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Low-Cost Wireless Neural Recording System and Software

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***Abstract*— We describe a flexible wireless neural recording system, which is comprised of a 15-channel analog FM transmitter, digital receiver and custom user interface software for data acquisition. The analog front-end is constructed from commercial off the shelf (COTS) components and weighs 6.3g (including batteries) and is capable of transmitting over 24 hours up to a range over 3m with a 25µV_{rms} in-vivo noise floor. The Software Defined Radio (SDR) and the acquisition software provide a data acquisition platform with real time data display and can be customized based on the specifications of various experiments. The described system was characterized with in-vitro and in-vivo experiments and the results are presented.**

I. INTRODUCTION

Light weight multichannel wireless neural recording microsystems are needed for recording brain activity in freely moving animals and prosthesis application. Wireless recording systems have found limited application compared to tethered ones, in part because of the high cost, limited functionality and excessive size and weight. A successful system will have practical transmission range, small-size/light-weight compared to the test subject, and a high channel count. The demanded channel count varies based on the experiments; for neuroscience experiments on animals tens of channels are needed where as in prosthesis applications a channel count over 100 is desirable.

A primary challenge in recording many channels with high fidelity is bandwidth. Analog transmission is desirable to reduce system complexity, but insufficient bandwidth will cause significant cross talk in analog multiplexed systems [1]. Using a wideband SDR radio we are able demonstrate a 15-channel analog system with low crosstalk while maintaining low cost.

Our neural recording system is diagrammed in Fig. 1 and consists of an analog FM transmitter using time-domain analog multiplexing and frequency modulation scheme, a USRP [2] software defined radio receiver controlled by a laptop, and data acquisition software built on top of the open source GnuRadio [3] framework. We have successfully used this small portable system for in vivo recording in Long Evan's Rats, Zebra Finches, Guinea Pigs and Marmoset Monkeys using both Micro-machined Michigan probes and traditional tungsten wire neural probes.

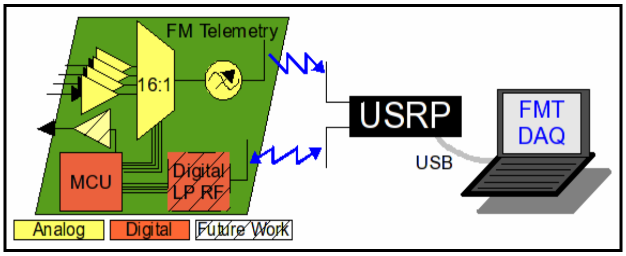

Fig. 1. Block diagram of the multichannel wireless neural recording system including FMT transmitter, USRP software defined radio and laptop running FMTDAQ acquisition software. Digital bidirectional communication and auxiliary channels are planned for the near future.

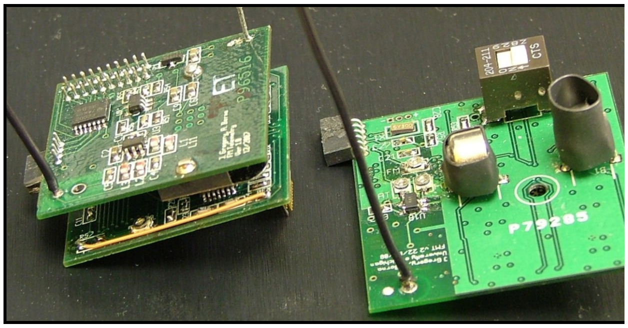

Fig. 2. FMTv1 (left) and v2 (right). This second version has a DC blocking capacitor at each input channel.

The paper is organized as follows: In section II the wireless recording system is described, Section III presents the in-vivo test results.

II. SYSTEM DESCRIPTION

A. *Neural Recording Transmitter*

Two versions of the FM transmitter (FMT) have been developed and the FMTv1 and FMTv2 are shown in Fig. 2. They share the same essential architecture and components with the primary difference that the FMTv2 channels are AC-coupled whereas in the FMTv1 the channels are DC-coupled. Fig. 3 presents the simplified schematic of the front end.

