A WIRELESS MICROSYSTEM FOR MULTICHANNEL NEURAL RECORDING MICROPROBES

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ABSTRACT

The first fully wireless microsystem has been developed to record neural signals from multichannel microprobes. The bio-implantable microsystem can sample and digitize neural signals and accomplish wireless bi-directional data and power transmission. It can reliably receive power from an external transmitter through a 5.12MHz inductive RF link over a distance of 1mm to 15mm. A bit rate of 33kbps is achieved for sending command data to the implant, and a bit rate of 2.56Mbps is achieved for recorded data transmission over a range of 10mm. The microsystem has been used to record neural signals from a rat's motor cortex *in-vivo*. The minimum detectable signal of this microsystem is 28.8 μ Vrms. The entire microsystem, including the active microprobe and coils, weighs 1.2g and consumes 12.7mW. The telemetry chip is fabricated in 1.5 μ m AMI ABN CMOS process with a die size of 4.6 x 4.7 mm².

INTRODUCTION

Chronic recording of multichannel neural electrical activity by microprobes is desirable and extensively used for understanding the operation of the nervous system [1]. Electrophysiological recording of interest ranges from the potentials generated by large populations of cells to the action potentials generated by individual neurons. All of these signals are small amplitude AC signals that must be detected from a background of interfering signals from other bioelectrical activities and other noise sources. Three-dimensional multi-channel recording arrays and additional on-chip signal processing circuits have been developed to achieve high quality, high selectivity recording [2, 3].

Current usage of battery-powered or wired systems for neural recording shortens the implant life. A battery is a potential source of failure if it leaks, and electrical leads and connectors carrying DC voltages and neural signals are particularly difficult to insulate and are a source of infection. Therefore, it is desirable to design an implantable telemetry system to receive power and command data from the outside world using inductive coupling, provide power and control signals to multi-channel microelectrodes, digitize the neural signals and transmit the results outside. This kind of telemetry microsystem can be used in many other applications related to remote sensing, powering and biomedical prosthesis and it is a typical implementation of a wireless integrated microsystem (WIMS).

This paper explores the idea of using Radio Frequency (RF) inductive coupling to transmit power and bi-directional data in neural recording applications. The system diagram is shown in Figure 1. The implantable part of the microsystem is composed of a telemetry chip interfaced with an active microprobe, a power receiving coil and a transmitter antenna. An external transmitter/receiver fulfills the tasks of delivering power and transmitting/receiving data to/from the implant.

Figure 1. Block diagram of the microsystem.

REQUIREMENTS FOR A WIRELESS SYSTEM

Many limitation and challenges exist in the design of the implantable telemetry system, which are analyzed below:

1. Radiation Limit

The external transmitter drives the external coil to transmit power and command data to the implant. Because RF power needs to pass through biological tissues and intensive RF electromagnetic (EM) fields may cause damage to tissues, the energy absorbed by the object exposed to the EM fields is of concern. IEEE recommends a standard for safety with respect to RF exposure [4]. It is noted that different limits are adopted for electric and magnetic fields, because they have different biological effects. Usually the magnetic field limits are more relaxed than electrical field limits in high frequency. The maximum fields depend inversely on the frequency, which dictates the use of low frequency carriers (<20MHz) for power transmission. Since the coupling coefficient between an external transmitter and a small receiver coil is typically less than 5% for distances of about 10mm, care should be taken in the design of the telemetry link. To maximize efficiency, a class-E amplifier could be used for power transmission, and the physical configuration of the transmitter and receiver coils and their distance could be optimized. In addition, an appropriate RF frequency should be used to reduce transmission loss. Carrier frequency from 1MHz to 10MHz has been used in this application.

