Low-Power Integrated Circuits for
Advanced Neural Interfaces

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Outline

• Biopotential amplifier design

• Wireless cortical recording system (Utah Integrated Neural Interface)

• Electrophysiology recording lab on a chip (Intan Technologies RHD2000)

• Wireless telemetry: locust escape response

• Wireless telemetry: dragonfly in-flight prey capture
From Beckman Institute to Beckman Institute

Caltech
Computation and Neural Systems program

University of Illinois
NeuroEngineering IGERT
Arnold O. Beckman (1900 – 2004)

B.S., Chemical Engineering, University of Illinois at Urbana-Champaign, 1922
M.S., Physical Chemistry, University of Illinois at Urbana-Champaign, 1923
Ph.D., Chemistry, Caltech, 1928

“Arnold O. Beckman developed the first commercially successful electronic pH meter... The innovative features of the pH meter, including an early use of integrated electronic technology, were the basis for subsequent modern instrumentation...”
Tools for Neuroscience: Revolutionizing Electrophysiology

Traditional electrophysiology instruments are big, bulky, and ill-suited for studying naturally behaving, mobile subjects. The goal is to replace all of this with a small IC.
Biopotential amplifier requirements

An integrated front-end amplifier for biopotentials should:

- Amplify signals in the **frequency bands** of interest;
- **Block dc offsets** present at the electrode-tissue interface to prevent saturation of the amplifier;
- Have sufficiently **low input-referred noise** to resolve biological signals in the low microvolt range;
- Have sufficient **dynamic range** to convey signals in the low millivolt range;
- Have much higher **input impedance** than the electrode-tissue interface and have negligible dc input current;
- Reject common-mode signals (**high CMRR**) particularly at 50/60 Hz; reject power supply noise (**high PSRR**);
- Consume little **silicon area**, and use few or no **off-chip components** to minimize size;
- Consume little **power**, to facilitate wearable or implantable applications.
Problem: integrating many low-noise amplifiers (without cooking cortex!)

At the turn of the century, existing integrated biosignal amplifiers were too noisy and/or consumed too much power, and many required one or two off-chip components per channel.

Power vs. noise:
Noise Efficiency Factor (NEF)

(Steyaert, Sansen, and Zhongyuan, 1987)

\[ \text{NEF} = V_{ni,rms} \sqrt{\frac{2I_{tot}}{\pi \cdot U_T \cdot 4kT \cdot BW}} \]

Quantifies tradeoff between power and noise

NEF is a function of:
- Input-referred noise
- Bandwidth
- Supply current

Best achievable NEF = 1
Biopotential amplifier design

Capacitor ratio sets midband gain.

Upper cutoff frequency \( f_H \) can be changed by changing OTA transconductance \( G_m \).

Lower cutoff frequency can be set below 0.1 Hz using no off-chip components. Pseudo-resistor element \( M_{PR} \) has small-signal resistance \( >10^{12} \Omega \).
Using drain currents in the 20 nA – 40 μA range, CMOS transistors can be operated in strong, moderate, or weak inversion by sizing W/L ratio.

For a given bias current, input-referred noise is minimized by operating the differential pair in weak inversion (subthreshold) and the current mirrors in strong inversion (above threshold).

\[ v_{n_{ia}}^2(f) = \frac{16kT}{3g_{m1}} \left( 1 + 2\frac{g_{m3}}{g_{m1}} + \frac{g_{m7}}{g_{m1}} \right) \]

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*Here’s what NEF does not consider:*

Also, other less “glamorous” support circuits can require significant amounts of power. For example, a **fast analog MUX** to allow many amplifiers to share a single ADC can consume a lot of power!
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Fully Wireless Neural Recording for Neuroprosthetic Applications

- Need to observe on the order of 100 neurons in motor and/or parietal cortex.
- Transcutaneous power and data transfer using inductive link and RF telemetry.
- Implant must operate below 30 mW to minimize tissue heating.

Data from 100 electrodes:
RF (902-928 MHz ISM band, 345 kbit/sec)

Power (~3 MHz coil; <30 mW)
Configuration/control signals (~20 kbit/sec)
Multi-channel neural recording devices produce lots of data!

