CENTER *for* NEUROTECHNOLOGY

a National Science Foundation Engineering Research Center

A 6.25 Mbps, 12.4 pJ/bit DQPSK* Backscatter Wireless Uplink for the NeuroDisc Brain-Computer Interface

***Differential Quadrature Phase-Shift Keying**

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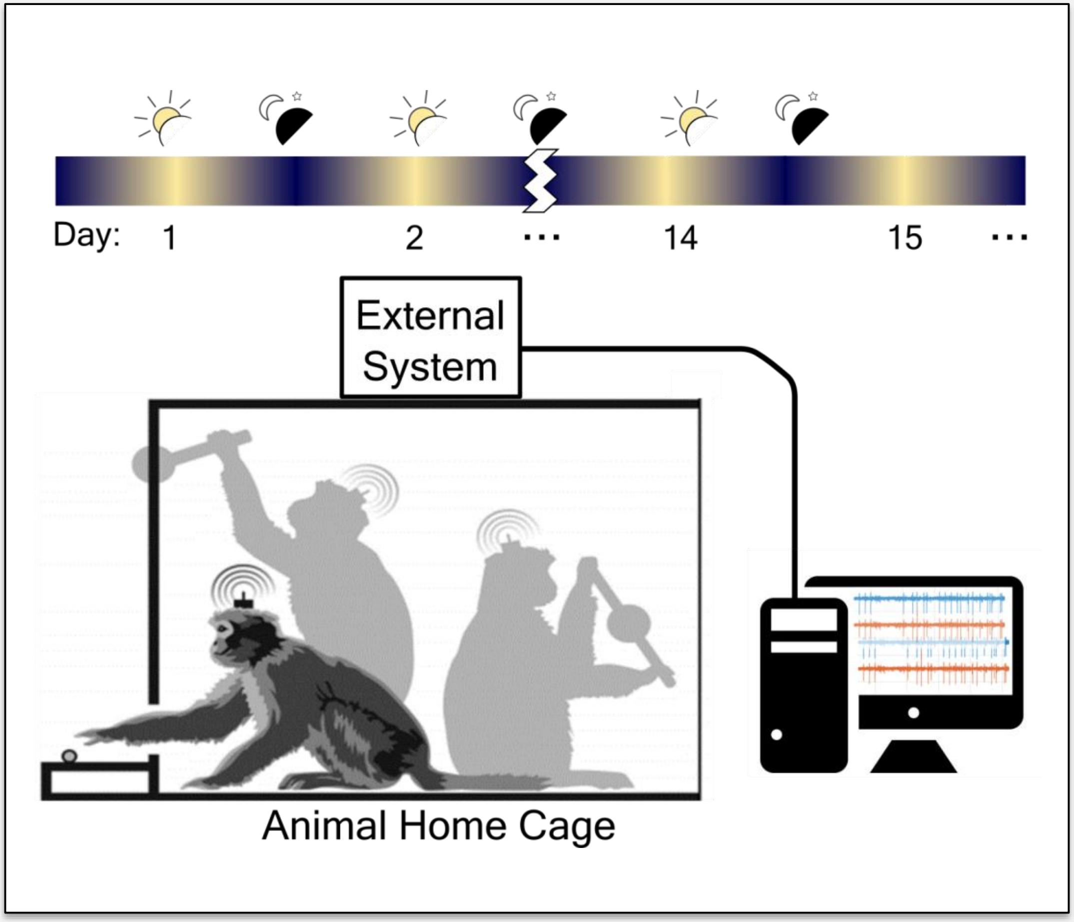
Outline

1. Motivation & Background
2. NeuroDisc Design
3. *In Vitro* and *In Vivo* Results
4. Conclusions & Future Work

Science Motivation



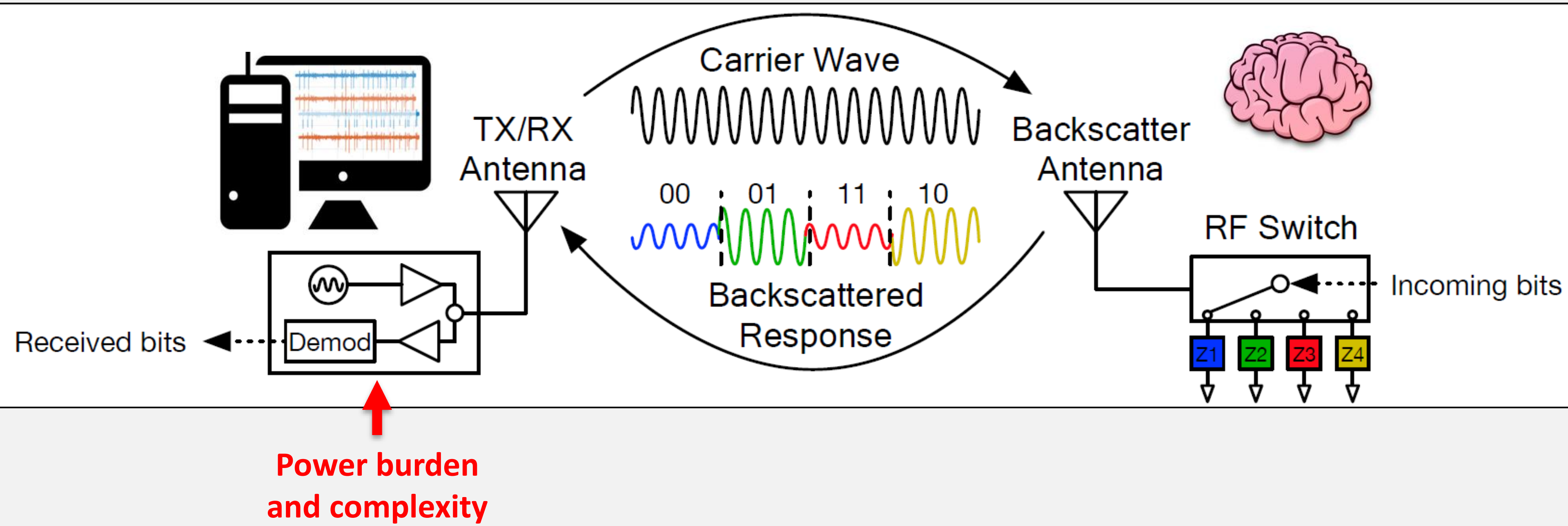
Objective

Uplink raw neural samples* from a **freely moving non-human primate** (NHP) with **minimal impact to the power budget**

