The reported RMS sampling clock jitter measured in Hu’s IL-UWB receiver is 8.0 picoseconds (ps) when the data rate is 125Mbps [17]. In our evaluation, jitter is modeled as a Gaussian-distributed random error in the received pulse sampling time. As shown in Sec. III, sampling jitter has the dominant influence in reducing the receivers’ reliability. In addition to the jitter, a number of secondary noise contributions were included in our simulations. One main noise source is the LNA. The LNA’s noise figure (NF, in dB) is a measure of degradation of SNR. The NF of the LNA is not mentioned in [17], but it is typically less than 5dB [18]–[20]. In our simulations, we consider the range of 4–6 dB to account for the impact of LNA noise on the reliability of the system. The thermal noise contributions are also modeled for all resistors and coils in the system.

III. RESULTS

Simulations were performed using the model details described in Sec. II. In our simulations, the bit error rate (BER) was evaluated as the primary measure of system reliability performance. Fig. 3 shows the system performance when the LNA noise figure is 4dB, 5dB, and 6dB. For each plot, the RMS sampling jitter is 8.0ps.
constant at 5dB.

The results shown in Figs. 3 and 4 indicate that the system cannot function reliably without the use of error correction. In particular, Fig. 4 demonstrates that sampling jitter plays the major limiting role in this system. Sampling jitter creates an error floor that limits the system’s reliability, independent of pulse amplitude. By using the convolutional error correction code, the error floor is effectively eliminated.

In order to realize the proposed system, the remaining challenge is to demonstrate an implementation of the convolutional decoder that satisfies the power constraints of implanted devices. To meet this requirement, analog decoding circuits may potentially be used, which have been demonstrated with power as low as 40pJ/bit [21].

### IV. CONCLUSIONS

In this paper, we evaluated the performance of a 125Mbps IR-UWB system for cortical implant devices by using a low-\( Q \) inductive coil link in the near-field domain. Large resistors are added to the data coils to lower the \( Q \) value. Using measured parameters from a previously reported injection-locking UWB receiver, we performed simulations to evaluate the feasibility and reliability of a UWB cortical interface operating at 125Mbps. Dominant sources of noise, timing jitter and pulse filtering are included in the evaluation.

From the simulation results, we conclude that even though the low-\( Q \) coils introduce significant attenuation of the received pulses, the system can still achieve acceptable performance if error correction is applied. The synchronization accuracy of IR-UWB system has the dominant impact on the receiver’s BER, but this effect is removed by the error correcting operation. Based on this evaluation, we predict that the UWB technique is a promising candidate for delivering very high data rates to cortical implant devices.

### REFERENCES


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**Fig. 4:** System performance when jitter-RMS=7.0ps, 8.0ps, 9.0ps; LNA NF=5dB.