**Method 1:** Use fast MUX and fast analog-to-digital converter (ADC); transmit exact shape of electrode waveforms

\[
100 \text{ electrodes} \times 16 \text{ kSamples/second} \times 10 \text{ bits/Sample} = 16 \text{ Mbit/second}
\]

**Method 2:** Set threshold for spike detection at each electrode; transmit one bit for electrode every millisecond

\[
100 \text{ electrodes} \times 1 \text{ kSamples/second} \times 1 \text{ bit/spike} = 100 \text{ kbit/second}
\]

Reduction in data rate by a factor of 160
Compromise to Reduce Required Telemetry Data Rate

Our Method: Use slow MUX and slow analog-to-digital converter (ADC); transmit exact shape one user-selectable electrode waveform

1 electrode ×
16 kSamples/second ×
10 bits/Sample

= 160 kbit/second

Simultaneously, detect spikes at each electrode; transmit one bit for electrode every millisecond

100 electrodes ×
1 kSamples/second ×
1 bit/spike

= 100 kbit/second

Total data rate =
160 kbit/second + 100 kbit/second + frame markers + parity bits = 345 kbit/second
Benchtop Testing of Assembled Devices at University of Utah

Assembled device with reference wire

Power/command transmit coil (2.8 MHz)

Underside of coil is electrostatically shielded (radial slits block eddy currents)

Teflon/glass spacer: 10 mm coil-to-coil distance

Telemetry received several cm away
In Vivo Testing of Fully Assembled Devices (Cat Somatosensory Cortex)

Electrode 0,1

Electrode 2,0

Total power transmission distance: 21 mm

Data telemetry (915 MHz) distance: 40 mm

Spike detection threshold set to -81 µV
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Digital Electrophysiology Interface Chips


Features

• 32 biopotential amplifiers with low input-referred noise (2.4 μVrms)
• Integrated 16-bit A/D converter supports sampling 32 channels up to 30 kS/s each
• Bidirectional SPI (Serial Peripheral Interface) bus with optional LVDS transceiver for robust digital data transfer
• Programmable amplifier bandwidth set by digital control registers (0.1 Hz to 20 kHz range)
• On-chip DSP high-pass filters for removing residual offsets from analog amplifier circuitry
• Auxiliary ADC inputs for interfacing additional sensors
• Individual amplifier power up/down for power minimization
• Low power operation: less than 500 μW per channel (depends on bandwidth, sampling rate)
• In situ electrode impedance measurement capability

RHD2132 32-channel digital electrophysiology chip: 8.0 mm x 8.0 mm QFN-packaged chip
4.8 mm x 4.1 mm bare die

In a nutshell: electrodes into one side of the chip, serial digital data out the other side.
RHD2132 Digital Electrophysiology Interface Chip – Simplified Diagram

Gain = 96
Gain = 2

in0

in1

in2

in31

ref_elec

amplifier bandwidth selection

on-chip \( R_{H1} \)

on-chip \( R_{H2} \)

on chip \( R_L \)

on chip off chip

Auxiliary analog inputs for external sensors (e.g., 3-axis accelerometer)

Auxiliary digital output (e.g. LED control)

ADC_ref

10 nF

GND

VDD

100 nF

1.225V voltage reference

16-bit ADC

16

control

MISO

MOSI

SCLK

CS

auxout

register file

temperature sensor

misc. chip configuration bits

digital controller with SPI interface

channel select

½ VDD

V_{ref}

Standard 4-wire SPI digital interface supports system modularity

Only two external capacitors required

Standard 4-wire SPI digital interface supports system modularity
RHD2000 Digital Electrophysiology Interface System

USB interface board supports up to 256 channels of recording at user-selectable sample rates between 1 kS/s and 30 kS/s.

USB 3.0 will support 2048+ channels.

Thin, flexible digital interface cables use LVDS (low-voltage differential signaling) to maintain high signal integrity over 10 meters using passive, daisy-chained cables.

