A Miniature Wireless Neural Recording System for Chronic Implantation in Freely Moving Animals

Mustafa A. Kanchwala, Grant A. McCallum and Dominique M. Durand, Fellow, IEEE
Department of Biomedical Engineering, *Case Western Reserve University,* Cleveland, OH, USA
gam19@case.edu

***Abstract*—Bioelectronic Medicine Therapies offer a promising alternative to traditional procedures for diseases such as epilepsy, and implantable devices are crucial for its development. We present here a miniature, low power, 2 channel wireless neural recording system with sampling rates of 20ksps to allow researchers to understand the neurological functioning to develop therapies in freely moving small animals. The wireless implant uses Carbon Nano Tube Yarn (CNTY) electrodes to interface with the nervous system and record signals. High data transmission rates are achieved by using an Ultra-wideband Impulse Radio (UWB-IR) transmitter and wireless switching control is provided by Bluetooth Low Energy (BLE). The UWB transmitter is primarily designed to make it chronically implantable in freely moving rats to record neural activity but is also applicable to the telemetry of any signals such as surface EEG. Preliminary experiments and bench test results have confirmed its functioning for a distance range of more than 5m with high data transmission rate and low power consumption.**

Keywords— Bioelectronic Medicine, Epilepsy, Wireless, Ultra-wideband, Implantable device, Telemetry, Neural recording, Peripheral nervous system, Central nervous system, Vagus nerve.

I. INTRODUCTION

Bioelectronic Medicine is a promising alternative to treat diseases without the use of traditional drugs. These devices interface with a nerve to record and manipulate its electrical activity. By recording these signals and identifying the underlying patterns it might be possible to treat a wide range of neurological disorders from epilepsy and cardiac arrhythmias to Parkinson's disease and Depression[1].

Implantable systems will play a key role in the development of closed loop Bioelectronic Medicine Therapies. However, while there are several implantable stimulators in the market, there are very few fully implantable real-time recording systems that have high data transmission rates, low power consumption and a miniature size. The existing high bandwidth recording systems are mostly external, and utilize tethered wires for connecting to the electrodes. This increases the risk of infection due to percutaneous connections and movement [2]. Those systems that are small enough to be fully implanted do not have sufficiently high data transmission rate to transmit raw neural data at high sampling rates, due to hardware and power restrictions. These issues can be addressed by developing a fully implantable wireless recording system with a high data transmission rate, low power consumption and a very small size, to analyze the neural signals for patterns associated with neurological disorders that can be corrected by stimulating the nerves in a closed loop system.

In this paper, we present a 2 channel wireless recording system with a sampling rate of 20ksps/channel that can be implanted to chronically record neural data from a freely moving rat. The system uses an Ultra-wideband Impulse Radio (UWB-IR) based transmitter to transmit raw data to a receiver connected to a host computer, with a BLE based control to start and stop the recording. UWB is used for transmission of raw data due to its high data rate and low power consumption that makes it best suited for this application, as compared by Ando et.al [3]. This paper is organized as follows. Section II describes the system architecture and circuit design of the proposed implantable wireless recording device and receiver. Section III shows the test results of the integrated system. Section IV concludes this paper.

II. CIRCUIT DESIGN AND IMPLEMENTATION

A. System Architecture

The wireless telemetry system shown in Fig 1, consists of an implant module (Fig 1 a) that records neural signals and a receiver station (Fig 1 b) that is connected to a host computer to display and store the recorded data. The implant module uses a low noise biopotential amplifier chip RHD2216 from Intan Technologies, LLC that is interfaced with the Carbon Nano Tube Yarn (CNTY) electrodes to provide a very flexible and low impedance interface to measure the neural signals [4]. The RHD2216 digitizes the signals and interfaces with a TI CC2640R2F, a 32-bit microcontroller with an integrated BLEv5 radio core that is used for collecting and processing the data. The BLE connection controls the operation of the implant from the host computer's user interface. Once the data is collected and hardware averaged to further improve the SNR [5], it is packaged into a series of 30 samples ready for wireless transmission to the receiver using a DecaWave DWM1000 Ultra-wideband Module. On the receiver side, the microcontroller CC2640R2F continuously polls the status flag of the Ultra-wideband receiver for the data packets and once data is received, the FPGA state machine fetches and stores this data, which is displayed on the modified Intan GUI and can be stored in the host computer for further processing.

