15 Channel Wireless Headstage System for Single Unit Rat and Primate Recordings

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Abstract-- **Continuous recording of single-unit neuronal activity is an important tool for studying normal and pathological brain function. Current systems typically tether implanted electronics both to remote data processors and power supplies. The tether constrains the animals' behavior and limits possible experimental designs. Ideally, neural activity could be recorded from behaving animals in a natural and enriched environment. In this paper we present the circuits, layouts and test data for a multi-channel wireless headstage system which includes the headstage transmitter and receiver components. The system was successfully tested in a rat and a macaque monkey implanted with cortical multielectrode arrays.**

Index Terms—**Single Unit recordings, bio-telemetry**

I. INTRODUCTION

Neuroscientists studying neuronal activity in awake, behaving animals typically use anywhere from one to several hundred extracellular electrodes. The electrodes are connected to a "headstage" device that amplifies neuronal potentials and is then connected to a recording system via a bundle wires that provide power to the headstage and neuronal data to the recording system. A series of limitations and challenges result from having a study subject tethered to recording equipment, the most significant being the considerable constraint on the behavior of the subject. This impediment motivates replacing the wires with a radio transmitter system [1-9]. Because many of the test subjects in the experimental laboratories are small animals, the size and weight of the system must be correctly adjusted to meet the animal's comfortable weight bearing capacity. Furthermore, since it is highly desirable to conduct chronic recordings, the power system of a radio transmitter should be designed to have adequate battery life and weight, which are inversely proportional to each other. These considerations were taken into account in our design in which transmitter headstage power consumption and RF output transmit power were minimized, but met practical system recording specifications for input channel sampling frequency and pre-amplifier electronic noise.

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A schematic of a wireless headstage system that meets our design objectives is presented in Figure 1. This system can broadcast 15 channels of continuous single-unit activity band limited to 10kHz with each channel sampled at 50kHz. The transmit range is up to two meters using a 3.4 gigahertz radio carrier with output power below the maximum FCC 15.209 limit.

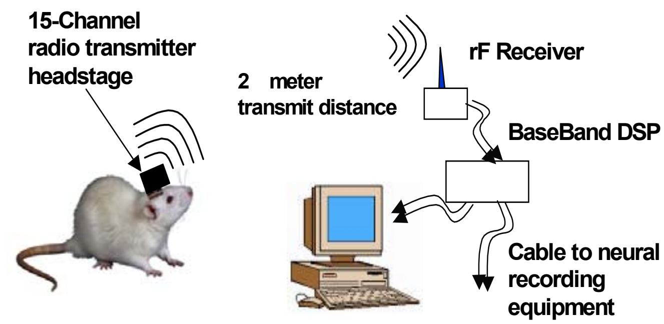


Fig. 1: 15 channel neural recording wireless system

A hybrid modulation scheme is implemented (see block diagram in Fig. 2) that provides greatly improved performance and noise immunity. This device will be moved into commercial production and suggested for use in neurophysiological laboratories that work toward development of clinical treatment of debilitating neurological impairments such as epilepsy, Parkinson's Disease and quadriplegia.