Four SPI digital interface signals (LVDS); power
RHD2000 Digital Electrophysiology Interface System

USB interface board supports auxiliary general-purpose analog and digital I/O. Selected amplifier channels can be routed to DACs for analog or audio output. FPGA interface code and C++ API are 100% open source.
RHD2000 Digital Electrophysiology Interface System

Interface GUI software 100% open source, written in C++ with Qt libraries for Windows, Max, Linux compatibility.
Biopotential Signals Acquired using RHD2000 Electrophysiology Chips

EMG: Bicep contractions

ECG: Heartbeat

signal frequency

- 1 Hz
- 10 Hz
- 100 Hz
- 1 kHz
- 10 kHz

signal amplitude

- 1 µV
- 10 µV
- 100 µV
- 1 mV
- 10 mV

neural spikes

EMG (internal)

LFPs

EEG

EMG: Bicep contractions
ECG: Heartbeat
Local field potentials (LFPs) and neural spikes from cortex of freely behaving mouse.

Biopotential Signals Acquired using RHD2000 Electrophysiology Chips

(Data courtesy of Jakob Voigts at MIT, Brown University, and open-ephys.org)
Intan Technologies chips are currently used in more than 25 countries worldwide.
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Certain neurons in insect brains respond selectively to looming visual stimuli.

**Locust cell response to looming target**

First Insect Telemetry Chip (2009)

- 11.0592 MHz quartz crystal
- Low-power crystal oscillator
- Digital controller
- Analog multiplexer-selector
- 9-bit ADC
- 902-928 MHz LC oscillator
- RF power amplifier
- Dipole antenna
- Neural signal amplifier
- Neural signal amplifier
- EMG amplifier
- EMG amplifier
- ADXL330 3-axis accelerometer (off chip)
- Differential electrodes
- ADXL330 3-axis accelerometer

2.6 mm x 2.7 mm, 0.6-µm BiCMOS
Complete Battery-Powered Wireless Telemetry Backpack

Circuit board measures 13.0 mm x 9.5 mm.

Mass = 790 mg (including batteries)

Supply current = 880 µA
Battery life = 2 hours

Telemetry Data (range >2 m)

- 2 neural channels (300 Hz – 5 kHz; 11.5 kSamples/s)
- 2 EMG channels (20 – 300 Hz; 1.9 kSamples/s)
- 3 acceleration channels (DC – 500 Hz; 1.9 kSamples/s)

Utah telemetry chip

3-axis accelerometer

quartz crystal

Batteries
Electrode wires are soldered onto PCB pads.

Receiver includes USB interface and realtime audio output.
Telemetry unit attached to locust
Wireless Telemetry from Jumping Locust
Audio = Neural Channel 1 (Right DCMD Neuron)

Courtesy Haleh Fotowat and Fabrizio Gabbiani, Baylor College of Medicine

Wireless Telemetry from Jumping Locust
Audio = EMG Channel 2 (Leg Extensor Muscle)

Courtesy Haleh Fotowat and Fabrizio Gabbiani, Baylor College of Medicine

Data obtained wirelessly from a freely jumping locust, in response to an expanding visual stimulus (top trace). A neural signal from the DCMD neuron, plus two EMG signals were monitored (middle traces). Accelerometer data shows the jumping event (bottom trace).

Goal: Telemetry From Free-Flying Dragonflies During In-Flight Prey Capture

Anthony Leonardo, HHMI Janelia Farm Research Campus
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3-D tracking of dragonfly body, wings, and head position, and prey location, at hundreds of frames per second.

Anthony Leonardo, HHMI Janelia Farm Research Campus
Next-Generation Insect Telemetry Unit

Mass = 790 mg
3.0V supply

Mass = 266 mg
1.5V supply
Further Size and Mass Reduction: Bare Die on Flex

Reduces mass by another 90 mg, to <180 mg with battery

Anthony Leonardo, HHMI Janelia Farm Research Campus
Spikes recorded wirelessly from target selective descending neuron (TSDN) on untethered, perched dragonfly
Size comparison of Bug1, Bug2, and Bug2Flex

**Bug1:** 13 x 9 mm², 790 mg

**Bug2:** 9 x 6 mm², 280 mg

**Bug2Flex:** 6 x 5 mm², 172 mg

(battery and antenna omitted in photo for clarity)
Far-field radiative power transfer \((1/d^2)\) at 915 MHz

- Higher power Tx \(\rightarrow\) longer range
- Unlike inductive coupling, longer range \(\neq\) larger antenna!