This work was supported by Ohio Third Frontier - CPT Sensory stimulation for epilepsy and the Seitz Family Donation

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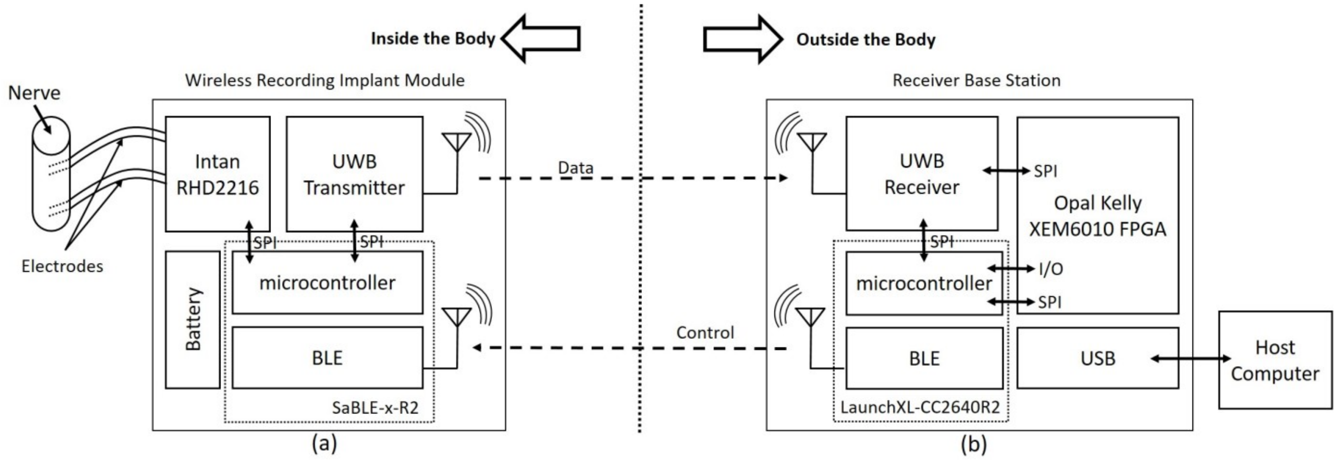

Figure 1: Schematic Diagram of the system. (a) The wireless recording implant module. (b) The receiver base station

B. *Wireless Recording Implant Module*

Our proposed two channel neural recording system shown in Figure 2 uses a 16-channel low noise differential amplifier chip from Intan Technologies, LLC (RHD2216) to record the neural signals. It is interfaced with SaBLE-x-R2 BLE module from Laird Technologies that uses a Texas Instruments 32-bit low power ARM Cortex M3 microcontroller with a BLE core (CC2640R2F) that collects the data and interfaces with a DecaWave DWM1000 Ultra-wideband module to transmit the acquired neural raw data to the receiver. This setup is powered by a 150mAh Li-Po rechargeable battery, and a TI LP5900 ultra-low noise LDO is used to convert the 3.7V from the battery to a regulated 3.3V supply. The different components work together in synchronization starting with the RHD2216, where the first 3 amplifier channels are tied together to form the first input, and the next 3 channels are tied together to form the second input. This allows us to perform hardware averaging to improve the Signal to Noise Ratio (SNR) [5]. These two inputs are connected to the Carbon Nano Tube Yarn (CNTY) electrodes [4], as these electrodes are biocompatible, flexible, have low impedance, and have demonstrated chronic neural recordings. The RHD2216 amplifies and digitizes the signals with a 16 bit resolution. The SaBLE-x-R2 interfaces with the RHD2216 and acquires the data at a sampling rate of 20ksps/channel, using a Serial Peripheral Interface (SPI). This data is stored in a buffer and hardware averaging is performed using 3 channels on both inputs. Every 16 bit averaged sample is then split into the higher 8 bits (MSB) and lower 8 bits (LSB) and then stored in the transmit buffer of the DecaWave DWM1000 UWB module using the SPI interface.

