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System Design of a Low-power Wireless Link for Neural Recording in a Visual Prosthesis

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***Abstract*—Restoring visual function in blind people through technology can be challenging but very beneficial in improving the quality of life. For most cases of blindness, the only option is to stimulate the visual cortex directly. Such a system requires external cameras, image processing and implanted electrodes. Powering, stimulating the brain, and recording neural activity is preferably done wirelessly to avoid infections. The wireless link for sending the neural activity (uplink) out of the brain is vital as the neural recording is for calibration and monitoring. Uplink requirements on (low-power) consumption at the implanted transmitter and a high data rate lead us to compare two promising wireless link options. A system-level analysis is carried out on the feasibility of impulse radio ultrawideband (IR-UWB) by a worst-case link budget. A low power CMOS IR-UWB transmitter consisting of an on-off keying (OOK) modulator and an impulse generator is proposed closely, fulfiling low-power and high data rate requirements.**

***Index Terms*—Low-power, impulse radio ultrawideband (IR-UWB), optical wireless communication, implanted transmitter, link budget, neural recording, intracortical visual prosthesis.**

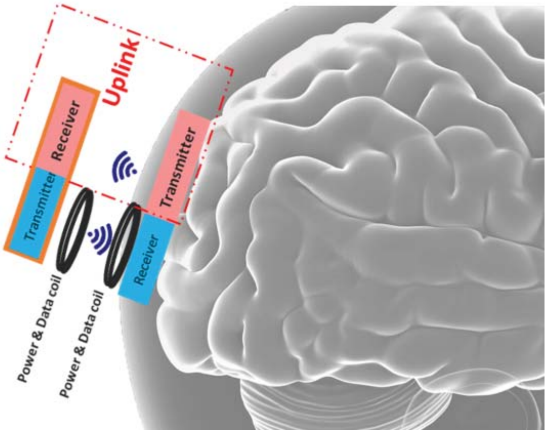

Fig. 1. Layout of the wireless system of the intracortical visual prosthesis.

I. INTRODUCTION

In modern therapeutic medicine, restoring sensory function is becoming successful with the proliferation of auditory implants for hearing recovery. However, restoring visual function can be quite challenging. In most cases of visual impairments, the sole option is to stimulate the visual cortex directly. The visual prosthesis system requires implanted electrodes, signal processing modules and a camera for capturing images in real-time. In avoiding infection and easing mobility, communication to the implanted electrodes through the skin is preferably done wirelessly. In this context, the goal of the NESTOR project is to implant 1024 electrodes [1]. The wireless system required for this visual prosthesis involves communication to the implanted electrode (downlink), neural recording from the implanted electrodes (uplink) and wireless power transfer. The neural recording (uplink) is needed for calibration and monitoring. The uplink is the focus of this paper. Figure 1 shows the wireless system layout, highlighting the uplink.

Developing a low-power implanted transmitter to get the recorded neural signal out of the brain (uplink) is quite challenging due to the high data rate required. It is even more complicated in the presence of nearly simultaneous reception of stimulation signal and wireless power transfer. In [2]–[5] several generic medical telemetry systems were reported. However, none is in the unique context of the 1024-count implanted electrode visual prosthesis, where sending simulating patterns to the implanted electrode is taking place concurrently. The main contributions of this paper are 1) comparing two promising options for the uplink; 2) proposing a tunable on-off keying (OOK) IR-UWB transmitter for low-power and flexible spectrum use; 3) analysing a worst-case link budget for the IR-UWB option to explore the feasibility of a moderate power consumption non-coherent external receiver.

This paper describes the system requirements for the communication link for sending recorded neural information out of the brain. The conditions lead us to compare two techniques that allow such low power requirements. After this, the link budget of the proposed system is analysed to demonstrate its feasibility. A proposed transmitter is designed and simulated at a circuit level on CMOS IC technology to address the miniaturisation and power consumption constraints. The remainder of this paper is structured as follows. Section II describes the uplink system requirements. Section III compares the two most promising options while Section IV draws a feasibility check by a link budget of the IR-UWB option. Section V describes the transmitter, Section VI briefly presents the simulation results and Section VII concludes the paper.