2. Temperature Increase Limit

The implanted microsystem's power dissipation should result in less than 1°C temperature rise in the surrounding tissues to avoid tissue damage. A simple model is used to calculate the maximum allowable power dissipation for the microsystem [5]. If the implant size is 15 mm x 15 mm x 2 mm, a power dissipation of at least 22.6mW is needed to increase tissue temperature by 1°C. If the total power dissipation of the microsystem is less than

Travel support has been generously provided by the Transducers Research Foundation and by the DARPA MEMS and DARPA BioFlips programs.

15mW, it can satisfy the maximum 1°C temperature rise requirement.

3. Channel Capacity of Data Link

Shannon's theorem gives a fundamental upper bound to the capacity of a link, C , in bits per second (bps), as a function of the available bandwidth, W , received power, P , and the channel noise modeled by an Additive White Gaussian Noise (AWGN) with power spectral density of N_0 watts/Hz, by the following:

$$C = W * \log_2 \left(1 + \frac{P}{W * N_0} \right)$$

It is obvious that wider channel bandwidth and higher signal power are preferred for higher channel capacity. But higher signal power increases the power consumption of the system, requiring a tradeoff between power and channel capacity.

4. Low Noise Design

Low noise electronics is another challenge in this neural recording application. Microelectrodes must be within 50-100µm of a neuron to record a usable action potential and they usually pick up signals from several adjacent neurons, which may need to be discriminated based on small differences in their waveforms. Even relatively low noise levels may degrade the reliability of such discrimination. Consequently, low noise amplifier (LNA) is necessary, especially for the active microprobe of the microsystem.

SYSTEM DESIGN AND RESULTS

The system block diagram is shown in Figure 1. It consists of the front-end circuitry that receives the RF signal from the outside transmitter, the logic and control circuitry, the on-chip Analog/Digital (A/D) converter, the active microprobe and the on-chip transmitter. The function of each of these subsystems is discussed below [3, 6].

Front-End Circuitry

The telemetry front-end receives power through the inductive link, generates regulated supply voltages, clock, reset and command data for other implantable circuits. The important front-end circuit blocks include voltage regulators, bandgap reference, ASK (amplitude shift keying) demodulator, clock regenerator and POR (power on reset). The detailed operation of these circuits is presented in [6].

For voltage regulators, line regulation is better than 1mV/V when the line voltage exceeds 6.5V, load regulation is better than 0.05V/mA when supplying a current of up to 25mA. The performance of the regulator ensures stable power supplies for implantable electronic circuits. The half-wave rectifier removes the noise by 36dB at 5.12MHz. The Power Supply Rejection Ratio (PSRR) of the regulator alone is 30dB at 5.12MHz.

The amplitude of RF carrier is modulated to transmit command bits to the implant. The ASK demodulator senses the amplitude shift of the carrier and generates raw command data. The ASK demodulator is fully-functional for data rates from 10 kbps to 400 kbps. The clock regenerator recovers the clock from the carrier and provides to the implanted electronics, which works well for carriers of up to 12MHz. The POR Circuitry generates a 303µs POR pulse whenever the microsystem is powered up to reset the entire system.

Logic Circuitry

After the ASK demodulator generates raw command data, it is further decoded by a Manchester decoder and command bits are latched into FIFO (First In First Out) registers. Manchester coding is used so that incoming data contains self-timing information after decoding, independent of the carrier frequency. If the command bits are correctly received, they will be stored in the command registers to control the functionality of the entire microsystem. Both the power supplies and time multiplexing control for the active probes are provided from the telemetry chip. The probe can be set up for single channel or multichannel recording. The control signals and operation for multichannel recording are illustrated in Figure 2.

Figure 2. Setting up the microprobe for multichannel neural recording.

Analog-Digital Converter

An on-chip 10-bit charge distribution ADC converts analog neural signals to digital format. The ADC sampling rate is 160kS/sec in order to sample from 8 channels with a per-channel bandwidth of 10 kHz. The maximum magnitudes of Differential Nonlinearity (DNL) and Integral Nonlinearity (INL) are less than 0.6 and 0.8 LSB, respectively. The 3dB bandwidth of the A/D Converter is 40 kHz, shown in Figure 3 and Effective Number of Bit (ENOB) is 9.3bit for input frequency below 10kHz.