*Researchers require both low- and high-frequency signals

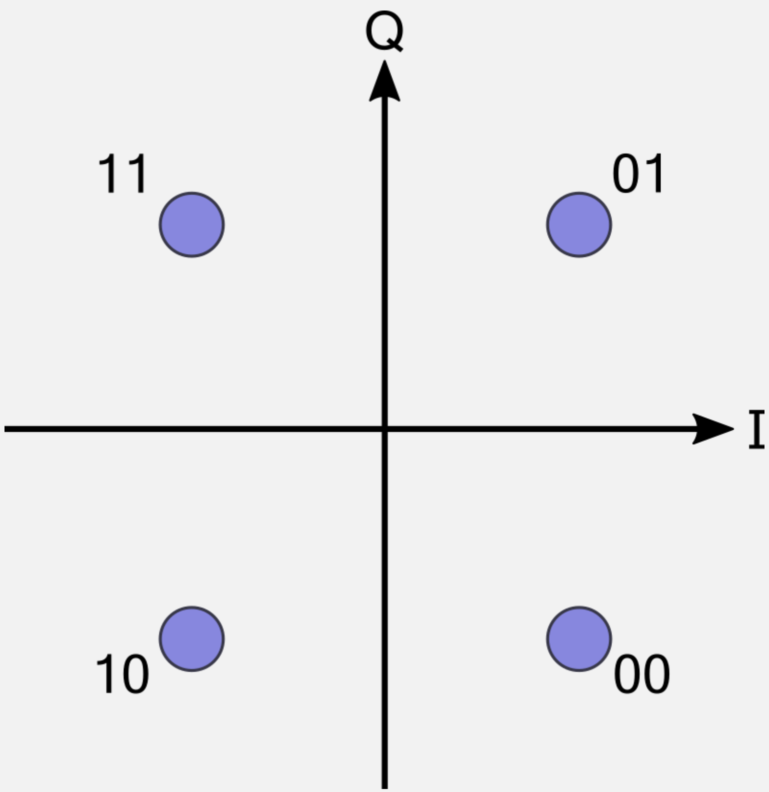
Backscatter Communication

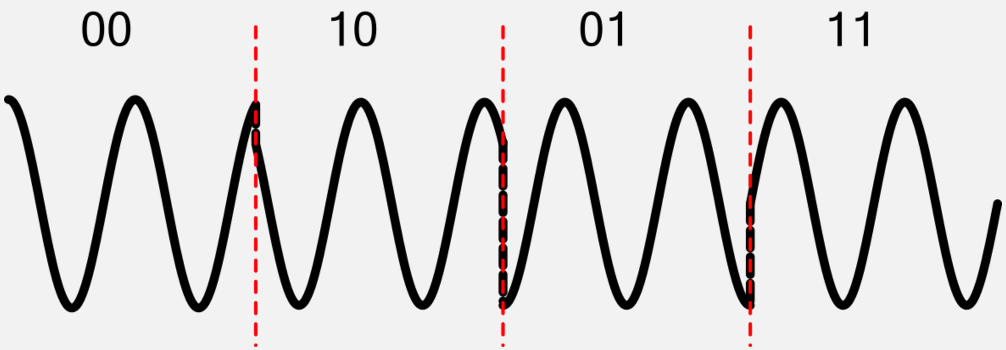
External system **NeuroDisc**



Backscatter achieves Mbps data rates at pJ/bit energy consumption

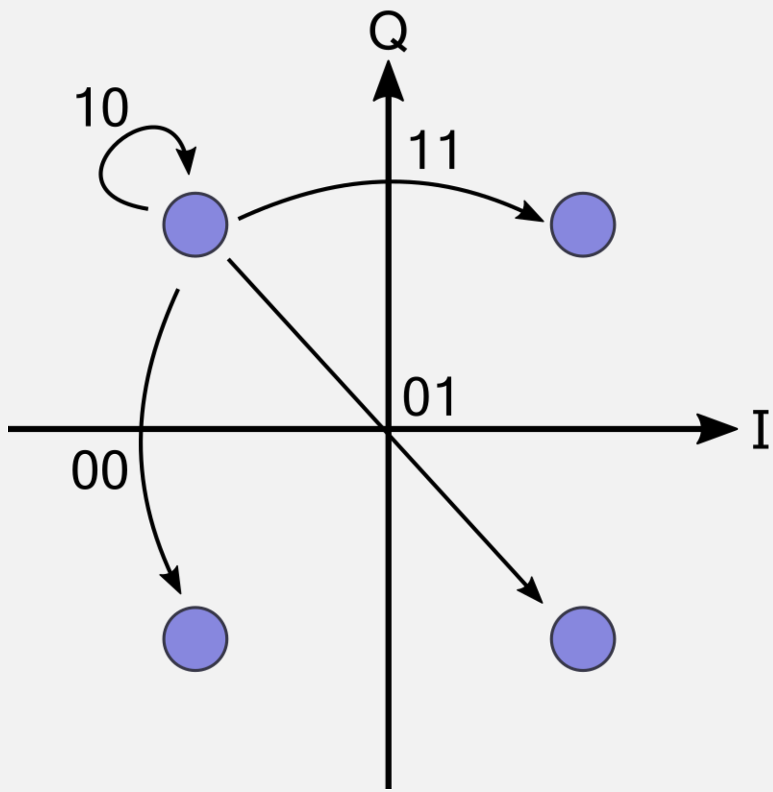
Quadrature Phase-Shift Keying

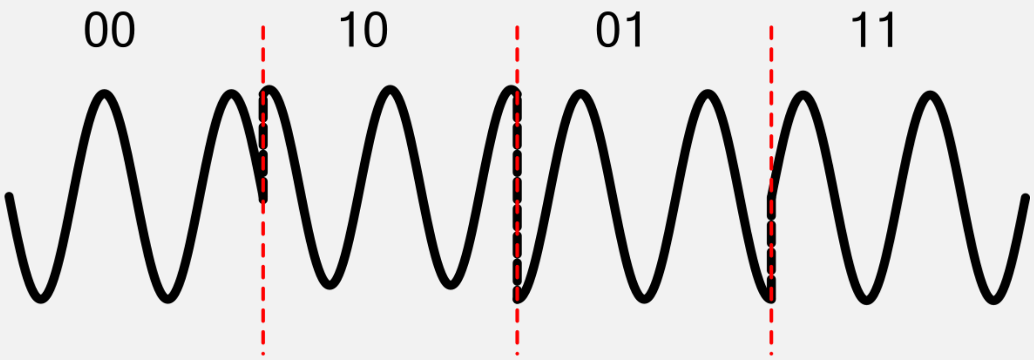




QPSK modulation encodes 2 bits per symbol

DQPSK



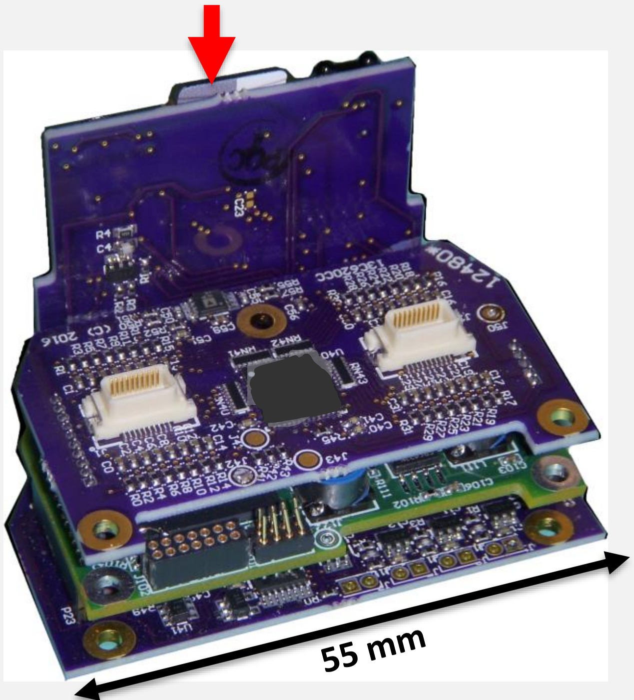


DQPSK modulation alleviates RX phase synchronization requirements

Collecting Neural Samples

NeuroDisc offers an energy efficient to alternative to conventional uplink methods

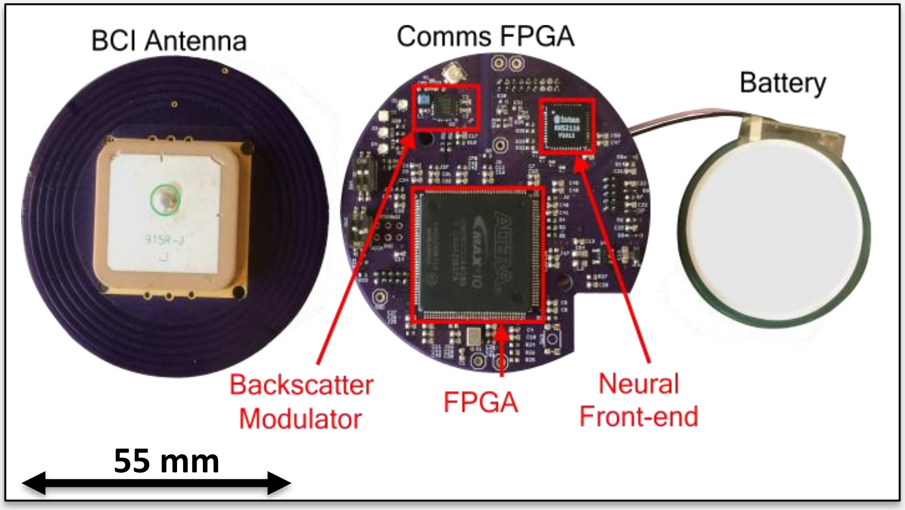
SD card: 1.24 nJ/bit at 80 Mbps



NeuroChip-3

S. Zanos et al., "The Neurochip-2: an autonomous head-fixed computer for recording and stimulating in freely behaving monkeys," IEEE Trans. Neural Syst. Rehabil. Eng., vol. 19, no. 4, pp. 427–435, 2011.

NeuroDisc (DQPSK Backscatter): 12.4 pJ/bit at 6.25 Mbps



NeuroDisc

Collecting Neural Samples

NeuroDisc offers an energy efficient to alternative to conventional uplink methods

NeuroDisc (DQPSK Backscatter): 12.4 pJ/bit at 6.25 Mbps

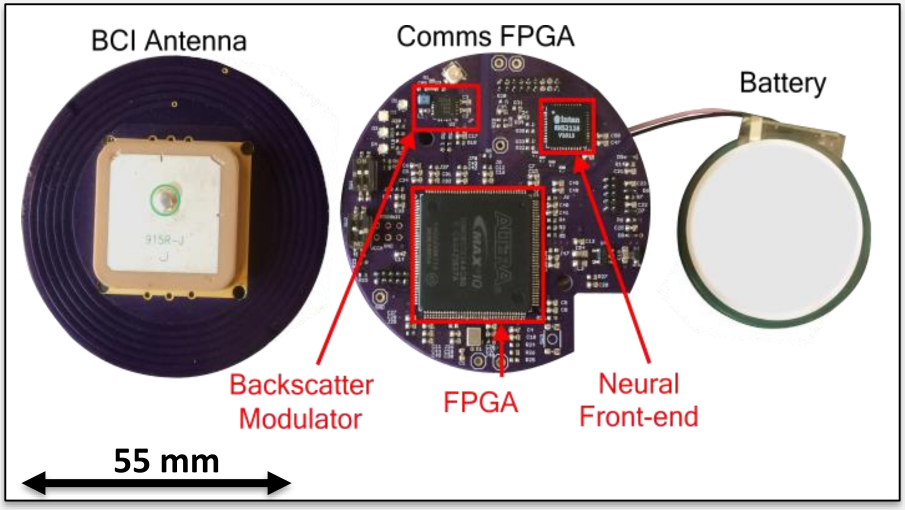
IEEE 802.11n Wi-Fi: 8 nJ/bit at 100 Mbps
Bluetooth Low Energy (BLE): 10 nJ/bit at 1 Mbps
UWB [Neuron 2014]: ~180 nJ/bit at 200 Mbps