1) *Analog Front End*

Due to electrode-electrolyte interface at probe sites, there is a significant DC offset as well as very low frequency drift potentials, which can saturate the subsequent circuitry. We originally used the approach from [1] in the FMTv1 and

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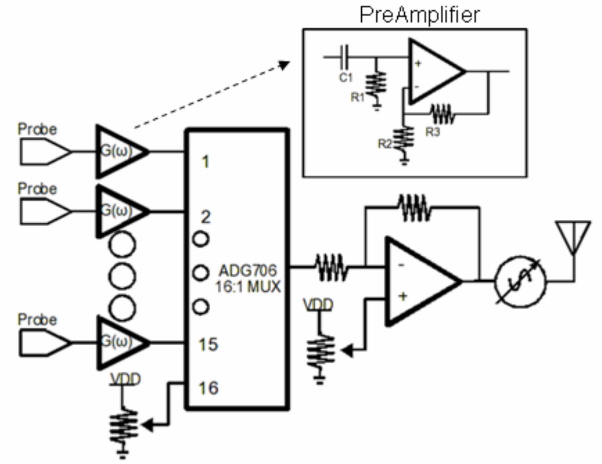

Fig. 3: Block Diagram of FMTv2/v1 Transmitter

used a 22MΩ resistor to cancel any DC bias; the resistor forms a high pass filter along with the capacitance of the probe. This approach relies on the very large DC probe resistance and relatively small input resistance to form a resistive voltage divider and cancel any DC offset. We found two problems with this approach in practice: first, the front-end frequency response depends heavily on the probe type because as mentioned the probe capacitance and this resistor form a high pass filter in signal path. Secondly, the very low frequency drifts were not sufficiently attenuated in in-vivo experiments with wire tungsten probes and therefore very large offsets were observed between channels. These offsets did not saturate the amplifiers, but increased the required bandwidth to over 40MHz.

We resolved this problem in our second version with the addition of a decoupling capacitor. This capacitor blocks the large DC probe potential and forms a first-order high pass filter with the resistor to filter out the low-frequency drifts. By keeping the decoupling capacitor much smaller than the probe capacitance, the attenuation due to the capacitive divider is minimized and reduces the impact of probe impedance on the channel's gain. For a 1MΩ probe, the limit is around 50pF. The frequency response of the FMTv2 channels with two different probes is shown in Fig. 4. As can be observed, the response is the same for both cases.

The criteria used in choosing the front-end off-the-shelf components were their noise, power, DC-offset, frequency response and size. The AD8609 (Analog Devices, Inc.) has a 400kHz gain bandwidth product, so a gain of 50 results in a low cut off frequency of 8KHz, which is sufficient for neural signals. It contains 4 amplifiers in each IC package making it suitable for small size applications with large channel counts. The non-inverting resistive feedback configuration was employed due to its large input impedance and stable performance

2) *Multiplexing and Demultiplexing the Analog Signal*

An ADG706 16 channel analog multiplexor is used for Time-Division-Multiplexing (TDM). One channel of the multiplexor is connected to an adjustable DC signal used for timing reference, which is referred to as the frame marker [4]. We examined several synchronization and demultiplexing algorithms including autocorrelation, step detection, and threshold detection. Threshold checking is the most straightforward method, which requires that the frame marker be much larger than spikes in other channels and has proven to be the most reliable without onerous computational requirements.

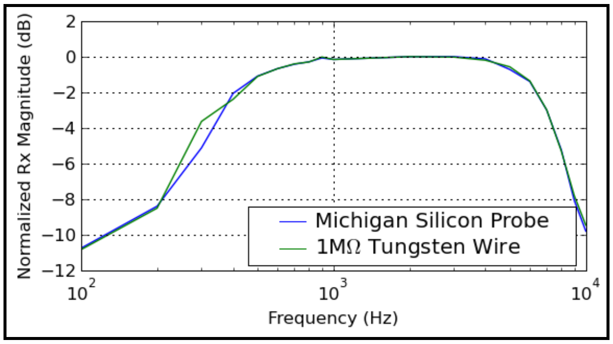

Fig. 4: Frequency response of the FMTv2 for a micro-machined Michigan probe and a 1MΩ tungsten wire probe measured in saline.