II. SYSTEM REQUIREMENTS

The requirements for the wireless link for getting the recorded neural signal out of the brain are different from those for the downlink which is for sending the stimulation signals to the brain. The requirements for the downlink have been reported in [6]. This section discusses the uplink requirements:

1) Data rate: neural activity typically takes place between 0.1 Hz - 5 kHz [7]. If sampling is done above the Nyquist frequency to avoid aliasing, 10 ksamples/s will be required. There will be 1024 electrodes implanted. If 7 bits are used for the analog to digital converter (ADC) for each sample, and 10 bits for channel separation, we get a data rate of 10 ksamples $\times$ 1024 electrodes $\times$17 bits/s = 170 Mbps. This data rate is over 200 times higher than what the downlink requires. However, with data compression and with partial read-out (only 10 percent of the electrodes), the required data rate can be reduced to about 23 Mbps. The data compression will require additional circuitry that will consume power as well.
2) Power consumption: a 1024-electrode system without wireless enablement will consume nearly 100 mW [8]. It is desired that a wireless version of the same system does not add very significant power consumption to the overall implanted electrode system, due to a limited power supply. As a research goal, we aim to consume less than 30% extra of 100 mW. Considering the downlink receiver and signal processing modules of the wireless system, it is desired that the implanted uplink transmitter stays below several milliwatts.
3) Security: with the rise of communication security breach cases, the wireless link needs to be secure, especially at the physical layer. Therefore short-range communication is proposed from beneath the skin to reach the receiver just outside the head.
4) Co-existence with other sub-systems: in the overall wireless system of the visual prosthesis, the downlink and wireless powering are also present. The wireless link should be able to cope with other sub-systems in terms of frequency spectrum use, interference, and cross talk.

III. KEY OPTIONS FOR UPLINK

Based on the system requirement for the uplink highlighted in Section II, a few wireless techniques satisfy these constraints. Through system studies and careful evaluation of the context, two key systems fit these requirements well, namely: impulse radio ultrawideband (IR-UWB) and optical wireless communication. IR-UWB communication involves transmitting modulated short-duration pulses. The spreading of these short pulses in the frequency domain is over a wide band. This wide band permits high data rate and the transmitter, which is at the implant side, can be designed to be low-power [9]. Optical wireless communication involves optical communication without optical fibres by using a photodiode at the transmitter side and a photodetector at the receiver side. Its infra-red frequencies enable high data rate communications, co-existence with other sub-systems and security.

Table I compares the pros and cons of IR-UWB and optical wireless communication. The IR-UWB transmitter can be made low-power because UWB signals can be easy to generate at minimal power [10]. Compared to the transmitter, the receiver (detection and demodulation) is more challenging (but it is outside the body). It also has the potential for very high data rates without a significant demand on the power consumption of the transmitter, due to its spreading in the frequency domain. In this way, it adequately fits the federal communications commission (FCC) spectrum mask restriction. It has minimal external interference, by selecting a suitable sub-band of the available 3.1 - 10.6 GHz band.

The optical wireless communication can be made compact, and it does not use antennas like the IR-UWB. It is also very secure as infrared frequencies are highly directional and difficult to tap. Its external receiver may not be as complicated as that of IR-UWB. However because the infra-red frequency is high and directional, it is not robust to misalignment (~2 mm) [4], and has high attenuation through the skin (1-4 mm penetration depth) [11]. To summarize, IR-UWB seems the more promising option, because of its low misalignment sensitivity and easy future integration with the downlink system. In the remainder of this paper, IR-UWB will be investigated more in detail.

TABLE I
COMPARING IR-UWB AND OPTICAL COMMUNICATION.

	IR-UWB	Optical Communication
Pros	Low-power transmitter High data rates Low external interference	Compact Very secure (infra-red) No antennas
Cons	Antenna size Synchronization Complex receiver design	Mis-alignment sensitivity Moderate power consumption High attenuation by the skin

IV. IR-UWB LINK BUDGET ANALYSIS

Going forward with IR-UWB communication, it is paramount to demonstrate its feasibility at system level by analysing the worst-case link budget in the visual prosthesis context.