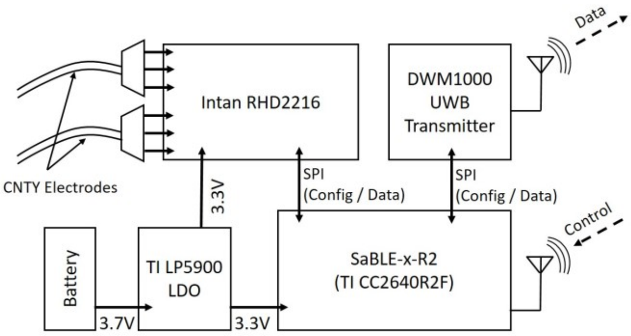

Figure 2: Block Diagram of the wireless implantable recording

DecaWave DWM1000 is compatible with the IEEE 802.15.4-2011 standard for UWB and uses a standardized frame format. A single transmission packet is ready when 30 data samples from both channels have been stored in the transmit buffer of the DWM1000 in the frame format shown in Figure 3. At this point, the microcontroller triggers the transmission of this packet by sending the transmit command over the SPI interface to the UWB module.

This process repeats every 30 samples and sends data packets wirelessly to the receiver. The receiver operation is explained below.

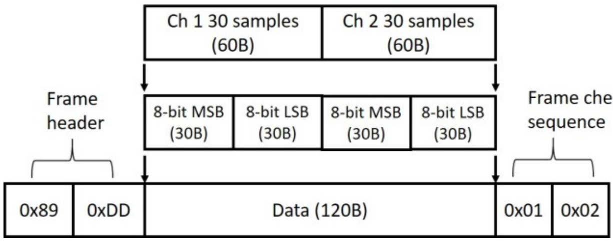

Figure 3: Ultra-wideband (UWB) transmission data frame format.

C. *Receiver Base Station*

The receiver performs bidirectional communication between the implant module and the user interface on the host computer. It allows the user to connect to the implant module and control its operation using inputs from the GUI. When the implant is transmitting neural data, the receiver collects it, and sends it to the host computer GUI to display and store on the computer.

The receiver base station shown in Figure 4 uses a Bluetooth Low Energy v5.0 (BLE5) LaunchPad development board (LaunchXL-CC2640R2, Texas Instruments, Inc), that has a

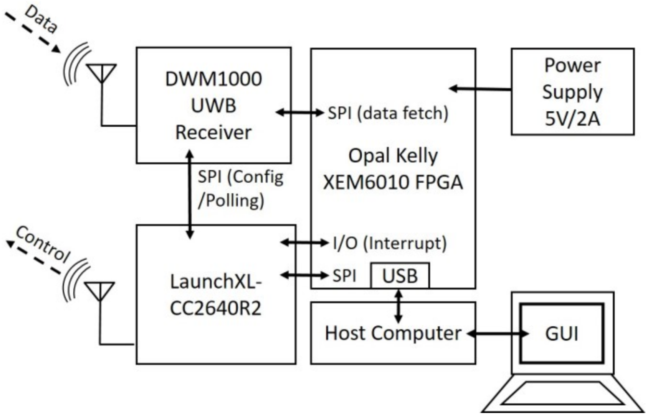

Figure 4: Block diagram of the receiver base station

CC2640R2F microcontroller with additional GPIO pins for interfacing. An Opal Kelly XEM6010 FPGA board interfaces with the microcontroller via SPI and the host computer using a USB connection. This allows interfacing with the GUI to display and store data collected by the FPGA from the DWM1000 UWB module that works as a dedicated receiver.

Control commands for the implant are sent from the GUI to the BLE microcontroller via the FPGA interface. The BLE radio sends these commands wirelessly to turn the recording On or Off. When recording is turned On, the UWB module on the receiver is actively waiting to receive the data packet. The microcontroller continuously polls the status flag of the DWM1000 and generates an interrupt when the receive flag is set. This signals the FPGA module to initiate the data fetch state machine to collect the data from the receive buffer of the DWM1000. Once the data is collected by the FPGA, it signals the microcontroller of a successful fetch and the microcontroller returns to polling for data packets again. The collected data is converted back to 16 bit samples by merging the 8 bit MSB and LSB, and is stored in the SRAM of the FPGA. This data is ready to be displayed by the modified Intan user interface software (open source software provided by Intan Technologies, LLC) that collects the data from the SRAM at 20ksps sampling rate, and displays it onto the GUI and stores it.