Figure 3. ADC bandwidth.

Active Microprobe

A 64-site, 8-channel active neural recording array [3] has been developed as shown in Figure 4. The 100µm² iridium recording sites are arranged in an 8x8 array along the electrode shanks. The vertical center-to-center site spacing is 100µm while the horizontal spacing is 200µm. The shanks are 3mm in length, taper from a maximum width of 85µm at the base to a sharp tip, and are approximately 12µm thick. The probe features a 64:8 front-end selector, which allows 24 unique site combinations to be chosen for recording. Eight on-chip capacitively-coupled pre-

amplifiers [7] provide an in-band gain of 40dB while removing the dc baseline polarization of the electrode. These amplifiers have a tunable low-frequency cutoff for selective recording of action potentials alone or simultaneous recording of action and field potentials [8]. The time-division multiplexer samples the eight amplified channels onto one data lead and the active filter removes the clock artifact while providing an additional in-band gain of 20dB. The integrated circuitry occupies 5mm² of die area.

Figure 4. Active neural recording probe on a nickel.

On Chip Transmitter

Digitized results are sent to the external receiver by the on-chip transmitter, whose carrier frequency is adjustable in FCC unlicensed band from 88 to 108 MHz by trimming capacitors in the on-chip ring oscillator. Feature bits are used to synchronize external receiving scheme.

A measurement is carried out to test the data communication link. The transmitter's loop antenna is built by 7-turn of AWG #38 copper wire, with a diameter of 8mm. An external receiving antenna is built by 30 turns AWG 32 copper wire with a ferrite core, its diameter is 12mm and length is 20mm. These two antennas are placed 10mm apart from each other. After the signal is received by the external antenna, it is amplified, filtered and fed to an OOK (On-Off-Keying) demodulator. The real-time demodulated digital output is compared with on-chip transmitter input data in Figure 5, where the data rate is 2.56 Mbps. The recovered data is sampled and saved for analysis.

The BER (Bit Error Rate) is an important criterion to evaluate the quality of a digital communication channel. The BER is measured to be less than 10^{-7} when the transmission distance is less than 15mm in this measurement.

Detailed measurements of the BER have been carried out and generally indicate that for distances of up to 15mm, the system operates reliably for bi-directional data and command transmission. It has been shown that RF power transmission does not degrade the recorded data transmission quality. The carrier frequency of the on-chip transmitter is 103 MHz for the measurement. When the distance between two antennas is 5mm, the induced 103 MHz sinusoid across the external receiver loop antenna is 56 mV (p-p), while the induced 5.12MHz sinusoid across the external receiver loop antenna due to power transmission is 740mV (p-p). However, the 5.12MHz noise is effectively attenuated because of the usage of a VHF-UHF amplifier and bandpass filter in the external receiver. At the output of the bandpass filter, the ratio of 103MHz signal to the 5.12MHz noise is 52dB.

In-vitro Measurement

In-vitro testing is carried out to verify the functionality of the microsystem in a wireless single-channel recording configuration.

The microsystem is powered by an RF link and placed in a saline solution, while the active microprobe's power supply and

control logic are provided from the telemetry chip. The distance between the power transmitter coil and the receiver coil is 5mm. An on-chip air-core loop antenna is separated by 5mm from an external ferrite-core loop antenna to transmit recorded data.

Figure 5. Real time OOK communication (2.56Mbps).

A 1 kHz sinusoid with an amplitude of 2mV (peak-to-peak) is fed to the saline solution, and the external antenna receives the transmitted digital results. The signals are reconstructed in MATLAB and its spectrum is plotted in Figure 6. SNDR (Signal to Noise & Distortion Ratio) in neural band (300Hz – 10 kHz) is 26dB, and the measured signal is 45-50dB above the noise floor. The noise of the microsystem was also characterized in *in-vitro* measurement to be 28.8 uVrms (root mean square), which dictates the MDS (minimum detectable signal) of the system.