An MSP430F20xx (Texas Instruments) micro-controller controls the multiplexor timing and channel selection. The embedded code was carefully written to ensure equal sampling times for all channels and by loading different firmware images we are able to multiplex between any 7 (or fewer) of the 15 available channels or all 15 channels plus the frame marker.

In order to achieve a per channel sampling rate of 22kS/s, the multiplexor is clocked at 352kHz. Higher sampling rates are supported, but increase power consumption

3) *Frequency Modulation*

The primary design criteria for the radio section were simplicity, robustness and low power performance. The output of the multiplexor is buffered by a high speed amplifier (AD8541) to preserve the transitions between channels when driving the VCO's varactor. A small amount of gain or attenuation can be applied to ensure the signal remains in the linear region of the VCO. A potentiometer (R7 in Fig. 2) is used to adjust the DC bias of the VCO input signal and allows us to tune the transmitter to avoid large interfering signals. The MAX2608 VCO (Maxim ICs)

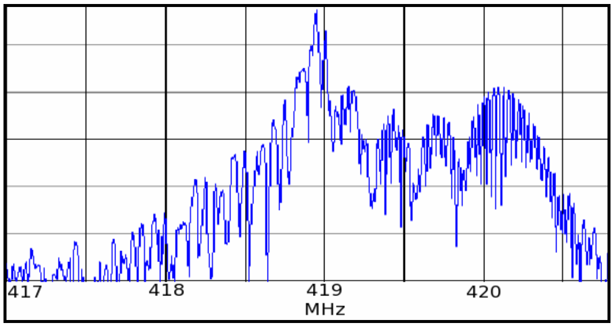

Fig. 5: Spectrum of received signal from FMTv2, captured through our FMTDAQ software.

operates between 300 and 500MHz and we transmit around 390MHz. This VCO has been previously used for a single channel wireless recording device [5]. The VCO IC includes a buffered output and for ranges up to 3m a separate power amplifier is not required. A single wire whip antenna is used, with a length of 4". Shorter antennas reduce the usable range.

4) Bandwidth Requirements

In order to avoid inter-symbol interference in the analog multiplexed signal, it is necessary to maintain sufficient bandwidth in 1) the buffer driving the VCO, 2) VCO response and 3) receiver radio. In the worst case, the multiplexed channel (carrying the neural signal) is a square wave with amplitude of the frame marker, which we set to be 50mV. To reconstruct the square wave, the VCO buffer's bandwidth requirement can be approximated from the Fourier Series of a square wave as:

$$F_{MAX} = 5\ F_{MUX} \tag{1}$$

where F_{MUX} is the multiplexing frequency. The required receiver bandwidth depends on the modulation coefficient f_m, which for MAX2608 tuned at 390MHz, is measured to be 14kHz/mV; the required receiver bandwidth is then:

$$F_{REQ} = f_m V_{pp} + 5\ F_{MUX} \approx 3.2\text{MHz} \tag{2}$$

where V_{PP} is twice the channel's amplitude, or 100mV. This matches the measured spectrum well, as shown in Fig. 5.

In-vitro Characterization of FMTv1 reveals the fidelity of neural channels and small cross talk of the system as shown in Fig. 6. The reported cross talk is for 8 channels of data however for 15 channels the same low cross talk was obtained. The FMTv2 lacks a solid ground plane which has led to cross talk between the preamplifier outputs and the high impedance inputs of nonconsecutive channels. This is not seen in the FMTv1.

B. Base Station and Software

1) Receiver Radio

We use the USRP from Ettus research with a TVRX daughter board for our receiver. The USRP [2] is an open architecture software radio, which connects via USB to a host computer. This setup provides us a wide bandwidth (up to 6MHz) and flexible demodulation options for future work, such as moving to gigahertz radio frequencies or bidirectional digital communication with minimal modifications to the receiver. An inexpensive, wide bandwidth whip antenna was used for data collection.

