Lightweight wireless headstages for small and large animal electrophysiology research

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ABSTRACT

Wireless electrophysiology has a power consumption problem. The simultaneous transmission of high-fidelity single-unit signals and injection of electrical stimulation pulses creates a tradeoff concern with battery weight and battery life. The typical solution is to increase battery capacity, but the added weight is often prohibitive for small animal models. Novel lightweight, low-power wireless solutions would allow researchers to conduct more complex awake behaving experiments in a wide variety of animal models, better informing our understanding of the nervous system.

Spike Neuro and the Wireless Electrophysiology laboratory at Duke University, Department of Electrical and Computer Engineering, are developing two new wireless solutions for real-time neural recording and electrical stimulation. With small animal models in mind, we developed ultralightweight Bluetooth solutions that provide 4 channels of recording only and 8 channels of recording + stimulation. We have demonstrated transmission of simulated signals over 12 ft while meeting power consumption goals and maintaining a low bit error rate. This provides an excellent lightweight solution for small animal researchers; however, these features do not scale to higher channel counts.

For higher channel counts in larger animal models (including rats), we have developed a novel low power hybrid wireless radio system. Our hybrid radio leverages backscatter modulation technology, utilizing an incident radio frequency (RF) signal to transmit high data rates, reducing the need for larger batteries. This technique uses passive reflection and digital modulation of the incoming RF signal that is digitally encoded for data communications. The active components are contained in a base-station (receiver) with only a passive chip antenna in the headstage, further reducing weight and current consumption. This system provides up to 16 channels of single unit recording and 2 channel of +/-1mA constant current biphasic electrical stimulation (up to +/-5V) while weighing < 8 g and requiring only 9 mA. We have demonstrated binary backscatter modulation and demodulation using a constant RF transmitter and demodulation receiver components.

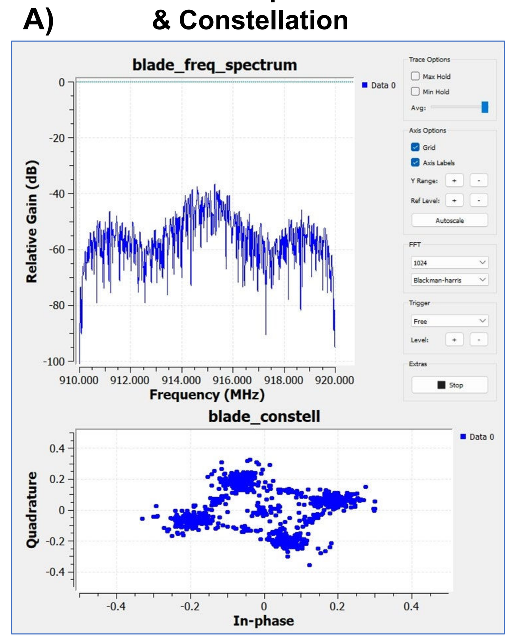
This novel wireless technology provides useful solutions for studying the neural basis of natural behaviors across a wide range of animal models. In our upcoming work we will add integrated electrical stimulation and test these devices *in vivo* demonstrating performance previously limited to wired research setups.

BACKSCATTER OVERVIEW

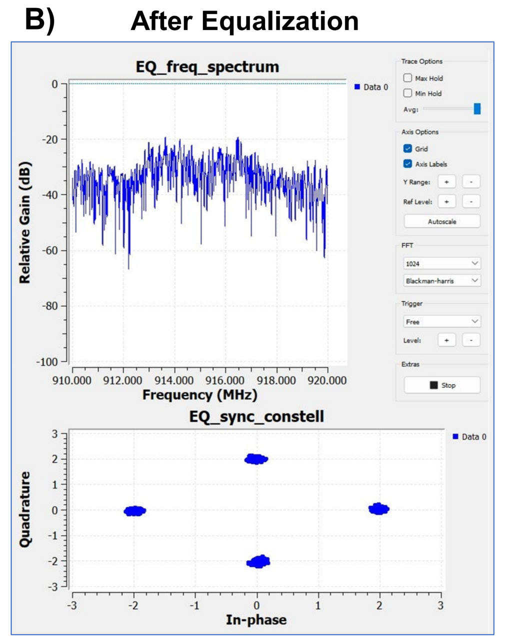
- Backscatter technology utilizes a base station to transmit unmodulated carrier signals and receive the reflected (backscatter) modulated carrier signal from the headstage.
- The headstage passively reflects and modulates the carrier signal enabling data transmission back to the base station.
- The carrier signal modulation is encoded to the neural recording through Quadrature Phase-Shift Keying (QPSK).
- At the base station receiver, the incoming signal is demodulated by comparing the phase of the received signal to reference phase states. The receiver then maps these phases back to the original bit pairs to recreate the neural signal.
- The main advantage of backscattering is its low energy requirements on the worn headstage while maintaining high data rates, bandwidth efficiency, and resilience to noise.

