A Low-Cost, Open-Source, Wireless Electrophysiology System

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Abstract— **Many experiments in neuroscience require or would benefit tremendously from a wireless neural recording system. However, commercially available wireless systems are expensive, have moderate to high noise and are often not customizable. Academic wireless systems present impressive capabilities [1]–[4], but are not available for other labs to use. To overcome these limitations, we have developed an ultra-low noise 8 channel wireless electrophysiological data acquisition system using standard, commercially available components. The system is capable of recording many types of neurological signals, including EEG, ECoG, LFP and unit activity. With a diameter of just 25 mm and height of 9 mm, including a CR2032 Lithium coin cell battery, it is designed to fit into a small recording chamber while minimizing the overall implant height (Fig. 1 and 3). Using widely available parts we were able to keep the material cost of our system under $100 dollars. The complete design, including schematic, PCB layout, bill of materials and source code, will be released through an open source license, allowing other labs to modify the design to fit their needs. We have also developed a driver to acquire data using the BCI2000 software system. Feedback from the community will allow us to improve the design and create a more useful neuroscience research tool.**

I. INTRODUCTION

New commercial medical analog front end integrated circuits from Texas Instruments [5] and others have combined entire high performance, multichannel biosignal acquisition systems into a single small package. A single, small integrated circuit provides a direct “electrode to digital” interface that includes programmable amplification, filtering and high-resolution (24-bit) analog to digital conversion. Similar innovations in integration have produced new Bluetooth 4.0 Low Energy (LE) system on a chip (SoC) devices [6] that combine a complete low-power wireless transceiver and microcontroller into a small package. Bluetooth 4.0 LE, while not originally intended for continuous data streaming, provides moderate data rates (up to 2 Mbps), with one of the lowest levels of energy consumption per bit in commercially available wireless technologies [7].

We have combined these two technologies with a small lithium-ion coin-cell battery enabling an entire 8 channel wireless biosignal recording system that is 25 mm in diameter and 9 mm high. By utilizing the built-in Bluetooth transceivers in modern laptops, smartphones and tablets, our wireless system eliminated the need for expensive proprietary neural data acquisition systems. If an external transceiver is desirable, or if the wireless system needs to be used with an older computer, an inexpensive USB Bluetooth 4.0 transceiver can be used (Fig. 2).

Compared to currently marketed wireless electrophysiology systems, our system had higher performance neural signal acquisition with lower noise and larger dynamic range, due to the use of a 24-bit sigma-delta analog to digital converter. It was similar in size and weight, but dramatically lower in cost (Table 1). The core technologies were developed for the mobile phone industry, making them widely available at low cost. The bill of materials cost is approximately $100 for the 8-ch system.

Similar non-commercial (academic) wireless recording systems offer improved capabilities, such as higher channel counts or lower power consumption [1]–[4]. However, these systems rely on custom application specific integrated circuits (ASICs), which are exceptionally expensive to develop and are produced in limited quantities, restricting their availability to only the group that developed them.

To overcome these limitations, we have developed a custom wireless data acquisition that utilizes entirely off the shelf components. By leveraging innovative technology, we were able to design a low cost, small form factor device that obtained high quality neural recordings. To accelerate the adoption of wireless electrophysiology methods, we are releasing the entire project under an open source license, such that other groups may freely modify and improve the design.

II. METHODS

A. Hardware - Component Selection

Tradeoffs are always required when designing a miniaturized, battery powered system. We prioritized minimizing the size of the design, with a special emphasis on minimizing the overall height, in order to reduce the torque that can be exerted on the animal via the recording chamber. A minimum battery life of two hours was required for the planned experiments.