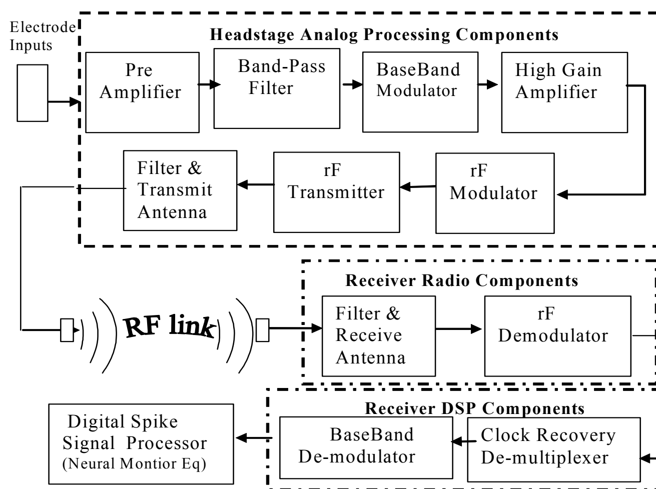


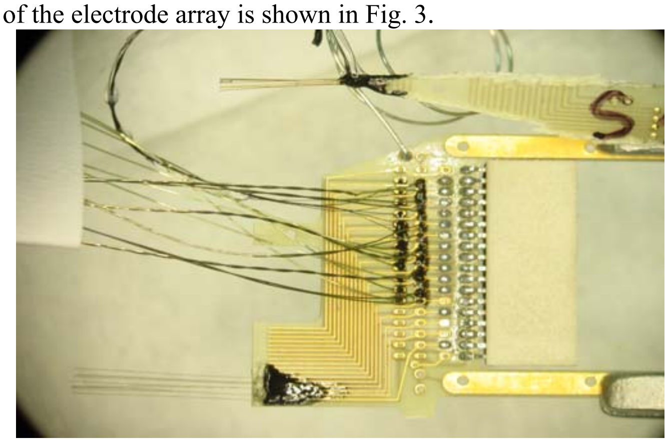
Fig. 2 Wireless recording system

II. SUGGESTED MICROWIRE ELECTRODES

Our wireless system was tested with microwire multielectrode arrays developed in the Nicolelis laboratory at Duke University. These arrays were designed to simultaneously record neuronal signals from several brain areas, such as the primary motor cortex (M1), the primary somatosensorial cortex (S1) in the rat. In addition, electromyorgaphic (EMG) activity can be recorded using microwires implanted in the muscles and transmitted using our system. Both microwire arrays and EMG wires were connected to an Omnetics 36 pin Nano dual row connector, which is typically imbedded in acrylic and affixed to an animal skull. The "headstage pre-amplifier" provides impedance matching, gain and drive output to the radio which broadcasts these signals to the receiver, which in turn is connected to a Plexon preamplifier. The Plexon preamplifier has a gain set to 50 and bandwidth set to .4hz to 10kHz.

A. Implantable Electrodes

The implantable electrodes consisted of 35 micron diameter Tungsten wire with a Polyimid insulation. The electrodes are spaced at 250-1000 microns center to center and typically have an impedance of 1.2 Meg Ohm with +/- .1 Meg Ohm tolerance measured at 1kHz in saline solution. These electrodes are single ended, and they are referenced to a common ground. The ground reference is achieved via connection to stainless steel screws installed on the skull. The signals obtained from these electrodes are routed to the wireless headstage connector, which is located in close proximity to the electrodes to minimize noise. An example of the electrode array is shown in Fig. 3.



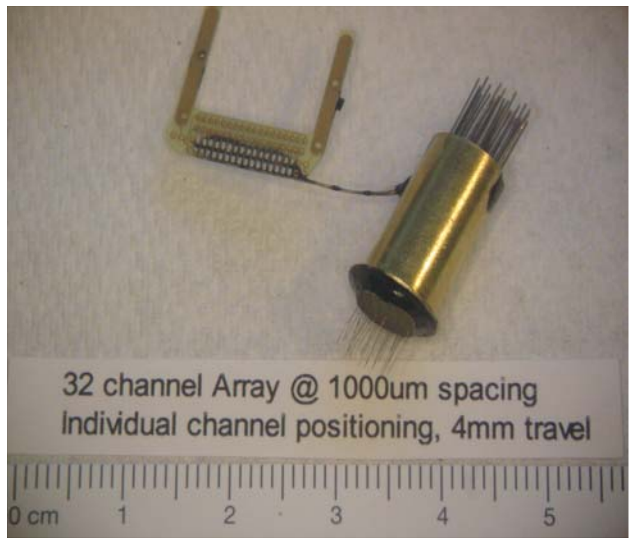


Fig. 3 Neuronal electrodes and positioner

B. EMG Electrodes

EMG electrodes are constructed using 150 micron diameter Stablohm 650 wire with polyimid insulation. Differential-pair recordings are implemented in which muscle electrical activity is recorded by two wires twisted together to form a twisted pair. The impedance of the EMG electrodes is 20 kOhm with +/- .8 kOhm tolerance measured at 1kHz in saline solution. The signals obtained from these electrodes are routed to the transmitter headstage connector and sent to a receiver connected to a Plexon EMG differential input headstage. This headstage has a gain of 20 and a 3db bandwidth of 20hz to 17hz. The output of this amplifier is routed to a Plexon preamplifier for filtering and amplification. The preamplifier has a gain of 50, 100hz to 4khz. Layout of the EMG electrodes is illustrated in Fig. 4.