RECEIVED QUADRATURE PHASE-SHIFT KEYING (QPSK) OF OVER-AIR SAMPLE DATA

A) Received Spectrum & Constellation



B) After Equalization



C) After Equalization & Costa Loop

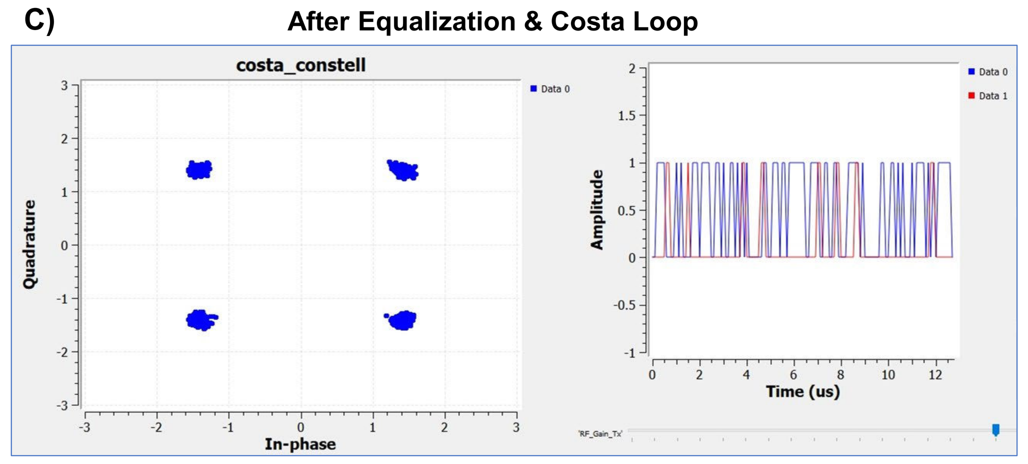
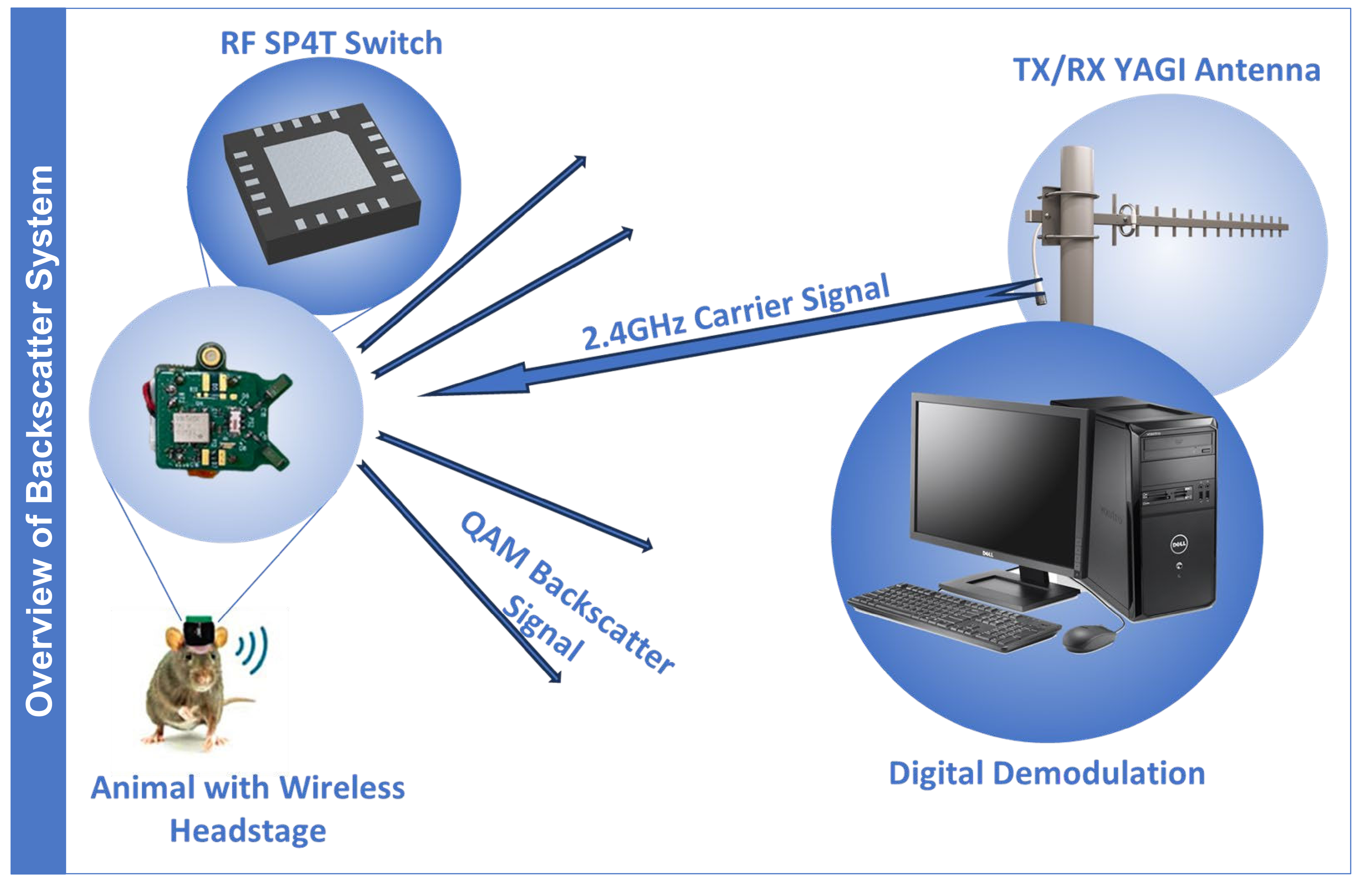