At the core of our system (Fig. 2) was a medical analog frontend integrated circuit (ADS1298, Texas Instruments)[5]. The integrated circuit provided very low noise signal acquisition, 0.4 μV rms at 250 S/s, increasing to 1.8 μV rms at 8 kS/s. High common mode rejection (-115 dB) combined

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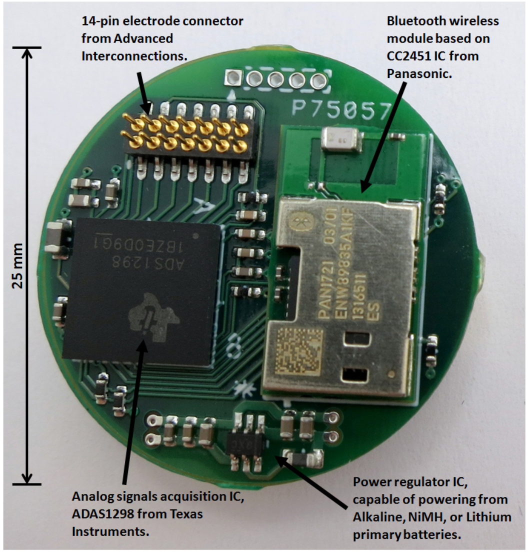

Figure 1: 8-Channel wireless electrophysiological data acquisition hardware, 25mm in diameter and 9mm in height not including the electrodes mating connector. On the left is the analog front end acquisition chip ADS1298 and on the right is the Bluetooth wireless module PAN1721. At the top is a 14-pin electrode connector, with 9 connections used. The power regulator chip is located at the bottom.

with right leg drive (RLD) enabled low level signal recordings even in high noise environments. The chip contained eight 24-bit analog to digital converters, capable of sampling all 8 channels at rates up to 32 kS/s. The sampling rate and amplifier gain were all software programmable, allowing simple adjustments for recording different types of neurological signals. Even at the highest gain setting (12), a large input range of +/- 100 mV allowed electrodes to be DC-coupled to sample low-frequency signals. This chip also includes a digital low pass third order sinc filter to attenuate high frequency noise. The frequency response of this filter changes automatically with the selected sampling rate (-3dB bandwidth at 0.262 of selected data rate).

For wireless communication we utilized the PAN1721 (Panasonic Corporation of North America), which is a prefabricated wireless module that includes the CC2541 SoC (Texas Instruments) and a chip antenna. The CC2541 combines a 2.4 GHz RF transceiver with an enhanced version of the 8051 microcontroller in a compact 6x6 mm package. The SoC is optimized for low power usage and was capable of operating using the Bluetooth 4.0 Low Energy protocol (BLE) or a proprietary communication mode. The effective range of the wireless link depends on the transmission power setting. To balance power consumption and wireless range, we selected 0dBm output power and achieved a wireless transmission range of ~10-15m.

Although the BLE protocol was designed for low throughput applications, we used this mode in our system to enable compatibility with the many BLE enabled devices currently available on the market. For applications requiring higher data throughput, a proprietary communication mode along with an accompanying custom receiver module can be used to achieve raw data rates up to 2 Mbps.

To provide regulated 3.0V power for the ADS1298 and PAN1721, we chose a high efficiency (94%) switching power supply (TLV61224, Texas Instruments). The power supply had a wide input voltage range (0.7 to 3.0V) to accommodate a variety of batteries with different chemistries, including single-cell alkaline, NiMH or Li-primary batteries. No noise from the switching power supply was observed.

To enable simple and safe connectivity to potentially delicate implanted recording devices, we designed a separate printed circuit board (PCB) to interface our flexible electrode array to the wireless system. We designed a custom electrode