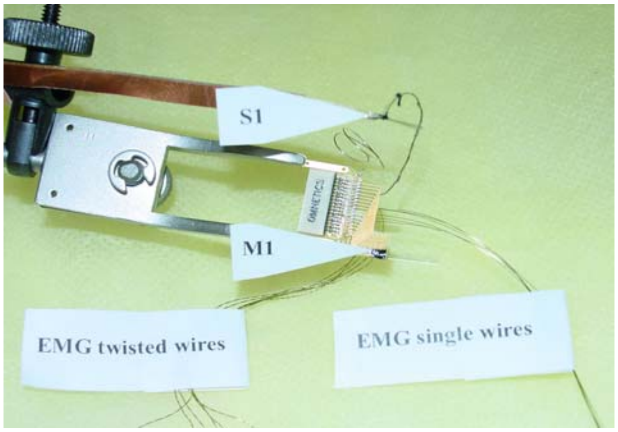


Fig. 4 EMG Electrodes

III. HEADSTAGE HARDWARE

Neural signals derived from implanted electrodes require analog signal processing prior to A/D conversion [1,2,3]. Gain above 80dB, bandpass filtering above 4th order and input referred noise below 5µV rms are stringent specifications of the signal preconditioning electronics [4]. Integration and packaging of these multi-channel analog functions into a lightweight, miniaturized form factor located physically close to the electrodes is also imperative. Technical specifications for the headstage transmitter are listed in Table 1.

TABLE I
15 Channel Transmitter Desired Specifications

Parameter	Value	Notes
Power Supply	2.8v@7ma	Regulated
Battery Life	>10 hr.	80mAhour Lithium Ion
Input voltage range	0.5v	
CM center	Gnd	Common mode Center
Gain	20 or 100	Selectable
Bandwidth	.5Hz–10kHz	Input Signal BW
Input impedance	100 MΩ	At 1kHz
Input referred noise	5µV	dc-10khz
W x L x H (mm)	32 x 32 x 9	
Weight	11.9 grams	Including battery
RF Center Freq	3.4Ghz	+/- 100Mhz BW
Transmit power	500µV/m	FCC Sec.15.109B(a)
Transmit antenna	3.4 Ghz	50 ohm patch type
Transmit range	2m	Up Directional

The size of the device was designed assuming the use of 0.35 µm CMOS technology and processes. Based upon a quad metal approach, the analog radio system has the dimensions of 1.9 x 3.92 mm, which is slightly less than 7.5 square mm of space. Each analog channel has a low noise, high gain bandpass preamplifier that follows baseband AM and rF FM VCO.

A. Pre-amplifier Circuit

The pre-amplifier (Fig. 5) uses a second order highpass cascaded architecture with one pole set by C_1 and the high impedance of the adjustable sub-threshold devices. The second highpass pole is set by the output impedance of the first stage amplifier and the C_2 value. The gain of the second stage is set by the resistor values of R_2 and R_1. R_2 can be adjusted by an electronic switch that sets the gain to either 20 or 100.

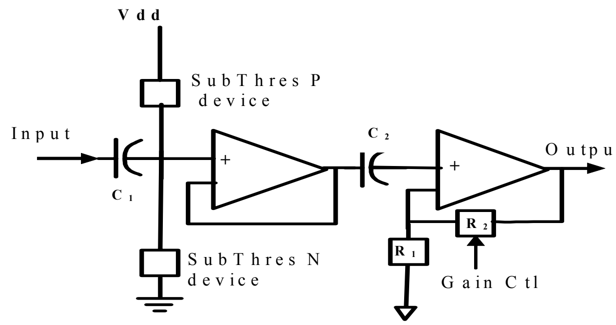


Fig. 5 Pre-amplifier circuit

B. Voltage Controlled Oscillators Circuits

The baseband AM VCOs use an N-stage voltage controlled oscillator (VCO) and a current starved delay cell (Fig. 6). The frequency is controlled by an off-chip bias voltage. For the center channel frequency, the VCO gain was selected to have a center frequency of 10.1Mhz. Each of the 15 AM channels are spaced from the VCO topology. Simulation results are shown in Fig. 6:

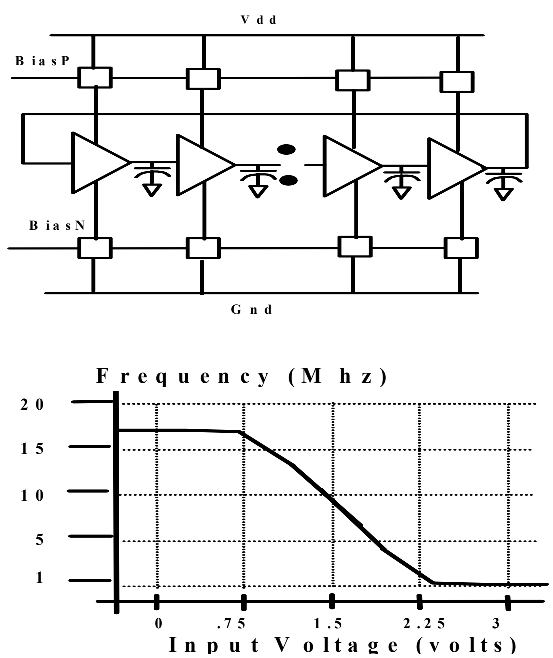


Fig. 6 AM voltage controlled oscillator

The architecture of FM VCO was chosen because of the 3.4Ghz frequency requirement (see schematic in Fig. 7).

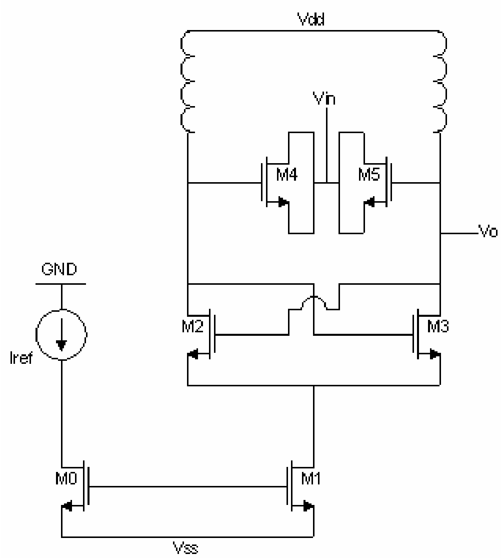


Fig. 7 FM voltage controlled oscillator

C. Headstage ASIC and Packaging

Multi-channel analog circuits are integrated and packaged of into a lightweight, miniaturized form factor located physically close to the electrodes. Figure 8 shows an example of a wireless neural preconditioning analog RF ASIC that was developed at TBSI as part of a neural data acquisition system [1,2].

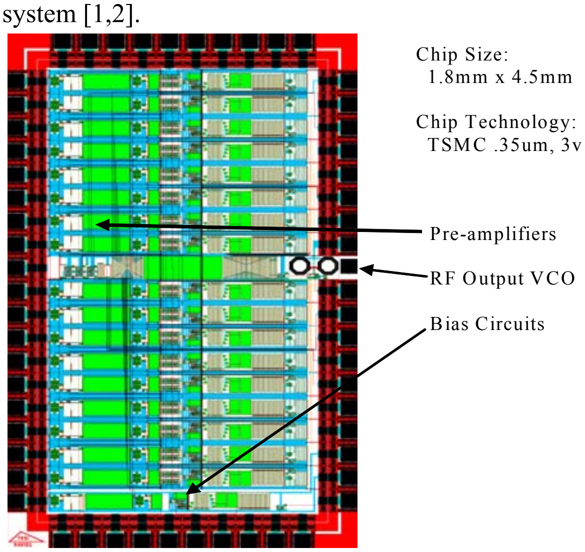


Fig. 8: Analog RF ASIC

The RF ASIC is packaged into a headstage sub-assembly with switch, battery and other passive components (Fig. 9).