D. Device Implementation

Figure 5(a) shows the wireless recording implant module and 5(b) shows the receiver base station. The implant module is implemented using 2 PCB boards attached together with a board-to-board connector. The bottom PCB holds the Intan RHD2216 chip and the SaBLE-x-R2 module. It includes a 12-pin Omnetics PZN-12-AA connector that connects to a JTAG programmer board for programming and debugging. The Top PCB has the DWM1000 UWB module and the TI LP5900 LDO to convert the battery voltage to a regulated 3.3V to power the entire setup. These two layers are then attached together using a board-to-board connector. Once programmed, the JTAG connector is removed and replaced with another connector that connects the electrodes and battery to the implant board, which is then encapsulated with medical grade biocompatible epoxy (EPO-TEK MED-301). A 150mAh Li-Po rechargeable battery is used to power the implant board, and is encapsulated in a separate package. Table 1 summarizes the transmitter specifications and performance. A percutaneous plug is currently used to recharge the battery when needed, however, it can be replaced by a wireless recharging circuit in the future, to make the device fully implantable.

The receiver base station uses a XEM6010 FPGA board mounted on the BRK6110 board to allow access to its I/O pins. A custom PCB board with the DWM1000 UWB module is interfaced with it, and the CC2640R2F LaunchXL board is mounted on top. The entire setup is powered by a 5V 2A power supply, and it is connected to the host computer using USB connection.

The Host computer runs a modified version of the Intan RHD2000 Series v1.5.2 GUI, with an additional "Init BLE" button to reset the Bluetooth microcontroller using the GUI, to initiate a new connection to the implant to establish control and receive the raw neural data.

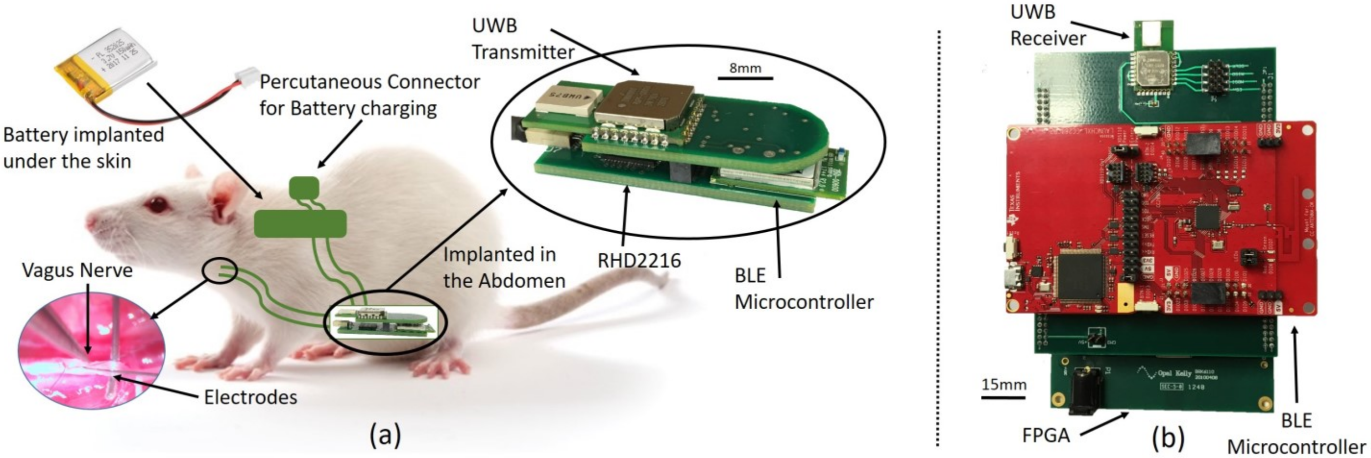

Figure 5. Proposed system implementation of (a) a 2-channel wireless recording implant module (b) the receiver base station