Modulated backscatter return link

- 5 Mbps data rate, \((11,16)\) Hamming encoding of each 11-bit ADC sample for single bit error correction, double bit error detection (SECDED)

Latest Version: Battery-Free 5Mbps Telemetry Chip with RF Power Harvesting and Backscatter Telemetry

Latest Version: Battery-Free 5Mbps Telemetry Chip with RF Power Harvesting and Backscatter Telemetry

10 neural amplifier channels sampled at 26.1 kS/s each
- 250 Hz – 10 kHz bandwidth
- ±2.4 mV range
- 5.7 µV rms noise

4 EMG amplifier channels sampled at 1.63 kS/s each
- 5 Hz – 700 Hz bandwidth
- ±24 mV range
- 43 µV rms noise

DC amplifier (gain < 1) monitors unregulated supply voltage

Latest Version: Battery-Free 5Mbps Telemetry Chip with RF Power Harvesting and Backscatter Telemetry

Latest Version: Battery-Free 5Mbps Telemetry Chip with RF Power Harvesting and Backscatter Telemetry

<table>
<thead>
<tr>
<th>Subsystem</th>
<th>Current (μA)</th>
<th>Total IC Supply Current (μA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neural amplifiers</td>
<td>10 x 16</td>
<td>160</td>
</tr>
<tr>
<td>EMG amplifiers</td>
<td>4 x 0.25</td>
<td>1</td>
</tr>
<tr>
<td>DC amplifiers</td>
<td>2 x 45</td>
<td>90</td>
</tr>
<tr>
<td>Analog mux</td>
<td></td>
<td>139</td>
</tr>
<tr>
<td>Amplifier / mux bias generators</td>
<td></td>
<td>80</td>
</tr>
<tr>
<td>11-bit ADC and digital control logic</td>
<td></td>
<td>320</td>
</tr>
<tr>
<td>LDO voltage regulator</td>
<td></td>
<td>60</td>
</tr>
<tr>
<td>Crystal oscillator</td>
<td></td>
<td>70</td>
</tr>
<tr>
<td>Backscatter modulator</td>
<td></td>
<td>15</td>
</tr>
<tr>
<td><strong>Simulated</strong> Total IC supply current</td>
<td>935</td>
<td></td>
</tr>
<tr>
<td><strong>Measured</strong> Total IC supply current</td>
<td>940</td>
<td></td>
</tr>
</tbody>
</table>

Minimum unregulated supply voltage: 1.31 V

**Simulated** Total IC power consumption: 1.22 mW
**Measured** Total IC power consumption: 1.23 mW

Measured DC power consumption of 1.23mW

- Amplifiers and ADC dominate: 1.0mW or 84%
- Backscatter communication is only 19μW or 2%
- Communication figure of merit is 4 pJ/bit

Eye diagram at 5 Mbps, 1 meter from receiver
Battery-Free Neural Telemetry Unit on Dragonfly for Flight Tests

Chip on flex (COF) packaging to minimize size and weight

- **Size:** 4.6 mm x 6.8 mm
- **Mass:** 38 mg
- Dominated by epoxy encapsulant and quartz crystal
- Antenna is carbon fiber + 50μm Ag wire dipole
10-Channel Telemetry Unit Transmitting Pre-Recorded Neural Data (1 Meter)
Acknowledgements – Insect Telemetry Projects

Anthony Leonardo
Janelia Farm Research Campus
Howard Hughes Medical Institute
Ashburn, Virginia, USA

Haleh Fotowat
Raymond Chan
Fabrizio Gabbiani
Baylor College of Medicine
Houston, Texas, USA

Matt Reynolds
Stewart Thomas
Duke University
Durham, North Carolina, USA
Questions?

For more information, see:

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