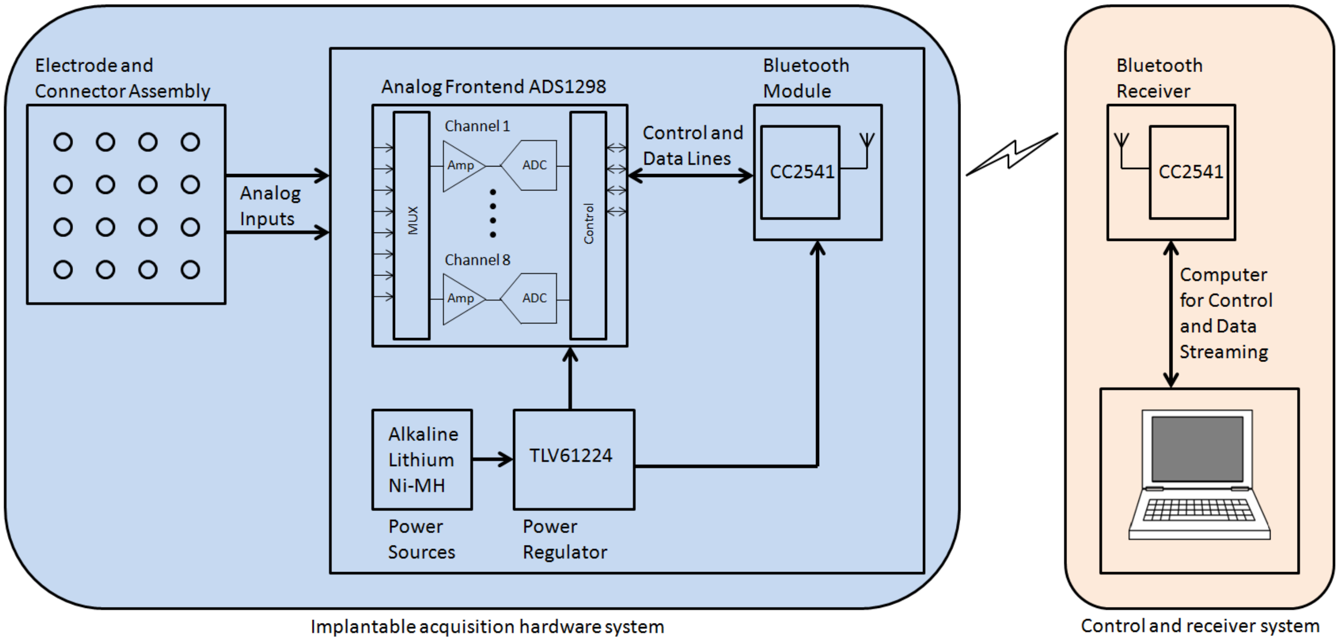

Figure 2: 8-channel wireless data acquisition system overall block diagram. The left block is the implantable wireless hardware. It contains the electrode and connector assembly along with the detachable wireless board. The analog signals are amplified and digitized with the analog frontend IC, ADS1298. The digital signal is then transferred to the Bluetooth module, CC2541, and packaged for wireless data transfer. The right block is the control and receiving system. It includes a Bluetooth receiver module and computer software system for acquiring the streamed data. Note that a custom Bluetooth receiver is not required for the receiving system. Devices such as laptops, smart-phones and tablets with built in Bluetooth 4.0 radio can be used.

adapter board with a female connector (Mezzapede, Advanced Interconnections). The flexible array was affixed to the adapter board using anisotropic conducting film (Elform). Using the rigid board as a structural support, we ensured plugging and unplugging the wireless device does not cause damage to the thin flexible electrodes (Fig. 3). This design allows the electrode adapter board to be permanently implanted on the subject, while the wireless data acquisition system can be connected and disconnected at will.

The completed system also included an infrared phototransistor that can be used with an external light source to record timing pulses and embed them in the wireless data. The recordings can then be precisely synchronized to eternal stimulation sources, such as visual or auditory stimuli.

Moreover, a recording chamber was designed and 3D printed to house the system during the acute experiments. This chamber includes an easily removable cap to replace the battery. The overall system was designed to be light and small enough to be used on rodents and robust enough to be used on primates.