Figure A) Frequency spectrum and constellation of a received QPSK-modulated random bitstream transmitted over the air at 1m. The constellation shows channel impairments and inter-symbol interference.

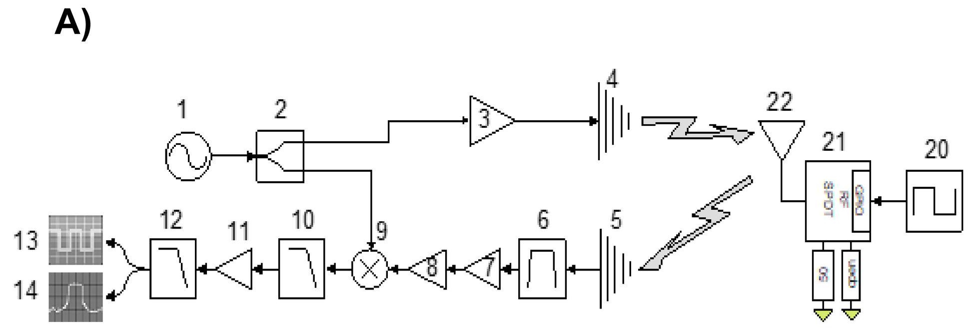
Figure B) After applying clock synchronization and a equalizer algorithm, the QPSK constellation can be recovered.

Figure C) Using a Costa Loop algorithm to lock to the carrier frequency and phase, the orientation of the QPSK constellation can be corrected, and a QPSK demodulator can be applied to recover the random bitsream.