Table II shows the link budget of the system at worst case, which is estimated based on literature. The FCC permits communication in the 3.1-10.6 GHz band at -41.3 dBm/MHz maximum transmit power [12]. Selecting the lower part of the band (3-5 GHz) is optimal because the wideband design complexity is lessened, less attenuation through the skin is present, and interference from WLAN at 5 GHz can be avoided. The thermal noise of a receiver matched to an antenna is -174 dBm/Hz [13]. With a bandwidth of 2 GHz for the IR-UWB signals, the noise floor (N_{floor}) is -81 dBm. Low noise amplifiers (LNA) of IR-UWB have a noise figure typically in the range of 4-10 dB [14]. Taking the noise figure (NF) of the LNA to be 10 dB, and using the formula for noise figure of cascaded stages [13], it highly unlikely that the noise figure of the entire receiver will exceed 15 dB.

The typical normalized signal to noise ratio (Eb/No) required by on-off keying modulation to reach a bit error rate of 10^{-7} with non-coherent demodulation is 15 dB [15]. Assuming the data rate equals the bandwidth which is easy to reach with IR-UWB, the signal to noise ratio (SNR) required

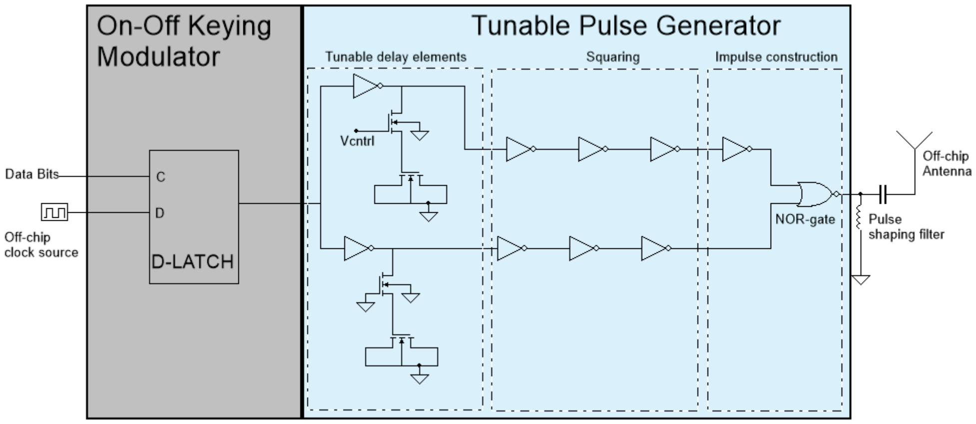

Fig. 2. Circuit schematic of the proposed IR-UWB Transmitter.

is not more than 20 dB taking into account a reasonable 5 dB buffer. With this in view, the estimated receiver sensitivity $S(dBm)$ is given by:

$$S(dBm) = \mathrm{SNR}(dBm) + \mathrm{NF}(dB) + N_{\mathrm{floor}}(dB)$$

$$= 20 + 15 + (-81) = -46\ dBm$$

With the maximum allowable transmit power of -41.3 dBm/MHz set by the FCC, the maximum transmission power equals P_{TX} = -9 dBm for the 3-5 GHz band. Therefore, the maximum allowable link losses PL_{MAX}, tolerable by the system, are $PL_{\mathrm{MAX}} = P_{TX} - S = -9 - (-46) = 37\ dB$. While this maximum allowable path loss of 37 dB can be quite small for free space path of over a few meters, in the context of the visual prosthesis, it is primarily sought to communicate from beneath the skin to just above the surface of the head which is about 5 mm [16]. Losses through 5 mm of skin are well below the estimated 37 dB for PL_{MAX}. From the results in [17], the worst-case transmission S_{21} was 30 dB at 5 GHz. Therefore, from this estimation, it can be concluded that the link will be closed with an excess of 6 dB. Therefore, the application of IR-UWB seems practical and realizable for the intended application.

TABLE II
IR-UWB LINK BUDGET ANALYSIS.