B. Hardware – Fabrication and Assembly

Miniaturized PCB fabrication and assembly can be expensive and challenging, especially for designs that utilize small features or advanced manufacturing techniques. To reduce cost, we have designed our wireless system using only moderately sized features, enabling most PCB manufacturing companies to successfully fabricate our design. We used a 4 layer PCB with 1 oz. copper for all layers. All traces were a minimum of 5 mils wide, spaced 5 mils from other traces. Via holes and pads were 10 and 20 mils, respectively.

C. Software

We developed embedded software for the on chip 8051 microcontroller to receive the data from the ADS1298 frontend and run the Bluetooth stack. The embedded application was developed around the operating system abstraction layer which is a control loop that handled the Bluetooth stack, hardware abstraction layer (HAL), tasks and events. Sampled data from the analog front-end were received by the microcontroller through the SPI port, buffered and then sent via low energy wireless link in short packets.

The open-source firmware for the on-board microcontroller allows researchers to create and download custom algorithms such as spike detection and data compression. The Bluetooth wireless radio module can directly pair with most modern smartphones, tablets and laptops for data display and logging, eliminating the need for an expensive, dedicated neurophysiology system. We additionally developed a driver for the BCI2000 [8] brain-computer interface system to provide real-time display and analysis of recorded neurological signals.

III. RESULTS

Our wireless data acquisition system was fabricated and assembled (Advanced Circuits). We tested the completed system using test signals recorded at different gain settings and sampling rates to confirm functionality. The input referred noise of the system was 0.4 µV RMS when sampling at 250 S/s and using a gain of 12, as expected. The average power consumption of the device was ~15mA at 3V. Powered by a standard Duracell CR2032 coin cell battery, the device lasted approximately 30-60 minutes, significantly shorter than our initial calculations.

We tested our wireless system *in vivo* in an anesthetized and paralyzed nonhuman primate (*Macaca nemestrina)* using 8 of 12 available electrodes in a custom µECoG electrode array (Fig. 3). The electrode array was implanted subdurally over primary visual cortex. Full screen stimuli with sinusoidally modulated luminance at 1, 2 and 4 Hz were sequentially presented. The corresponding evoked potentials were recorded. The power spectral density showed strong modulation at frequencies driven by the luminance modulation of the stimulus (Fig. 4).

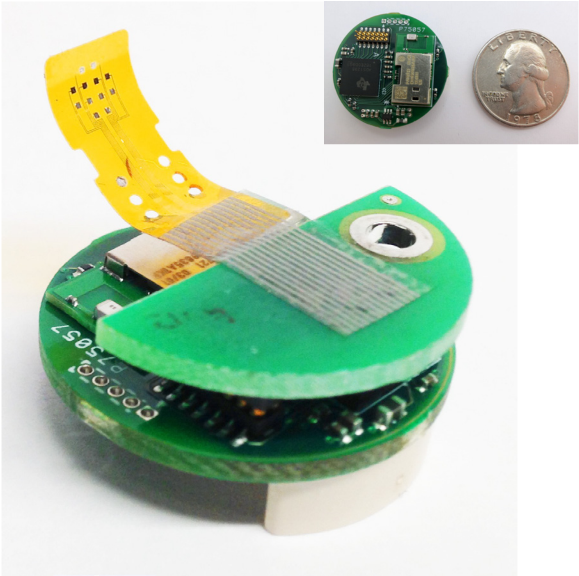

Figure 3: Electrode adapter board and wireless board assembly. Connection was made using a 14-pin, 1 mm pitch Mezzapede connector. The assembly can be chronically implanted and enclosed in a 1 inch diameter chamber. (Inset) Size comparison with a US quarter.

IV. DISSCUSION

We have successfully demonstrated the design and fabrication of a small wireless data acquisition system capable of recording neurological signals. The system was validated in an acute experiment in a primate using a subdurally implanted µECoG electrode array.