LARGE ANIMAL SYSTEM



A)



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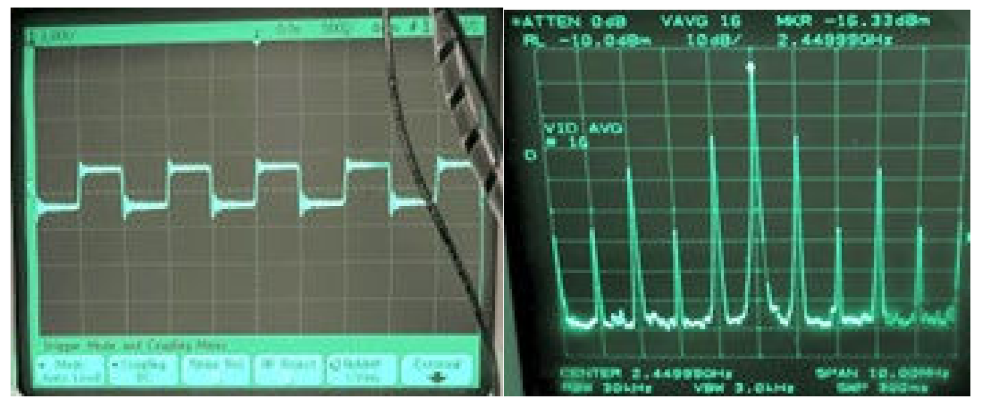

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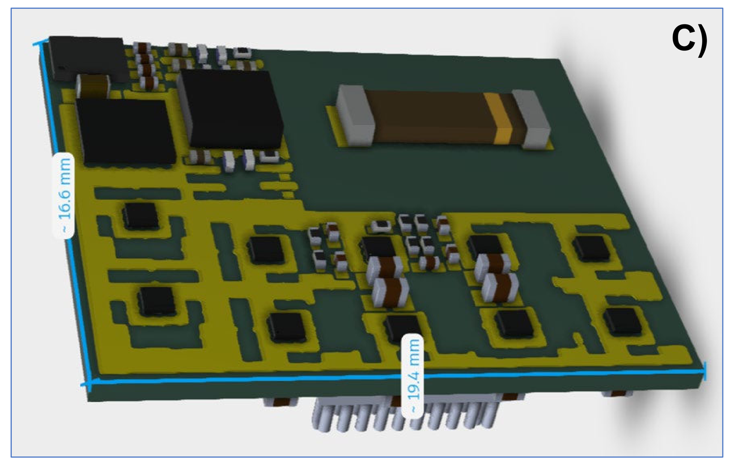


D)

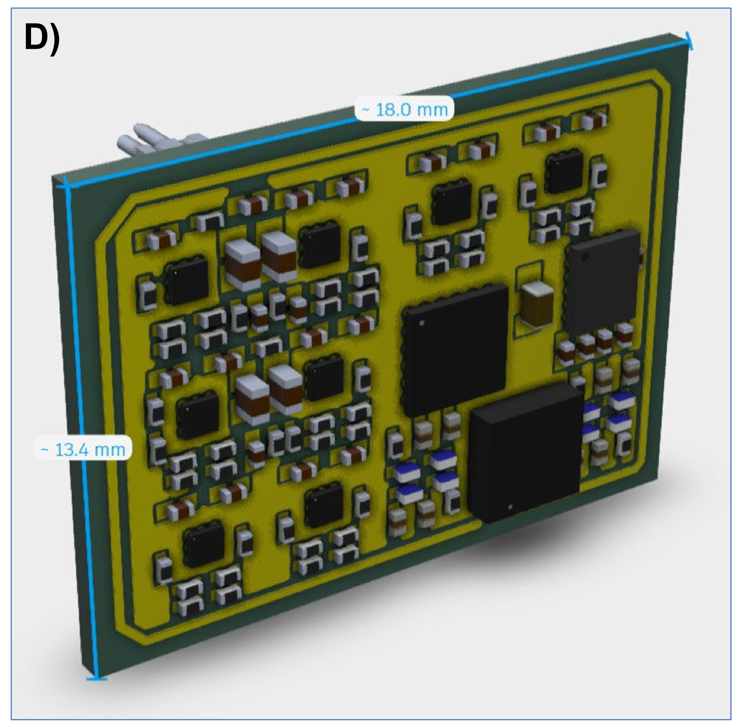


Figure A) Simplified backscatter system test demonstration using 1 MHz square wave and Binary Phase-Shift Keying (BPSK): block diagram, received BPSK-demodulated time-series signal and frequency spectrum.