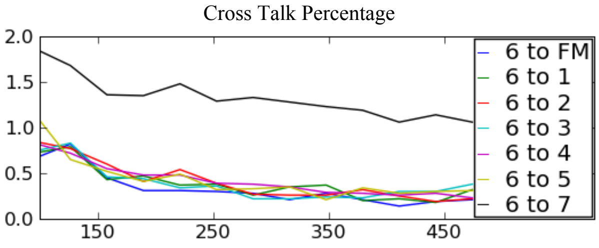

Fig. 6: Cross talk vs. channel amplitudes for FMTv1; Ch6 has the signal while the rest of channels inputs are grounded; the cross talk is less than 2% for all the channel amplitudes up to 500μVpp; the largest cross talk is on the immediate adjacent channel.

TABLE 1
SUMMARY OF DEVICE PROPERTIES

Properties	FMTv1	FMTv2
Number of Channels	15	
Channel Band Pass	.1-7kHz	
Ch. Sample Rate	22kS/s (programmable)	
Preamplifier Gain	51 V/V	
Noise Floor	25μV$_{rms}$	
Range (4" ant)	3m	
Power Consumed	10mW	
Lifetime	>24 Hrs	
Weight	10.8g	6.3g
Size	3.0x3.0x0.8cm^3	3.6x4.0x1.0 cm^3
Center Frequency	396 MHz (tunable)	

2) Receiver Data Acquisition Software

Our data acquisition software, called FMTDAQ, is based on the open source GnuRadio framework [3]. We have written a custom graphical interface and low level code for tracking and demultiplexing the received data stream. Advanced features include; RF spectrum display, audio recording via the laptop audio card, basic spike detection and real time display of spikes (Fig. 7) and the multiplexed and demultiplexed waveforms. We perform data taking with a laptop with a 2.5GHz dual core processor. We can record 4MHz of bandwidth with 16bit sampling resolution to disk and provide plots for monitoring data quality in real time.

To facilitate data taking by our collaborators, we created a disk image based on the Fedora GNU/Linux operating system with all of our DAQ software and hardware preconfigured. The image is distributable by CD or USB memory stick and most modern consumer desktops and laptops can be booted directly from the media into a fully configured data taking environment.

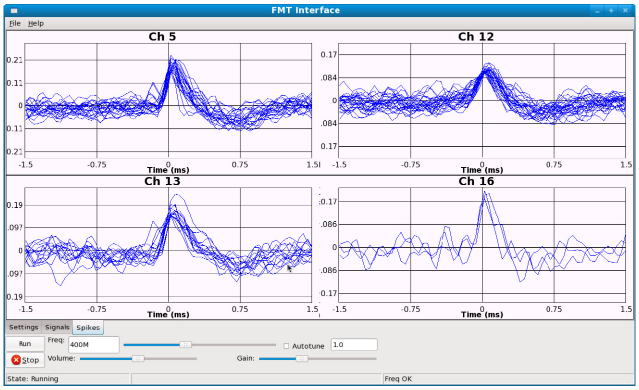

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Fig. 7: Screen shot of FMTDAQ real time spike display.

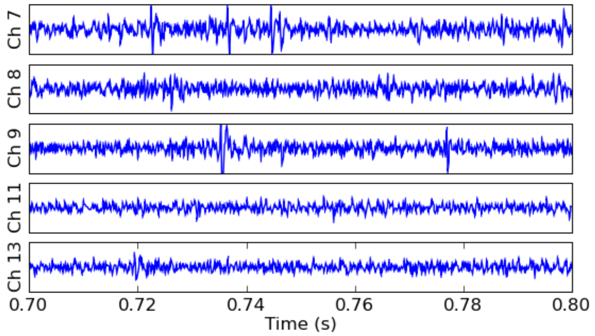

Fig. 8: Four of 15 channels recorded from a Marmoset Monkey with the FMTv2. The full scale is ±100μV.