Thermal Noise at 2 GHz bandwidth	-81 dBm
Esitmated Noise figure of receiver	15 dB
Typical SNR required	20 dB
Estimated receiver sensitivity	-46 dBm
Maximum transmit power @ 2GHz bandwidth	-9 dBm
Loss tolerable	37 dB
Estimated S21 @ 5 GHz through skin	30 dB
Excess	6 dB

V. PROPOSED TRANSMITTER

Following the feasibility of the IR-UWB by the link budget analysis, it is paramount to look into one of the most critical parts: the implanted transmitter. From the system requirements in Section II, it has become clear that the transmitter should be low-power due to limited power supply constraint at the implant side. To achieving this, the IR-UWB transmitter can be designed as a radio frequency integrated circuit (RFIC) rather than with discrete microwave components [10]. These so-called microwave integrated circuits (MICs) take more space, consume more power and are expensive to produce in large amounts. The IR-UWB can be implemented in RFIC using CMOS technology. Since the transmit power of IR-UWB is low due to the FCC restriction, a simple CMOS IC is sufficient. This renders CMOS RFIC transmitter low-power and allows for integration with the downlink implanted receiver in the future.

Figure 2 shows the overall circuit diagram of the proposed CMOS IC IR-UWB transmitter. The IR-UWB transmitters comprise mainly of the modulator and the impulse generator. The design of the transmit antenna, which will be connected to the chip is also an important aspect but is beyond the scope of this paper. For simplicity, to aid low-power consumption, an on-off keying modulation (OOK) scheme is used to modulate the short pulses (impulse signals) that will be generated by the impulse generator. The modulator can be implemented in CMOS technology by a simple D-Latch [18]. The data bits and the off-chip clock source are fed as the control signal and D-input of the latch respectively. The resulting signal is fed to the impulse generator.

Implementing the impulse generator on CMOS technology can be done by a tunable delay element, followed by pulse squaring, a NOR-logic gate for impulse forming, and finally pulse shaping filters which can be implemented off-chip. For tunable delay elements, a voltage controlled shunt-capacitor as in [9] is proposed. The tunable delay elements help in adding some flexibility in tuning the spectrum of the impulse signals. For proper impulse forming using NOR-logic gates, the squareness of the signals coming from the tunable delay lines is crucial, and this is done by using three inverters on both the reference line and the delay line for symmetry.

VI. SIMULATION RESULTS

The IR-UWB transmitter is simulated in Cadence software using 180 nm technology at the circuit level. The supply voltage is 1.8 V. An external off-chip oscillator is assumed with an ideal clock source. The modulator and tunable impulse generator are designed. An ideal parallel inductor followed by a capacitor in series models the pulse shaping filter, non-ideal components will not affect the power consumption since the filter is passive. With a pulse repetition frequency of 1 GHz to permit 250 MHz gross data frequency, the transmitter (modulator and impulse generator) consumed 2.8 mW. This gross data frequency of 250 MHz demonstrates a 250 Mbps potential to be recovered at the receiver. However, this may be much lower at the external receiver in order to acquire processing gain to support a non-coherent receiver. Although power consumption is not a priority for the part of the system outside the human head, a non-coherent receiver is less complicated and avoids power hungry synchronization.

VII. CONCLUSION & FUTURE WORK

In this paper, the system requirements for the wireless link for neural recording (uplink) was presented, showing the need for a low-power transmitter with high data rates. Comparing two key options, the impulse radio ultrawideband (IR-UWB) and optical wireless communication, showed different trade-offs but the low misalignment sensitivity of the IR-UWB over the optical communication makes it more attractive. The worst-case link budget of the IR-UWB demonstrates its system-level feasibility. The proposed CMOS IR-UWB transmitter demonstrated low-power consumption (under 3 mW) and also a high data rate (over 50 Mbps) potential. The uplink system promises to deliver a robust link for the compressed low data rate architecture that will enable monitoring and calibration of the implanted visual intracortical prosthesis.

Future work will involve the investigation of compact antennas to support the system successfully. Also, a non-coherent receiver design will be attempted to avoid synchronization and keep the external receiver in moderate power consumption.

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