Figure 6. Spectrum of the received signal for *in-vitro* testing.

In-vivo Measurement

As shown in Figure 7, the implantable part of the microsystem is composed of a telemetry chip interfaced with an active microelectrode, a power receiving coil and a data transmission antenna. They were assembled on a flexible board, which could be easily bended and was chosen for the convenience of implanting.

Figure 7. The assembled microsystem.

The microsystem shown above has been tested in animals to verify *in-vivo* operation in acute studies. The microsystem was

implanted in the motor cortex of the rat [9], and the animal was administered general anesthesia throughout the surgical procedure. The microprobe was inserted to the point where the recording sites were estimated to be 0.5–1.2 mm below the cortical surface.

The *in-vivo* results are shown in Figure 8, where each channel from 8 channels is recorded for 0.95 second. The preamplifiers provide a total gain of 1,600 in this measurement. If referred to the input of the active microprobe, the average noise of 8 neural channels is 52 Vrms in this measurement. The plotting is expanded to show a detailed spike in channel 6.

Figure 8. The recorded multichannel neural signals *in-vivo*.

Finally, Table 1 summarizes the performance specifications for the entire system and its individual circuit blocks.

Circuit Blocks	Specification	Power Consumption
Four Regulators	Line Regulation: <1mV/V (input 6.5-20V) Load Regulation <0.05mV/mA (I_{load} < 25mA) VDD1 = 3.4V VDD2 = 1.7V	For Entire Front-End Circuitry 527 μ W
Clock Recovery	Recover up to 12MHz clock	
POR	POR Pulse width = 303 μ s	
ASK	Data rate: 10k-400kbps Carrier frequency: 5.12MHz Modulate depth: 30%	
Control Logic		3.1mW
On-chip Transmitter	Carrier Frequency: 88-108MHz Bit rate: 2.56 Mbps, Bit error rate < 10^{-7}	2.2mW
10-bit Charge Re-distribution ADC	Clock: 2.56MHz	1.1mW
	Speed: 160 kS/s	
	ENOB: 9.3 bit	
	DNL < 0.6LSB, INL < 0.8LSB 3dB Bandwidth: 40kHz	
Active Microprobe	8 Channel Time-multiplexing	2.73mW
Die Size	4.6 x 4.7 mm ²	Total Power 12.7mW
Process	Double poly, double metal AMI ABN 1.5 μ m CMOS	

Table 1. Summary of the System Performance.

CONCLUSIONS

The first fully wireless microsystem for multichannel neural recording has been reported. It includes a telemetry chip, an active neural recording microprobe, a power receiving coil, a data transmission antenna and an external transmitter/receiver. Powered by a wireless RF link, the bio-implantable microsystem can sample and digitize neural signals by using an on-chip 10-bit charge-redistribution A/D converter. Digitized results are sent to the external receiver by an on-chip OOK transmitter, whose nominal carrier frequency is in the FCC unlicensed band, from 88 to 108MHz. The command data is transmitted to the implant by modulating the amplitude of the 5.12MHz power delivery carrier. The microsystem has been tested *in-vitro* and *in-vivo*. Fully integration of the microsystem enhances the reliability and accuracy of the system. This microsystem consumes a total of 12.7mW and is fabricated in AMI ABN 1.5 μ m CMOS process.

ACKNOWLEDGEMENT

The authors thank Dr. D. Anderson, Dr. D. Kipke, B. Casey, K. Kong, A. Hoyord, R. Vetter for timely helps in testing. This project is supported by NIH-NINDS contract 5N01NS002329-001 and this work made use of Engineering Research Centers Shared Facilities supported by the National Science Foundation under Award Number EEC-0096866. Travel support has been generously provided by the Transducers Research Foundation and by the DARPA MEMS and DARPA BioFlips programs.

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