WL1807MOD WiFi

TI.com

nRF24L01+ BLE

Sparkfun.com



NeuroDisc

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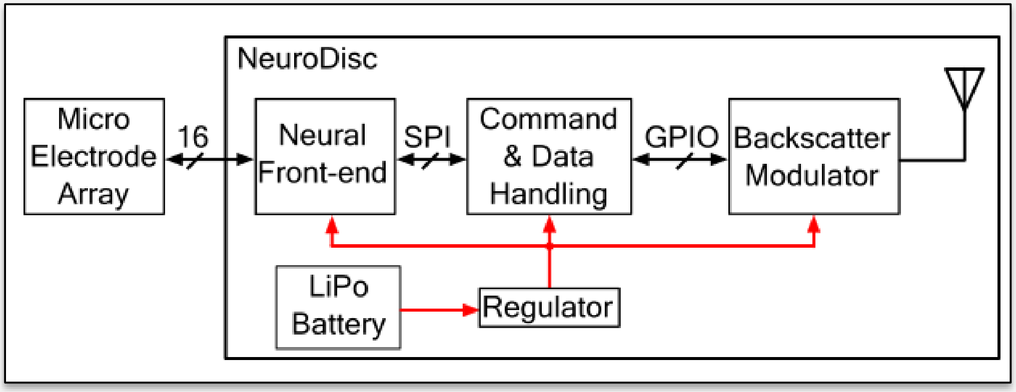
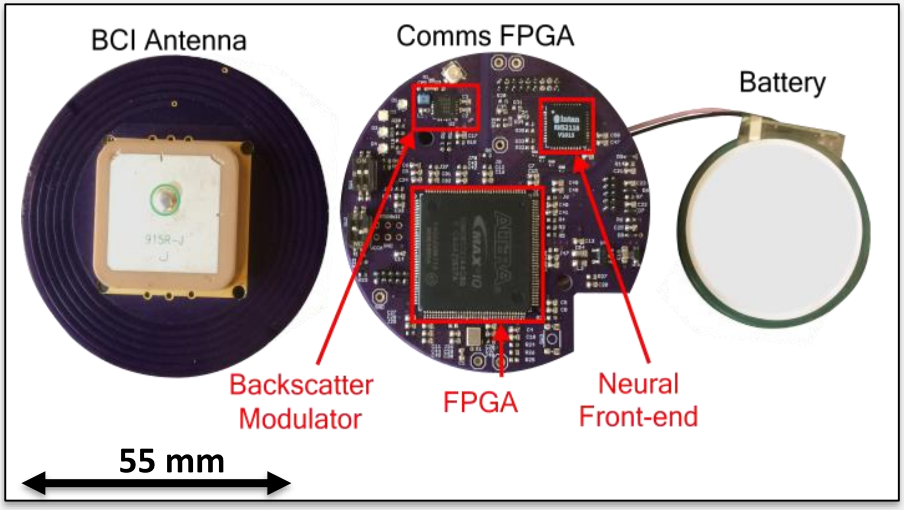
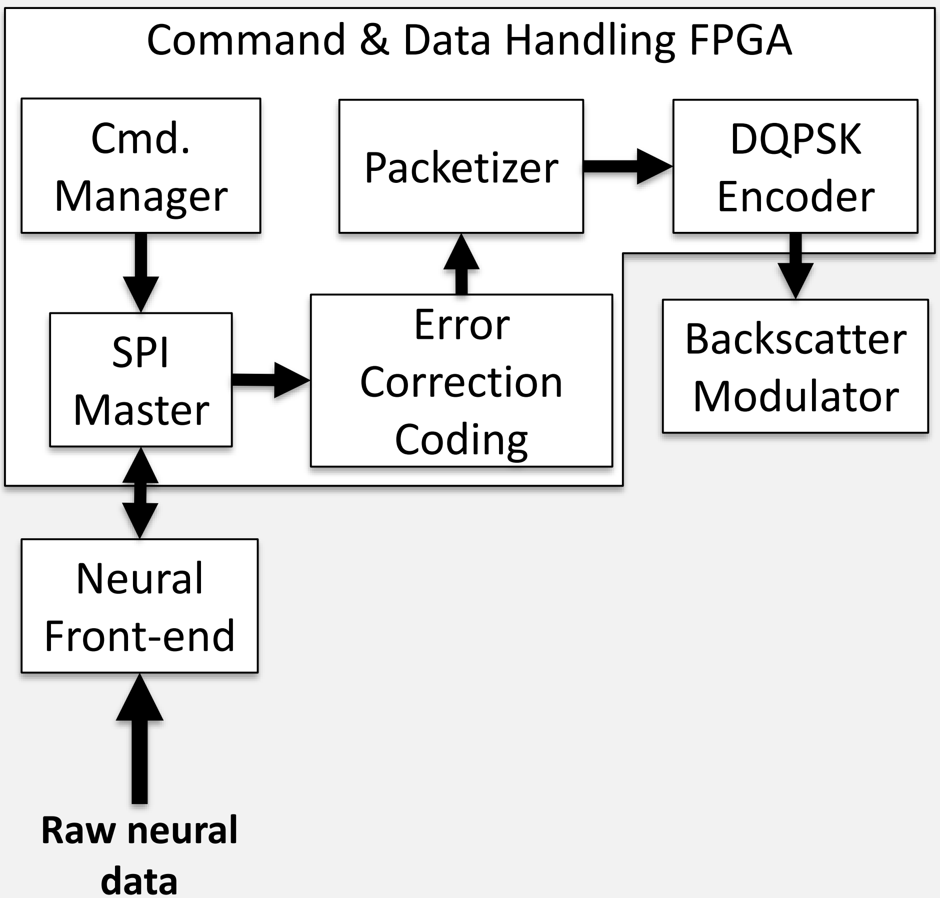
NeuroDisc System Overview



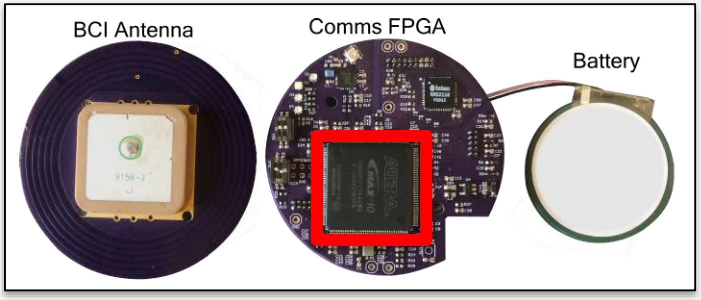


Complete system could be integrated onto a single chip

NeuroDisc

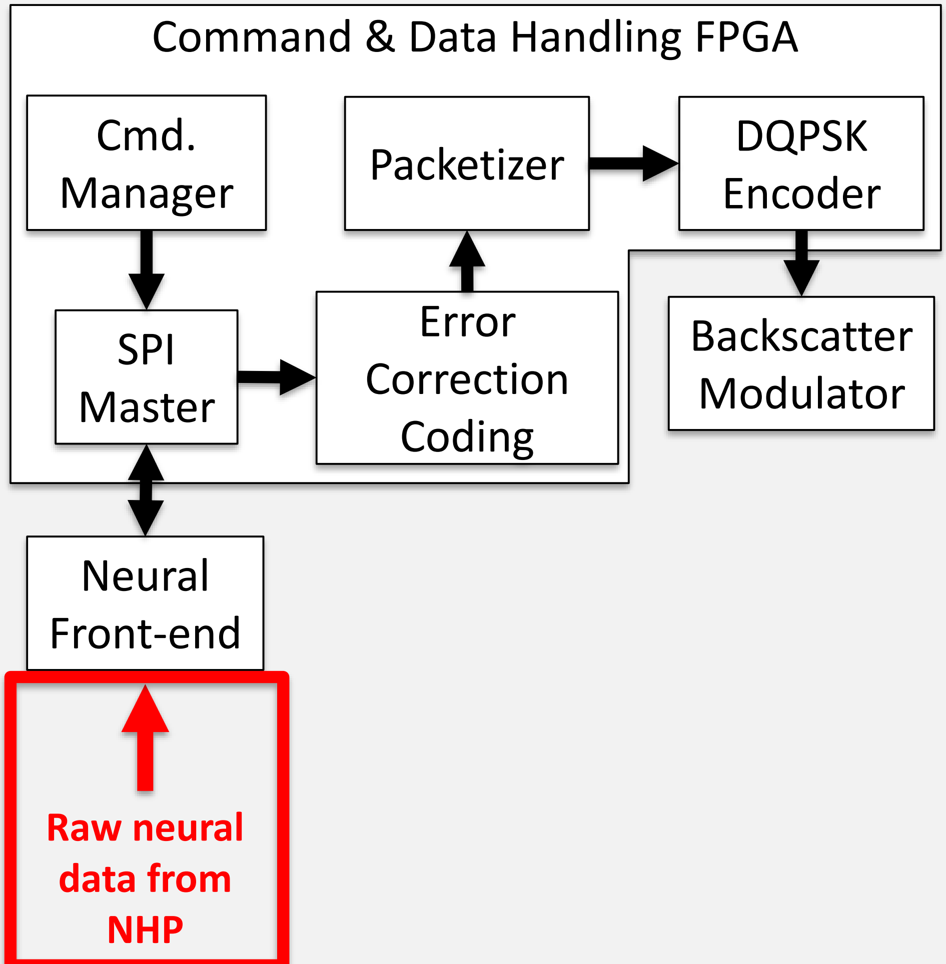


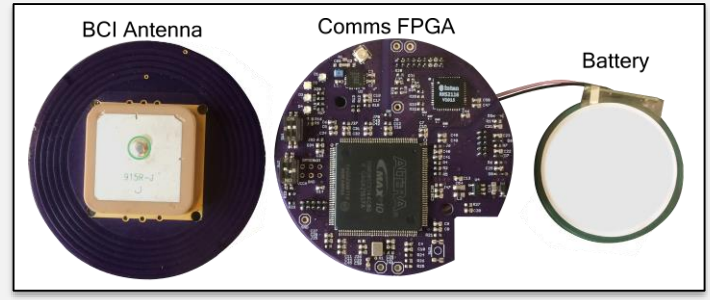
Command & Data Handling FPGA
Cmd. Manager
Packetizer
DQPSK Encoder
SPI Master
Error Correction Coding
Backscatter Modulator
Neural Front-end
Raw neural data