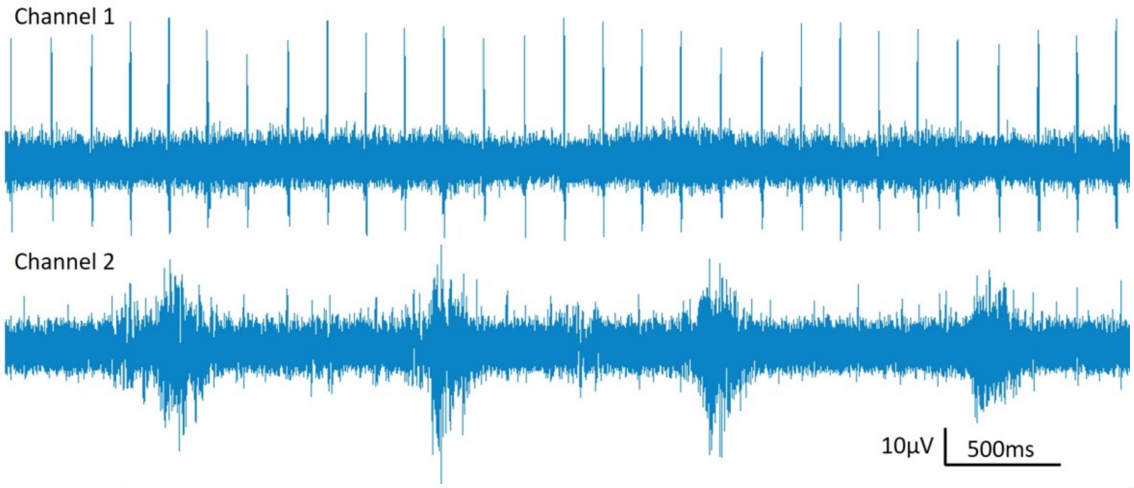

Figure 6. Data recorded from CNTY electrodes implanted outside (Channel 1) and inside (Channel 2) the vagus nerve using the wireless recording system

III. MEASUREMENT RESULTS

A. *Experimental Validation*

To validate the system, acute animal experiments are performed by connecting the transmitter module to the percutaneous connector on a chronically implanted, anesthetized rat, with 2 CNTY electrodes implanted next to the left cervical vagus nerve (channel 1) and 2 inside the left cervical vagus nerve (channel 2). Data is recorded differentially at 20ksps/ch with an SNR of 7.92dB and is shown in Figure 6. Channel 1 clearly shows ECG signal recorded by the electrodes outside the nerve, however, no other activity is recorded. In comparison, channel 2, where the electrodes are implanted inside the nerve does not show any ECG signal, but shows vagus nerve neural activity that corresponds to the breathing cycle. Having 2 channels allows us to establish that the signal is indeed neural and not motion artifacts. The wirelessly recorded data was comparable to that observed using a wired Intan RHD2216 system on the same animal.

TABLE I. TRANSMITTER SPECIFICATIONS AND PERFORMANCE

System Parameter	***Value***
Number of Channels	2
Recorded Bandwidth	0.1Hz – 5kHz
Sampling Frequency	20 ksps
Sampling Resolution	16 bit
Telemetry Frequency	6.4GHz
Power Supply	3.7V
Battery Life[a]	~ 11Hrs
Max Power Dissipation (3.3V)	45.5mW
Transmission Range[b]	>5m
Dimensions[b]	44.5 x 16.6 x 9.9 mm^3
Weight[b]	6.87 g

[a] With a 150mAh battery

[b] Without encapsulation

IV. CONCLUSION

A miniature low power wireless neural recording system is presented in this paper that uses UWB to transmit 2 channels of raw neural data acquired at 20ksps/ch using CNTY electrodes. A BLE connection allows the user to control the implanted device from a GUI, which also displays and stores the received data. The implant is powered by a Li-Po battery that can be recharged through a percutaneous port. It has a working range of more than 5m and has been validated by acute studies in rats. Its overall size is comparable to existing, commercially available low bandwidth implantable devices that have been verified in chronic animal studies. Future modifications to this device can allow it to be used for multichannel EEG recordings as well as for transferring neural data files recorded and stored by wearable devices using the UWB wireless transmission.

ACKNOWLEDGMENT

The authors would like to thank Joseph Marmerstein and the chronic CNTY electrode implant surgery team for their help in performing animal experiments.

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