Figure B) Backscatter test setup: two Yagi antennas for transmitting CW signal and receiving backscattered signal; one target bd approximately 2m away, with chip antenna and binary-switched impedance to create a BPSK-modulated backscatter signal..

Figure C) 3d model of a proposed 16-channel backscatter headstage pcb with chip antenna

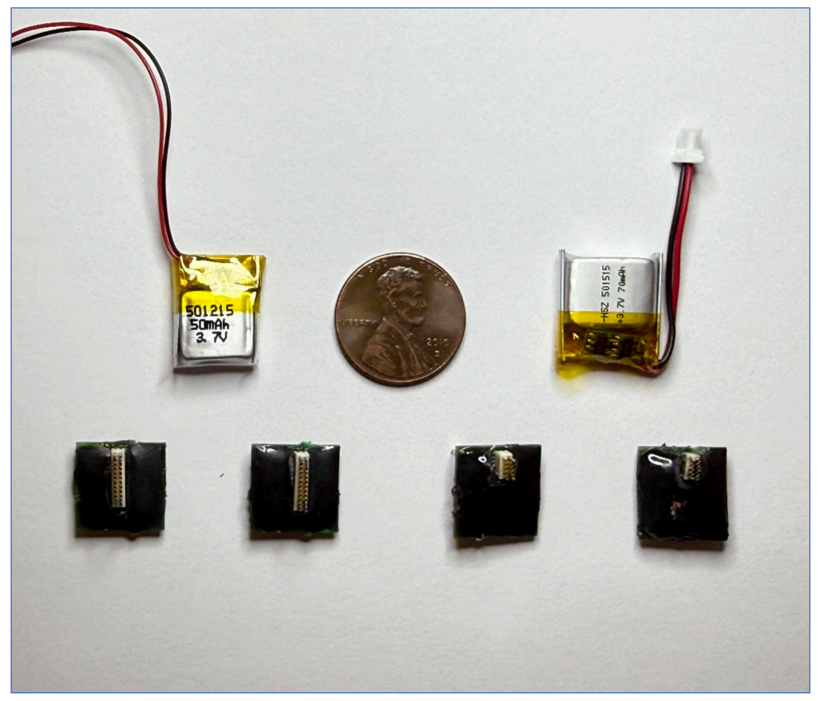
Figure D) 3d model of a proposed 16-channel backscatter headstage pcb with edge loop antenna

PROTOTYPE SPECIFICATIONS

	Large Animal System	Small Animal System
Weight (including battery)	< 10.0 grams	Recording only: < 3.3 grams Recording and Stimulating: < 3.8 grams
Channel count	16 channel recording, 2 channel stimulating	Recording only: 4 channels Recording and Stimulating: 8 channels
Sampling rate (per channel)	30 kSps	30 kSps
Battery life (40mAh)	> 6 hours	> 6 hours
Protocol	Backscatter modulation	Bluetooth®
Software	Open Ephys	Open Ephys
Connector interface	Omnetics, Molex	Omnetics, Molex

SMALL ANIMAL SYSTEM

A)



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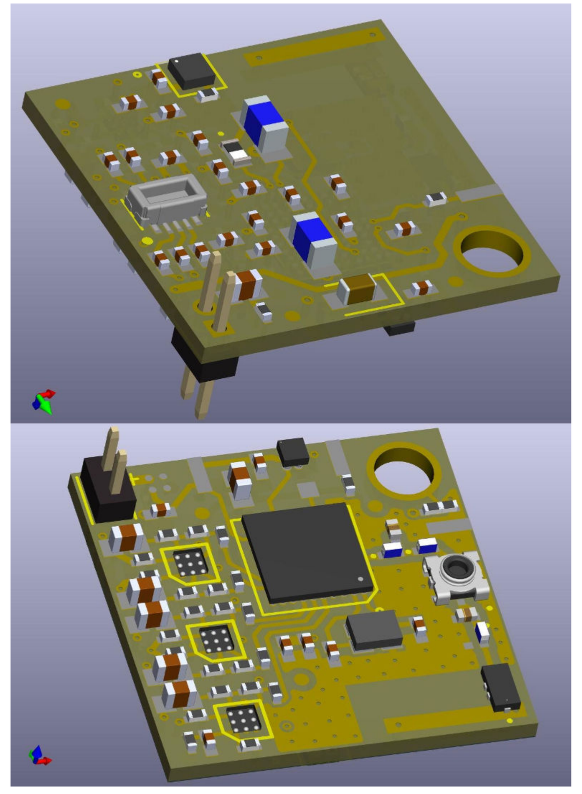