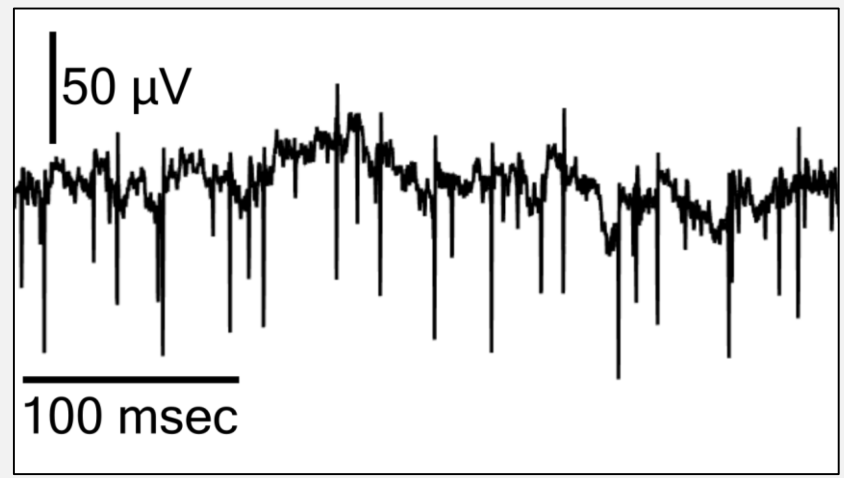


BCI Antenna
Comms FPGA
Battery

NeuroDisc

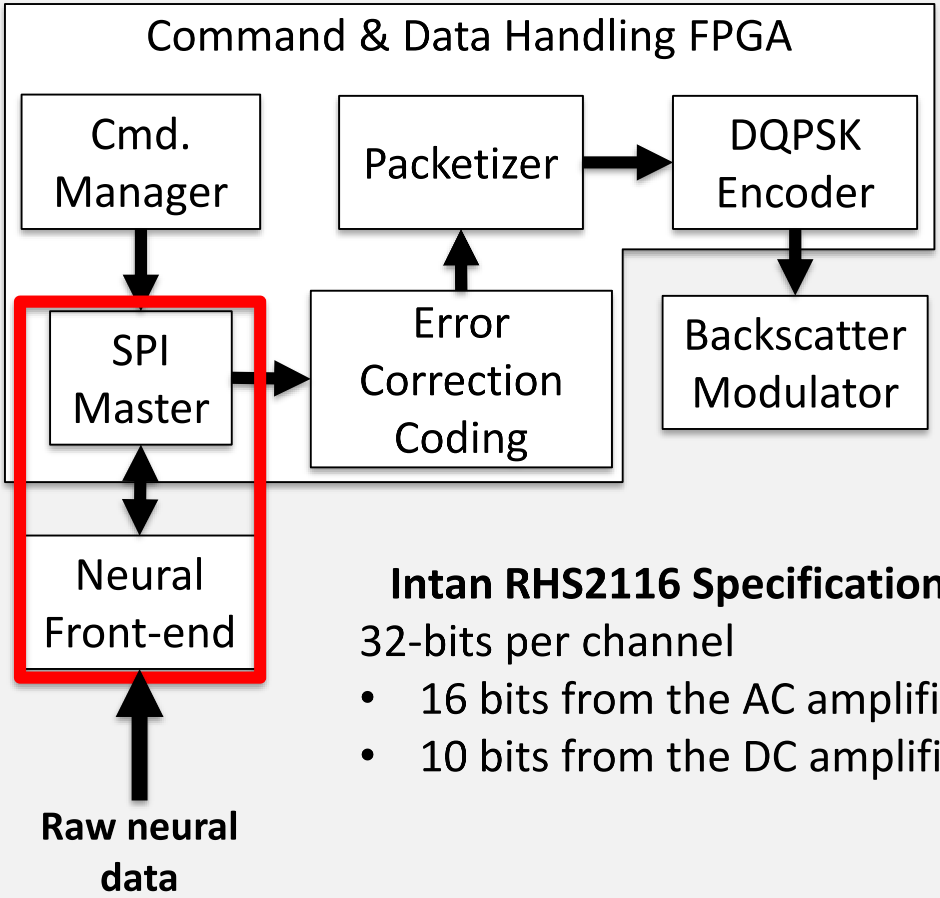






Neural front-end can capture local field potentials and neural spikes

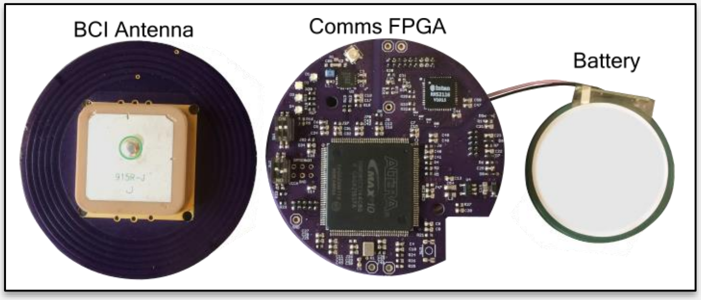
NeuroDisc

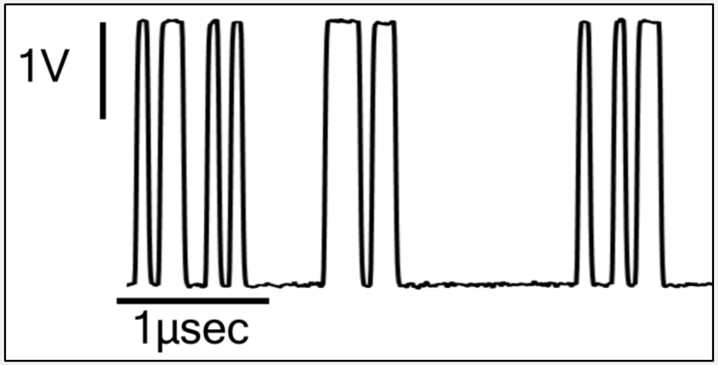


Intan RHS2116 Specifications

32-bits per channel

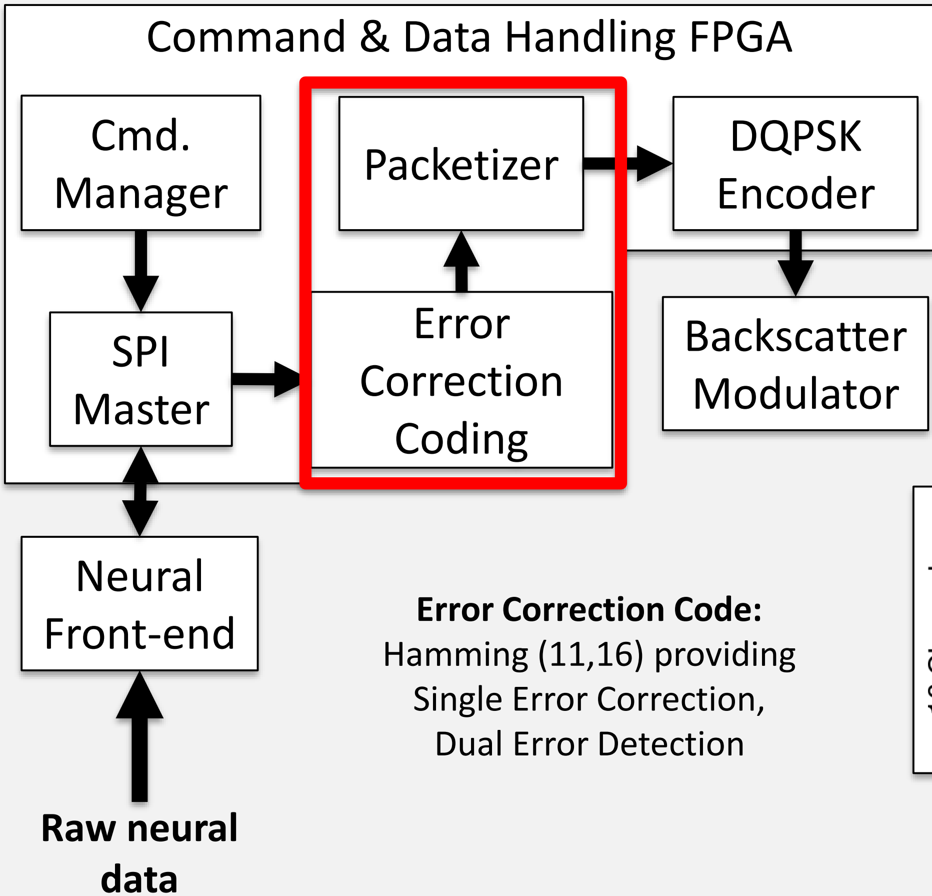
- 16 bits from the AC amplifier
- 10 bits from the DC amplifier



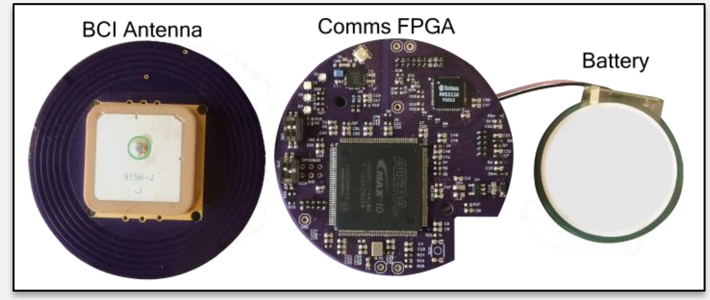


Digitized data from the neural front-end

NeuroDisc



Error Correction Code:
Hamming (11,16) providing
Single Error Correction,
Dual Error Detection