III. IN VIVO TEST RESULTS

The FMT has been used for data taking with Long Evan's Rats, Zebra Finches, Guinea Pigs and Marmoset Monkeys. An example waveform from the FMTv2 with a Marmoset Monkey is shown in Fig. 8 and Fig. 9. One concern with analog multiplexed systems is channel leakage in forms of cross talk or inter-symbol interference (ISI); there are two main sources for crosstalk: 1) insufficient bandwidth that causes the signal to fail to settle when demodulating large channel counts multiplexed in time,. 2) capacitive coupling between channels in the front end; this type of error is often attributed to layout problems.

The input referred noise of the neural transmitter channels is below 25uV$_{rms}$ which is measured after demodulating and demultiplexing the received RF signal, as shown in Fig. 10. The channel noise stays well below 25μVrms for up to 3m which is a practical range for neuroscience experiments on small unrestrained animals. We also demonstrated signal fidelity at various angles needed in experiments involving unrestrained animals in Fig. 11.

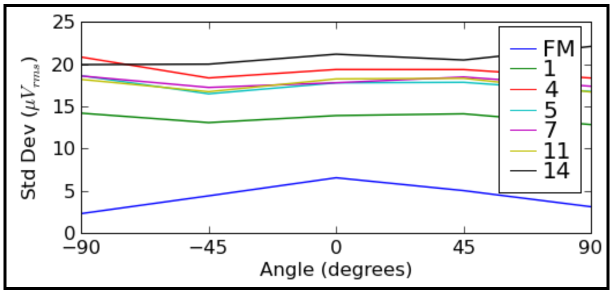

Fig. 10: Input referred noise does not significantly increase up to 3m. The FM channel indicates noise due to the communication channel plotted as an effective input referred noise. Recorded in the RF/EMI shielded anechoic chamber at The Johns Hopkins University.

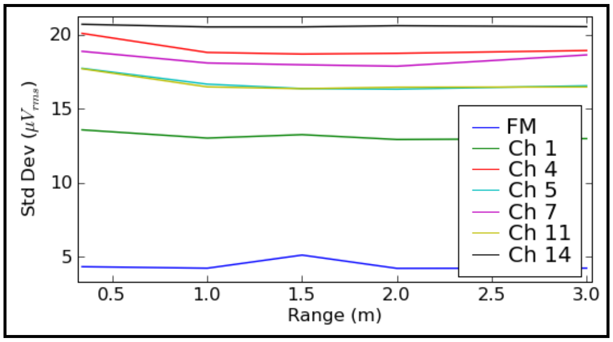

Fig. 11: Angle dependency measured at 1m. Recorded in the RF/EMI shielded anechoic chamber at The Johns Hopkins University.

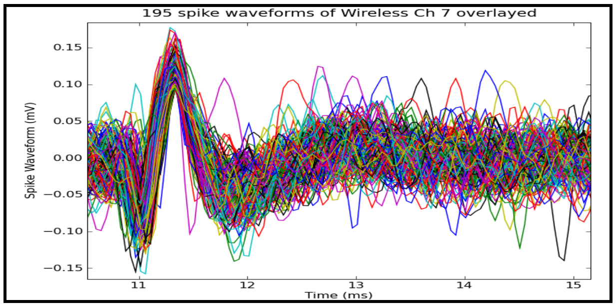

Fig. 9: Overlay of spikes on channel 7 from Marmoset monkey collected with FMTv2. Spikes were found using simple threshold detection.

IV. CONCLUSION

A low cost, multichannel, wireless neural recording transmitter along with the hardware and software for recovering individual channels is designed and developed using merely commercial off the shelf components. The system works reliably for a range of 3m at any angle, operates up to 24 hrs and weighs 6.3g. The size of the transmitter system can be substantially reduced by integrating the front-end and VCO components, which is currently being implemented.

Expensive Commercial software packages tied to particular hardware is an impediment to widespread use of new technologies and we will continue to develop our software package to allow free and easy access. We are currently working to incorporate additional data channels, bidirectional communication, and stimulation into the system. This will not only widen the scope of applications of this particular system but also enable additional behavioral neuroscience experiments previously impossible.

ACKNOWLEDGMENT

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