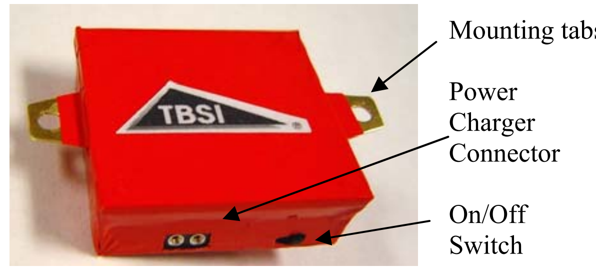


Fig. 9: Headstage transmitter packaging

The weight of the headstage subassembly is 11.9 grams and the size is 1.25 inches square by .37 inches tall. The on/off switch and battery re-charger connector is shown on the side. Mounting brackets are also shown on each side.

IV. HEADSTAGE RECEIVER SYSTEM

The receiver system contains an RF receiver unit followed by a baseband DSP unit. The RF receiver picks up the low level transmit carrier of the headstage and demodulates this carrier to baseband signals. The DSP unit converts the baseband signals to analog outputs or digital outputs. A DSP was chosen because of the software tuning required for the baseband modulation. The analog outputs from the DSP unit can be fed directly into a neural recording system preamplifier. Figure 10 illustrates the receiver system:

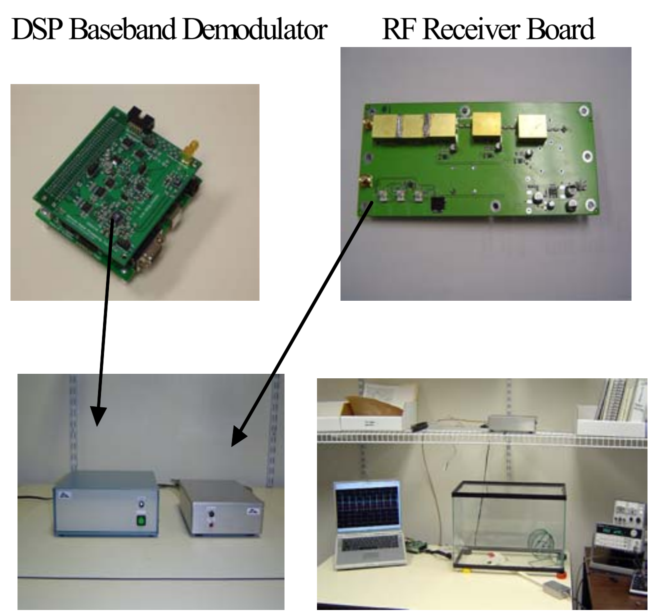


Fig. 10: Receiver system components

V. TEST RESULTS

The wireless headstage system was tested using a +1.5V and –1.5V bipolar power supply. The results of test measurements are shown in Table II:

TABLE II
Measured Test Results

Measured Parameter	Value	Notes
Battery Life	>13 hr.	With 2 hour charge
Input voltage range	1.25v	Vp-p
Gain	20 to 600	Selectable
Bandwidth	0.5Hz–5kHz	Input Signal BW
Sampling Rate	50kHz	Per channel
Input impedance	40 MΩ	At 1kHz
Input referred noise	7.5μV	dc-10khz
W x L x H	32 x 32 x 9	mm
Weight	11.8 gm	Including battery
RF Center Freq	3.4Ghz	+/- 100Mhz BW
Transmit power	130μW	FCC Sec.15-205
RF VCO phase Noise	-43dBc	
Transmit range	>2 meters	Up Directional
Transistor Count	135	Per channel

The overall transceiver accomplishes a high correlation between the input signal and the received/demodulated signal as shown in Fig. 11. For artificial signals > 50 μV a reproduction of > 50% of the original is attainable. For signals > 300 μV, the reproducibility is > 90%.