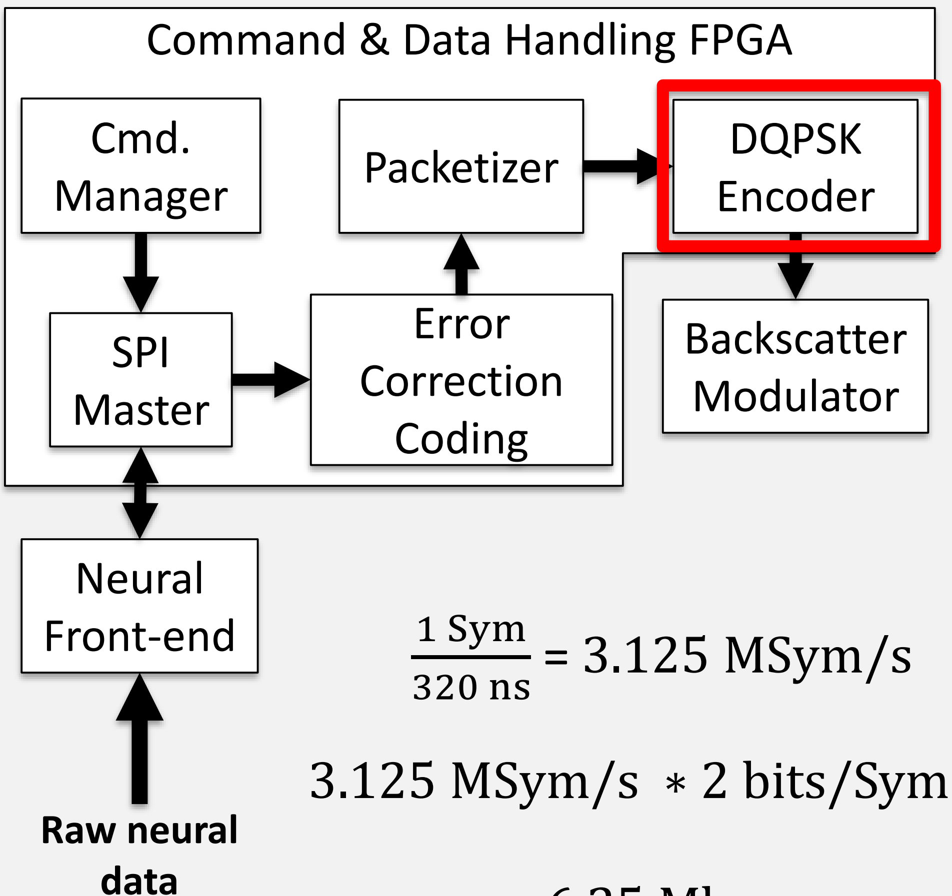


4 x 16 bits (16 Channels)

Frame Marker	CH0 (1/3)	CH0 (2/3)	CH0 (3/3)
Frame Marker	CH1 (1/3)	CH1 (2/3)	CH1 (3/3)
	⋮		
Packet Counter	CH15 (1/3)	CH15 (2/3)	CH15 (3/3)

Data is compiled into a packet with frame markers and a packet counter

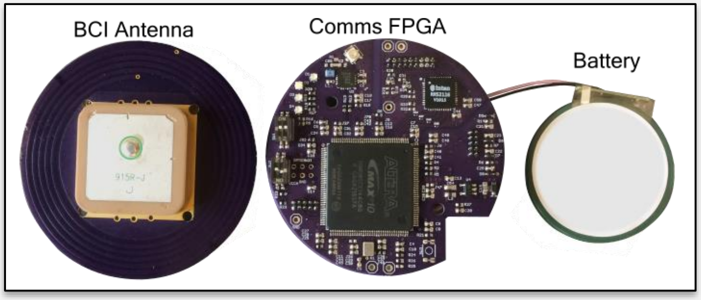
NeuroDisc BCI

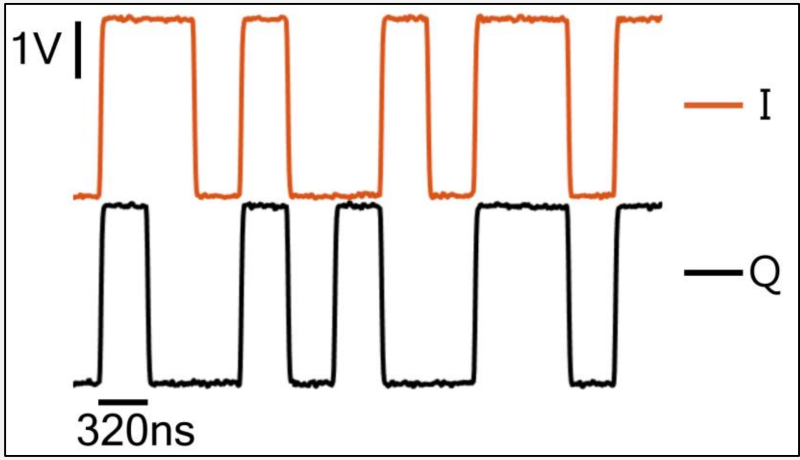


$$\frac{1\ \text{Sym}}{320\ \text{ns}} = 3.125\ \text{MSym/s}$$

$$3.125\ \text{MSym/s} * 2\ \text{bits/Sym}$$

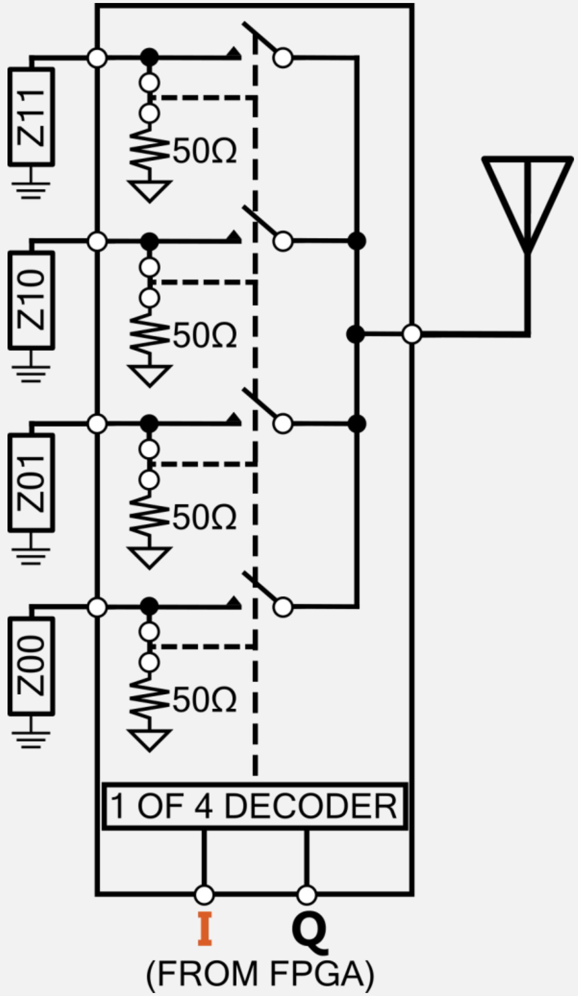
$$= 6.25\ \text{Mbps}$$



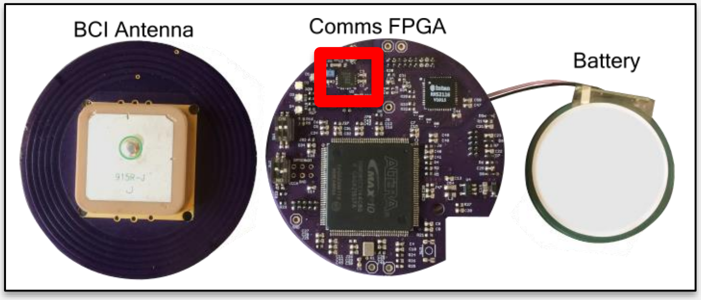


DQPSK state machine encodes the data into modulator control signals

RF Uplink: Modulator

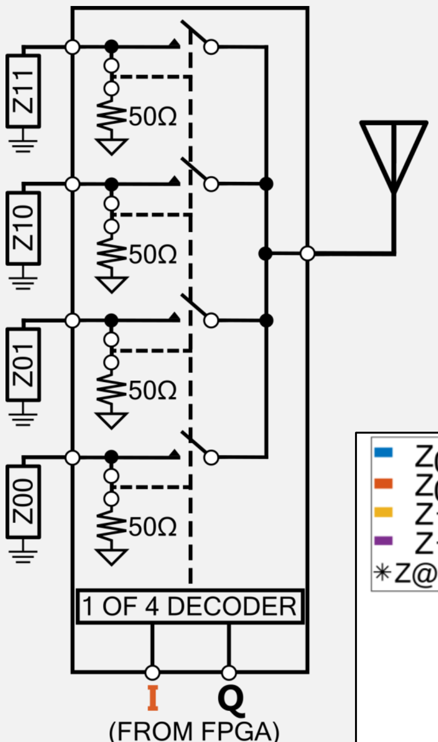


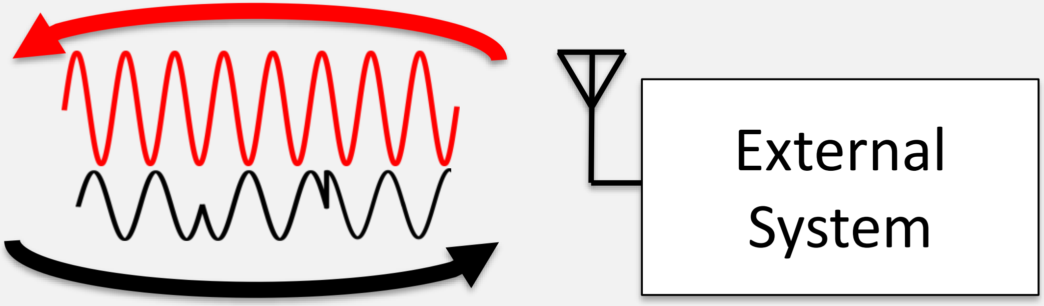
ADG904 RF switch using discrete components to implement a DQPSK constellation