Figure A) Small headstages, comparing different lithium-polymer battery sizes and capacities

Figure B) Small Bluetooth 4-channel spike recording headstage on 0.5" x 0.5" pcb

BLUETOOTH HEADSTAGE TEST SETUP AND DATA

C)

Figure C) Test setup for Bluetooth headstage testing: 2 ft. range vs position vs lost packet rate

D)

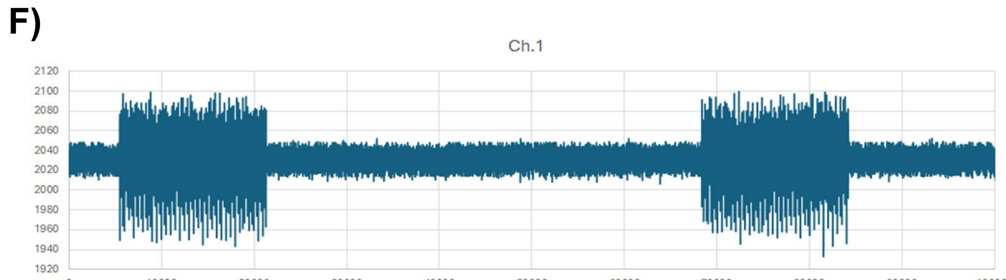
Figure D) Bluetooth USB transceiver with dual antennas, provides spatial diversity to minimize signal dropout and RF packet loss

E)

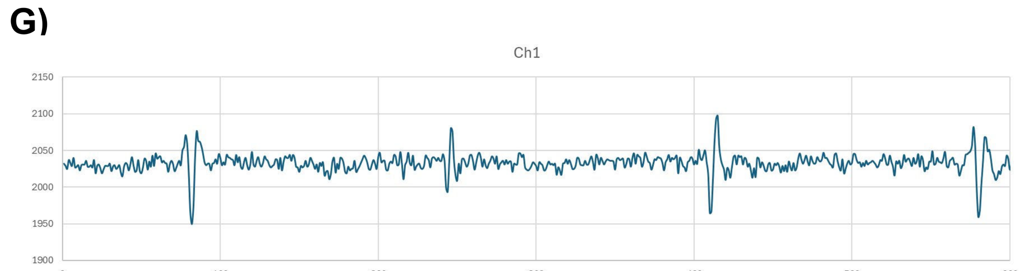
Dual-antenna Bluetooth USB transceiver dongle	two ant vertical & parallel	two ant vertical & parallel	two ant vertical & parallel	two ant 120 deg	two ant 120 deg	two ant 120 deg
TX Power(dBm)	0	0	0	0	0	0
Sample Interval (us)	15	15	15	15	15	15
SSADC_BUF_SIZE	156	156	156	156	156	156
ATT Payload Size (<=244byte)	244	244	244	244	244	244
Sample Bytes#/Payload	234	234	234	234	234	234
Connection Interval(ms)	10	10	10	10	10	10
Sample Rate(kSps)	67	67	67	67	67	67
Data Throughput(kbps)	800	800	800	800	800	800
No. of lost packets	45	53	70	70	60	58
No. of received packets	25455	25450	25467	25479	25483	25491
Total no. of packets	25500	25503	25537	25549	25543	25549
Lost Percent(%)	0.18	0.21	0.27	0.27	0.23	0.23

Figure E) Lost packets vs test parameters, data streaming from headstage to Bluetooth USB transceiver with 800 kbps data throughput and transceiver antenna positions

F)



G)



Figures F & G) Captured over-the-air simulated neural data input (mp3) into Bluetooth headstage and USB Bluetooth transceiver & PC as output. Sampled at 16kSps. (Zoomed in, Fig G)

Not pictured: Noise performance testing of Bluetooth microcontroller internal ADC, using a 1.5V battery: Noise ~ +/-3mV avg.

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