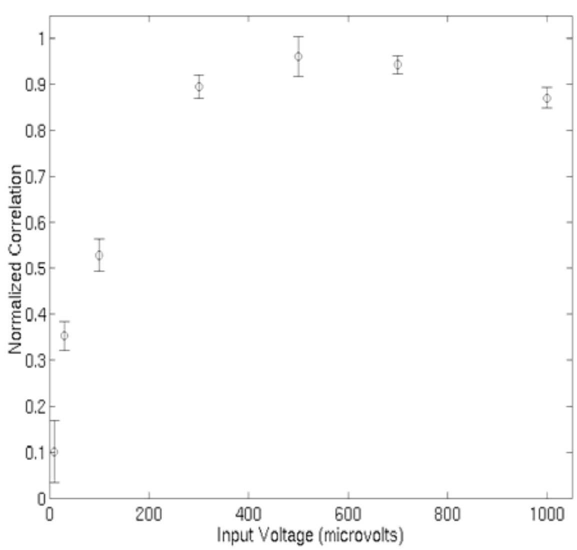


Fig. 11: Input-output correlation

The system was tested in freely moving rats. Seven 10-minute recording sessions were conducted. In each session, 15 channels of neuronal activity were simultaneously sampled. The electrodes were implanted in motor cortex two months prior to testing. The gain was set to 600 for the rat recordings. Figure 12 illustrates a rat with headstage transmitter mounted on its head. In addition, activity sampled on one of the channels (channel 5) is shown.

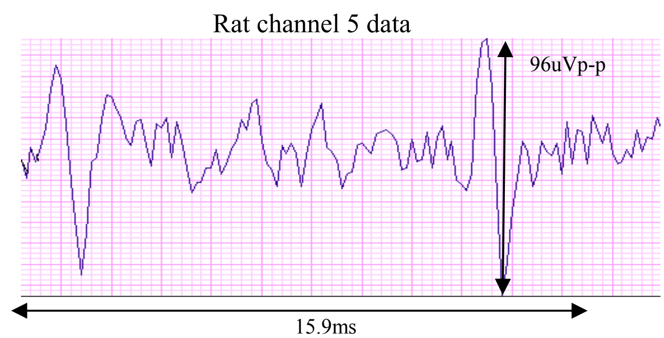


Fig. 12: Rat with headstage and Channel 5 data

To test the equipment in a monkey, a rhesus macaque was comfortably seated in a primate chair. The monkey was previously trained to sit quietly in the chair while investigators sorted its units recorded with cortical multi-electrode implants. We tested our equipment on a dorsal premotor cortex (PMd) implant that contained 32 microwires in a square arrangement with a 1-mm separation between the wires. The monkey was implanted seven months prior to this testing. Of the 32 electrodes, we recorded from 15. For the monkey recordings, the gain was set to 500. Two example recordings (channels 9 and 11) are shown in Fig. 13.

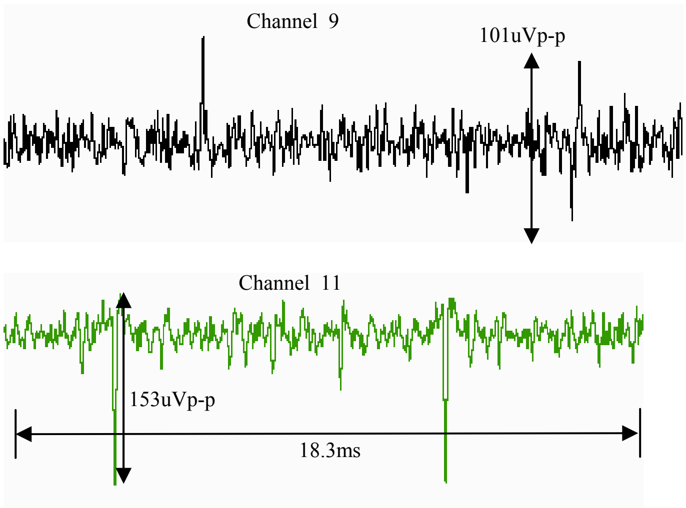


Fig. 13: Single Unit data recorded from a monkey dorsal pre-motor cortex

VI. CONCLUSION

A design of a battery powered 15-channel wireless neural recording device has been described and tested in rats and monkeys. The headstage device has a transmit range sufficient to allow for continuous recordings from animals in their natural environments. The power consumption of the neural transceiver makes long-term recording possible from a small rechargeable battery packaged along with the IC. Device behavior closely corresponds to design parameters both with artificial signals and with *in-vivo* recordings.

VII. ACKNOWLEDGMENT

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