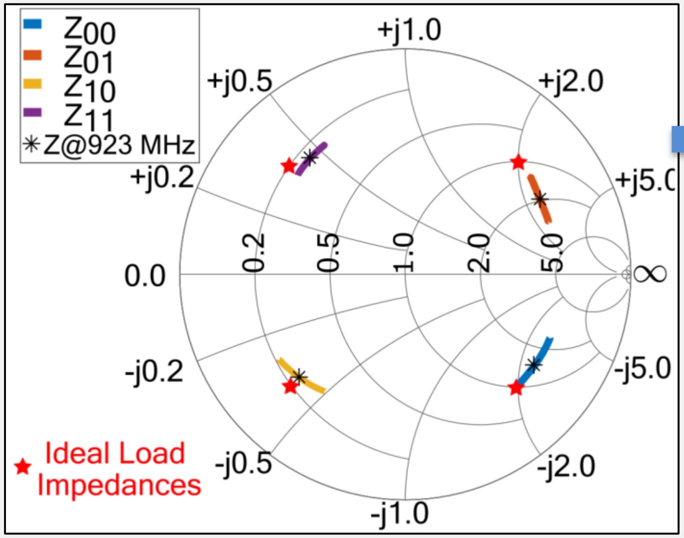


GPIO control signals actuate the RF switch while consuming only 78 µW (23 µA @ 3.3V)

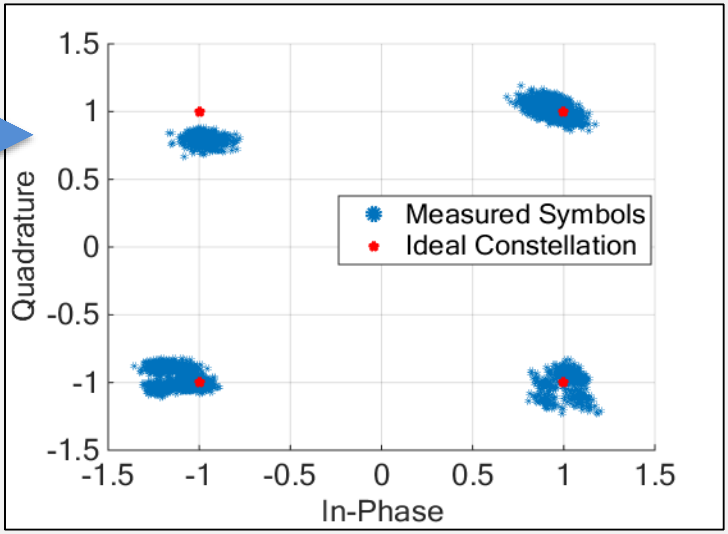
RF Uplink: Modulator







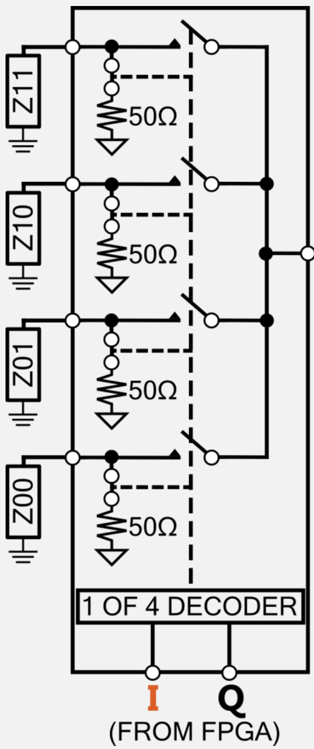
Measurement of the RF switch states on the NeuroDisc



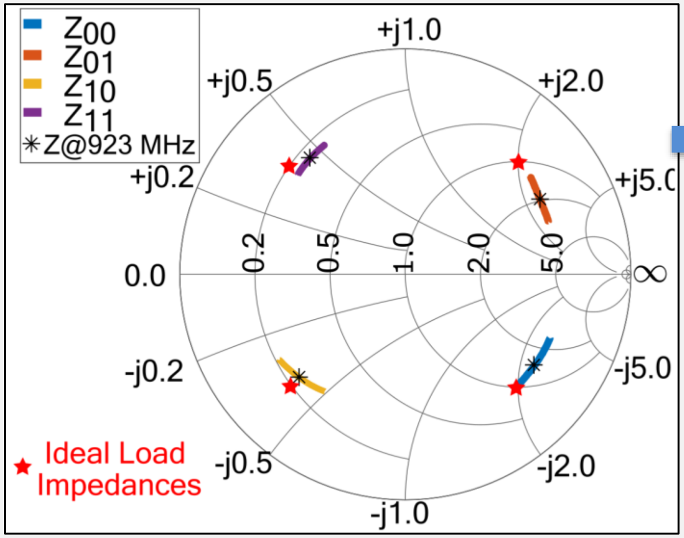
Received symbol constellation

S. J. Thomas et al., "Quadrature amplitude modulated backscatter in passive and semipassive UHF RFID systems," IEEE Trans. on Microwave Theory and Techniques, vol. 60, no. 4, pp. 1175–1182, April 2012.

RF Uplink: Modulator



Inductive elements could be replaced by shifting the impedance into the capacitive half-plane on the Smith Chart



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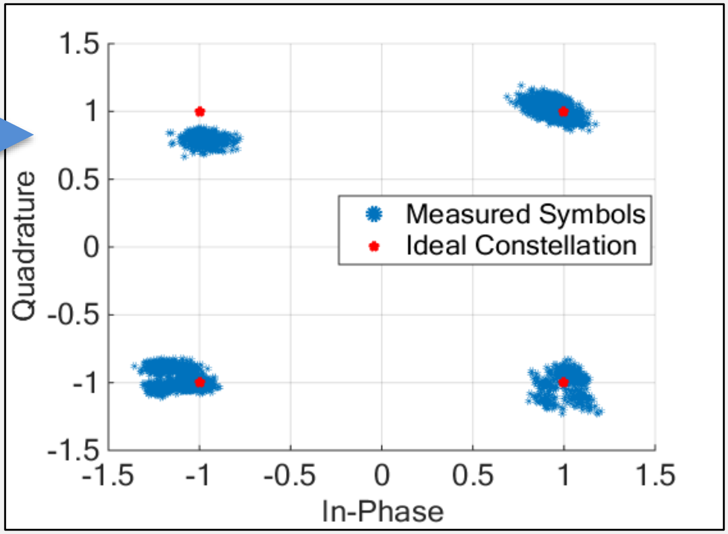