In future work we will optimize the embedded software to reduce power consumption and investigate different battery technologies to extend the system battery life. Additionally, operating the wireless system in Bluetooth 4.0 BLE mode limited the overall bandwidth to 40-50Kbps, which restricted the sampling rates available for use. Increasing the data rate will allow higher channel counts and higher sampling rates. The ADS1298 can also be replaced with one of the RHD2000 series digital electrophysiology interface chips (Intan Technologies), yielding a 32 or 64 channel wireless system without increasing the physical size of the system. However, the cost of the system will dramatically increase ($400 - $700). We utilized a prefabricated wireless module for our first prototype to speed development. Future designs could integrate the CC2541 directly onto the main PCB to reduce the size of the wireless system.

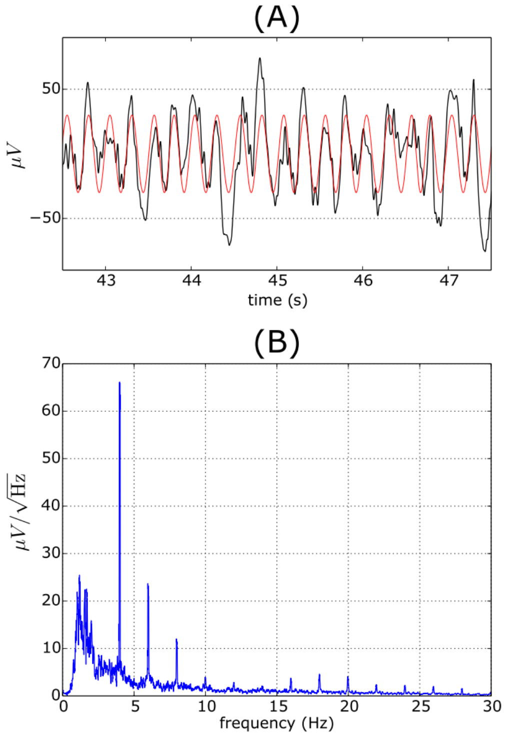

Figure 4: Wireless recording is validated in primary visual cortex of an animal viewing sinusoidal luminance modulation. (A) The black trace shows µECoG recorded in one channel. Visual cortex activity is driven at 4 Hz, responding to both the bright and dark contrast phases of the 4 Hz luminance modulation. The best-fit 4 Hz sinusoid (plotted in red) illustrates a tight phase locking with the visual stimulation. (B) The power spectral density of this channel indicates high SNR in the driven component of the µECoG compared to broadband power.

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Parameter	***Our System, ADS1298 analog frontend***	***Triangle BioSystems Intl., W5***	***University of Michigan, FMTv2 [9]***	***Georgia Inst. of Tech, WINeR-5 [10]***
Device Dimension	25mm diameter × 9 mm height	24.4 × 18.6 × 10 mm	36 × 40 × 10 mm	
# of Recording Channels	8	5	15	32
Analog Input Range	0.2 – 2.4 V (maximum input $V_{p\text{-}p}$)	4mV (maximum input $V_{p\text{-}p}$)		
Gain	1 – 12 (programmable)	800	51	77.1 dB
Resolution	24-bits		16-bits	8-bits
Sampling Rate	250 S/s – 32 kS/s (programmable)	50 kS/s	22 kS/s (programmable)	58-680 kHz (programmable)
Bandwidth	Adjustable (DC Coupled)	0.8 Hz – 7 kHz	0.1 Hz – 7 kHz	0.1 Hz – 10 kHz
Input Referred Noise	0.5 µVrms (at 500 S/s, G=12)	5.5 µVrms (for 500Hz – 5 kHz)	25 µVrms	4.9 µVrms
	1.8 µVrms (at 8 kS/s, G=12)			
SNR	112 dB (at f_{in} = 10Hz, G=6)			
CMRR	115 dB			139 dB
Input Impedance	1 GΩ	12 MΩ		
Battery Life	1 Hour	4 Hours	24 Hours	
Wireles Range	10-15 m	4 m	3 m	1 m

Table 1: Wireless acquisition systems performance comparison