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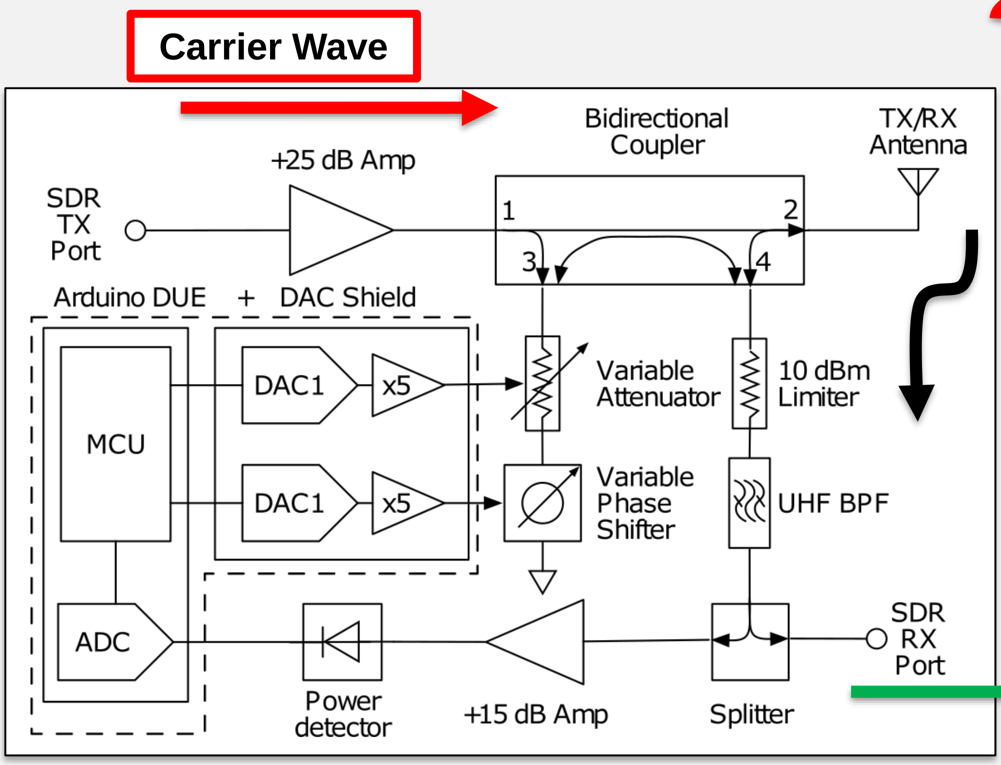
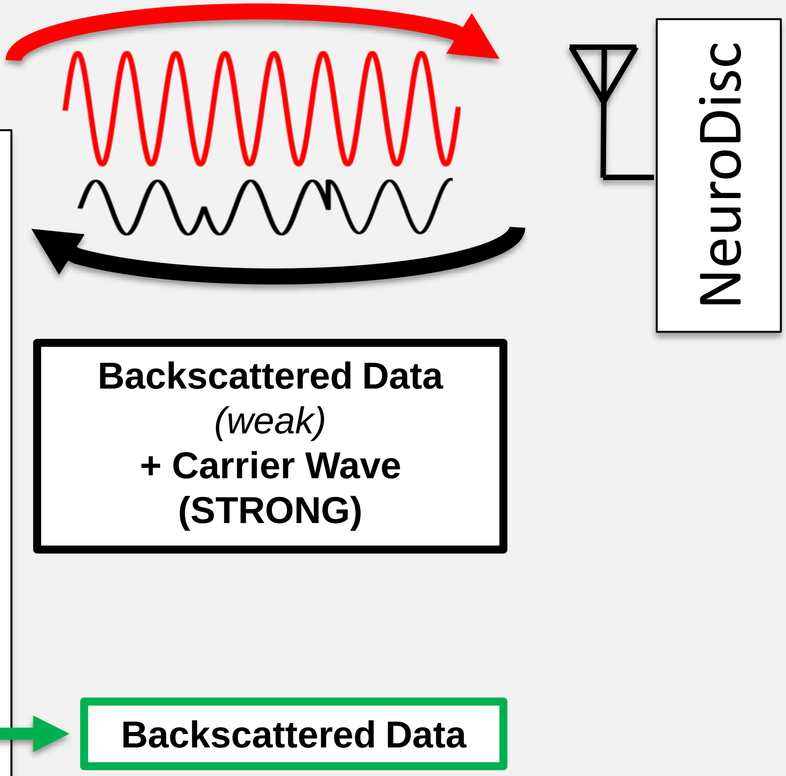
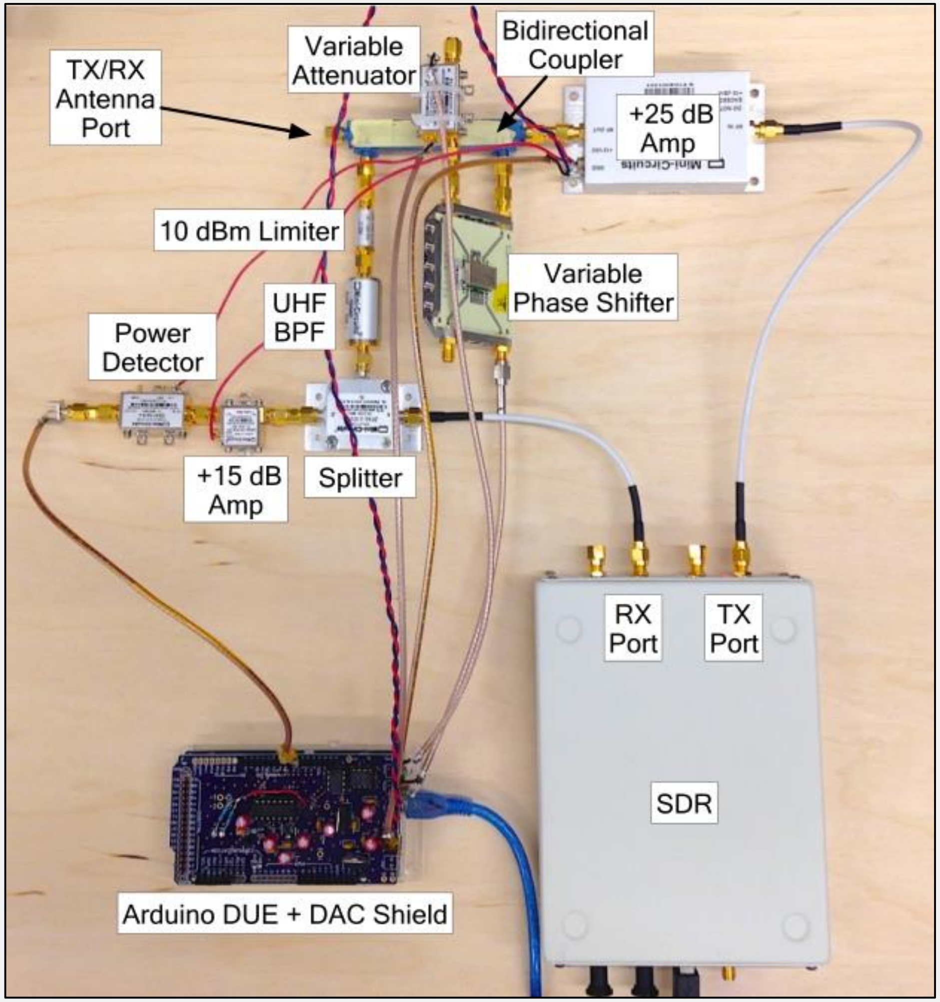
Full-duplex External System





Block diagram of the full-duplex external system

Full-duplex External System



Open-source software-defined radio system with self-jammer cancellation

All parts are COTS except for Arduino DAC shield

Receiver sensitivity of -86 dBm at 6.25 Mbps

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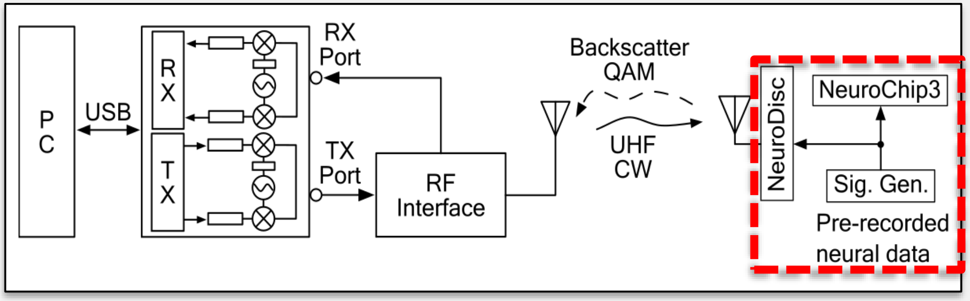
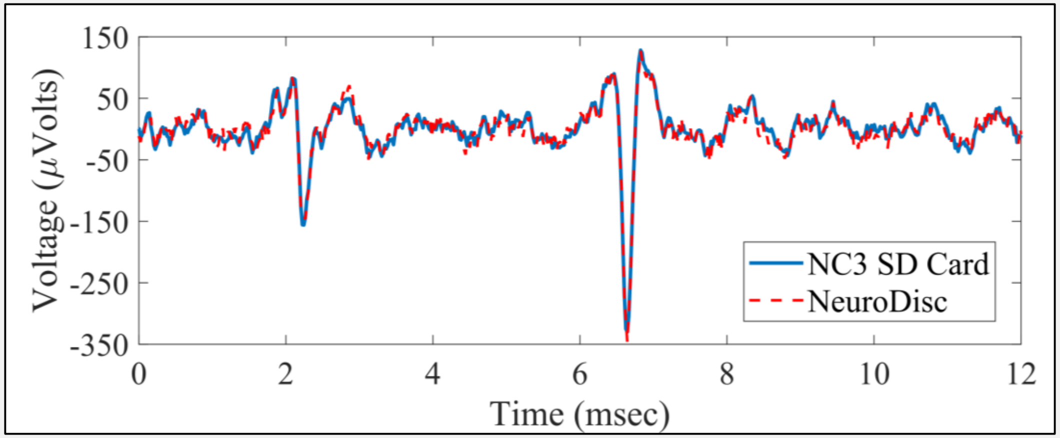
In Vitro Results

Good agreement between the NeuroDisc and the NC3

NeuroDisc and NeuroChip-3 simultaneously measured pre-recorded neural data



Experimental setup: Receiver had direct line-of-sight at 0.3 m. Uplink rate was 6.25 Mbps



Comparison of the same pre-recorded data wirelessly uplinked by the NeuroDisc and saved on the NC3 SD card

S. Zanos et al., "The Neurochip-2: an autonomous head-fixed computer for recording and stimulating in freely behaving monkeys," IEEE Trans. Neural Syst. Rehabil. Eng., vol. 19, no. 4, pp. 427–435, 2011.

In Vivo Results

Successful measurement and uplink of neural spike data from an anaesthetized pigtail macaque (*Macaca nemestrina)*

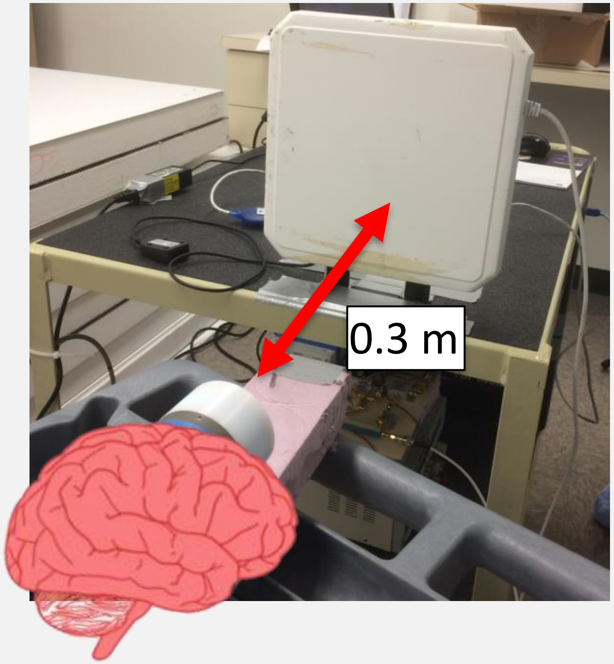
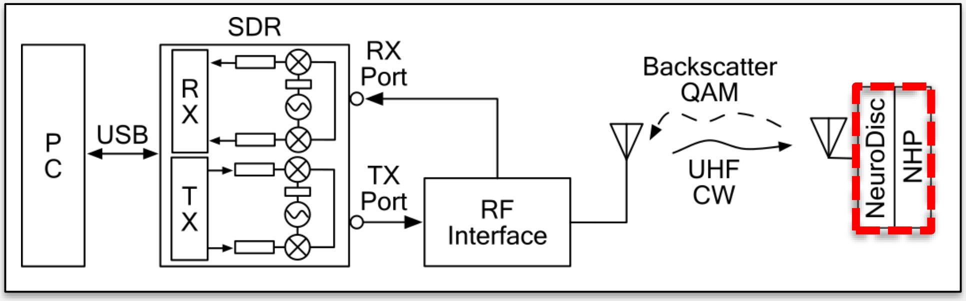


Photo of *in vivo* measurement setup

All *in vivo* measurement procedures were conducted under approval by the UW IACUC



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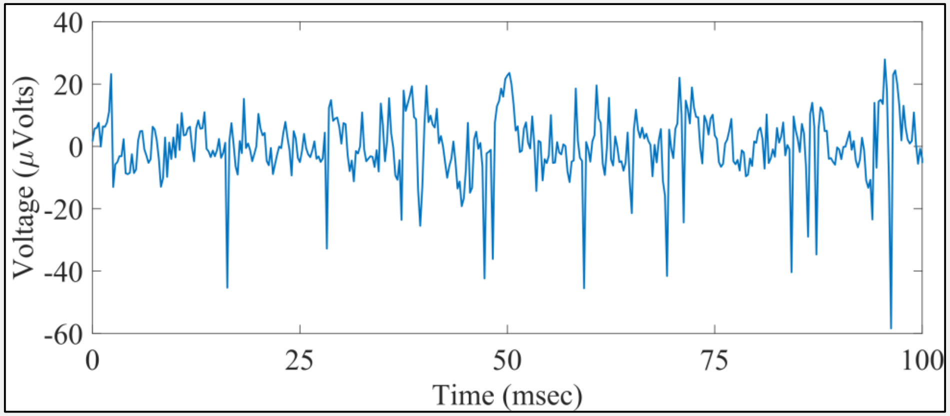

One of eight channels measured at 5 kHz with BPF between 1 Hz – 2 kHz

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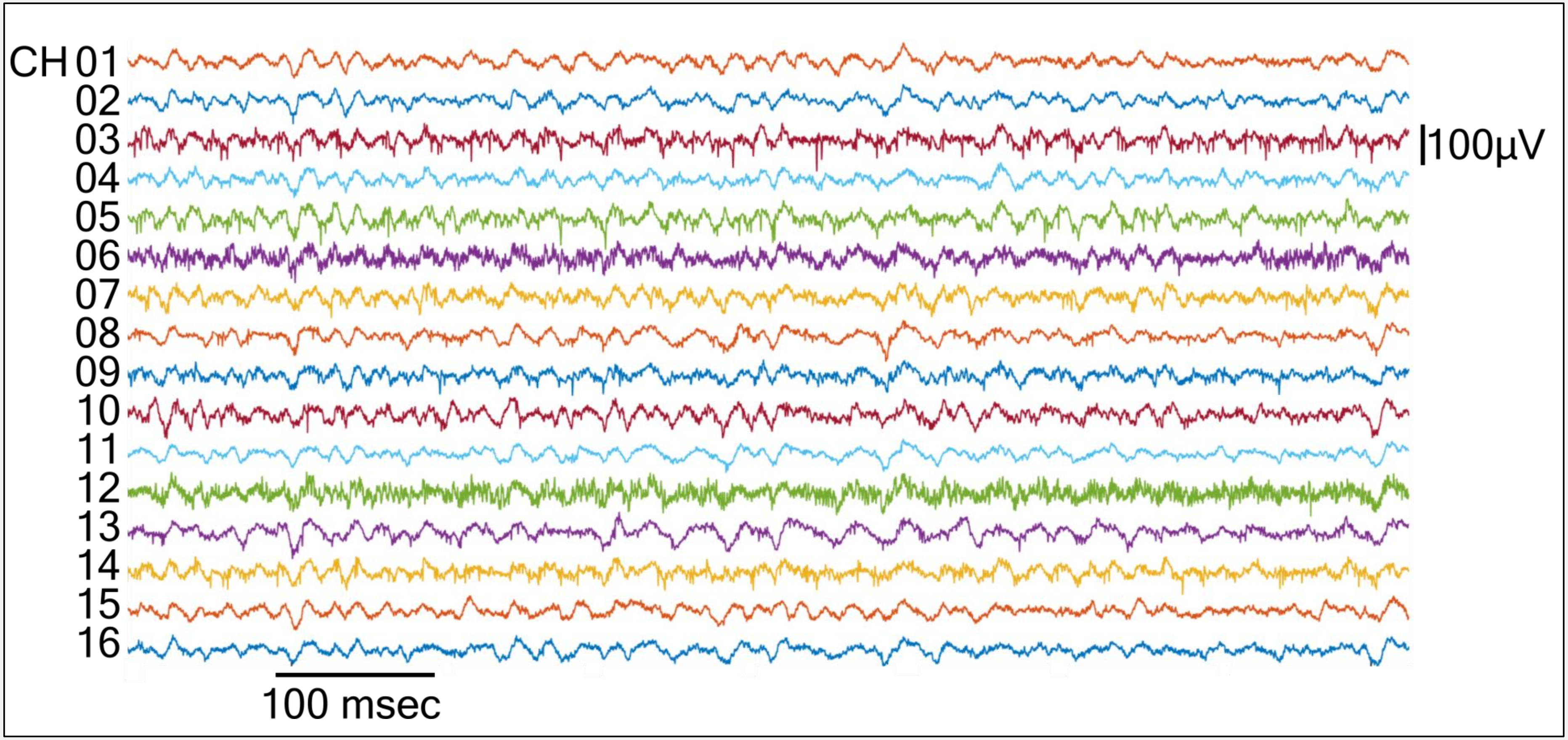
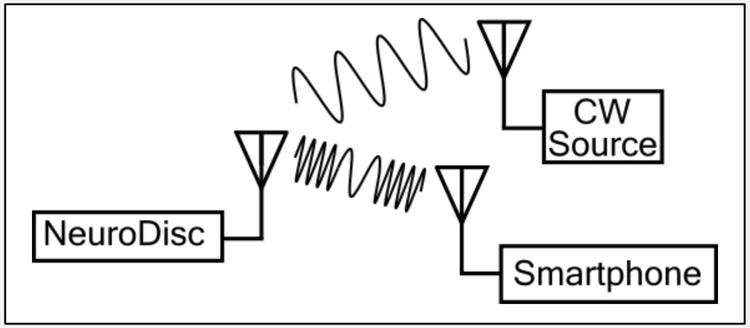
Work in Progress

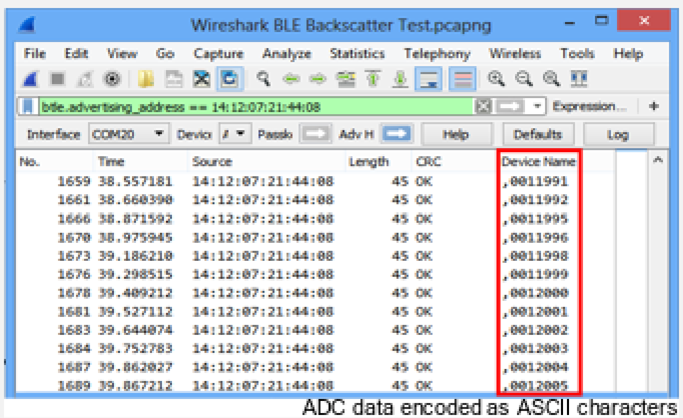
25 Mbps uplink for 16 channels at 20 kSps



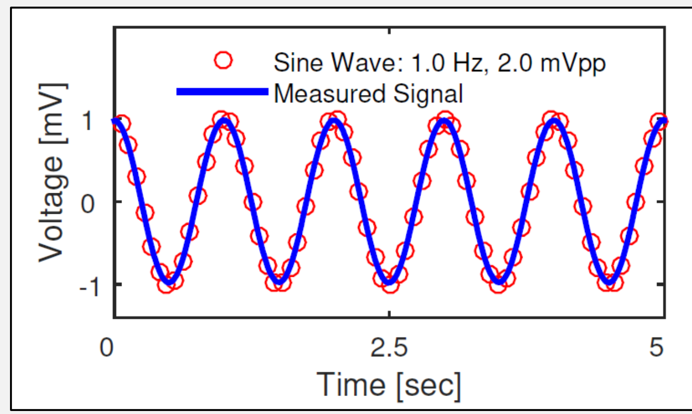
Work in Progress

Bluetooth Low Energy (BLE) Compatible
Backscatter Communication System for Wireless Sensing





Analog sensor data is uplinked in BLE-compatible advertising packets to any unmodified BLE receiver



Sensor data can be reconstructed at the receiver

J. Rosenthal and M.S. Reynolds, "A 158 pJ/bit 1.0 Mbps Bluetooth low Energy (BLE) compatible backscatter communication system for wireless sensing," IEEE Wireless Sensor Networks Conference 2019. (accepted)

Acknowledgements

- Co-authors:
  - Eleftherios Kampianakis
  - Apoorva Sharma
  - Prof. Matthew S. Reynolds
- UW Depts. of Biophysics & Physiology, BioE
- Washington National Primate Research Center

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Thank you for your time!

Questions?