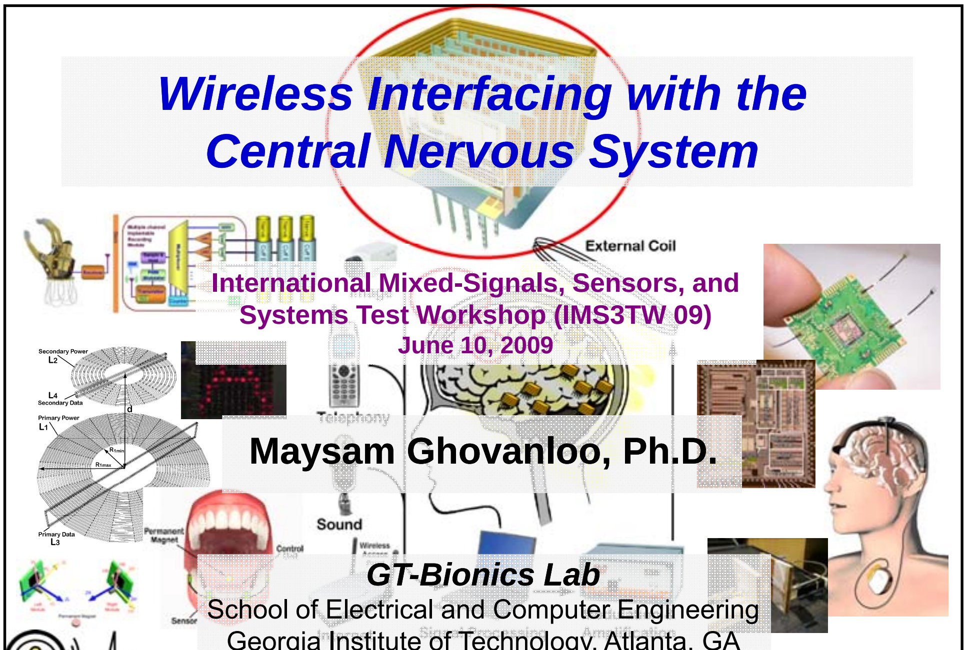
Wireless Interfacing with the Central Nervous System



International Mixed-Signals, Sensors, and Systems Test Workshop (IMS3TW 09)
June 10, 2009

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Motivation

- Healthy People 2010: 54 million Americans (~20%) living with disabilities and the number is on the rise especially among elderly (Age 65+).
- 11,000 cases of severe Spinal cord injury (SCI) per year add to a total population of ~250,000.
- 55% spec
- Most

Advanced technology development to improve the quality of life for the most severely disabled individuals.

Injury or Disease	Population	Annual Incidence
Paralysis of extremities	2,000,000	N/A
Spinal cord injuries	250,000	11,000
Effects of stroke	4,000,000	600,000
Multiple sclerosis	350,000	N/A
Cerebral palsy	500,000	~10,000
ALS	30,000	5,600

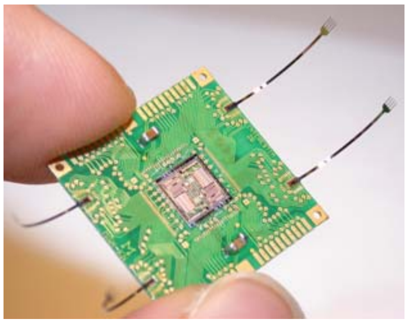
Source: Christopher and Dana Reeve Foundation

Outline

Wireless Neural Interfacing

- Wireless implantable neural stimulating system (Interestim) for neuroprostheses application
  - Design challenges
  - Modular architecture
- Wireless implantable neural recording system (WINeR) for neuroscience research application
  - Design challenges
  - FSK-TDM-PWM
- A multiband transcutaneous wireless link for high performance implantable microelectronic devices
  - Orthogonal coils

A Multichannel Wireless Neural Stimulating System for Neuroprosthetic Applications



Auditory and Visual Prostheses

Cochlear Corporation

- **Auditory Prosthesis:**
  - 10% of the world population experience a limited quality of life because of hearing impairment.
  - USA statistics:
    Profoundly deaf: 0.4 million
    Hearing Impaired: 20 million

- **Visual Prosthesis:**
  - World statistics:
    Profoundly Blind: 45 million
    Visually Impaired: 180 million
  - USA statistics:
    Profoundly Blind: 1.3 million
    Visually Impaired: 10 million

Dobelle Institute

Cochlear and Retinal Implants

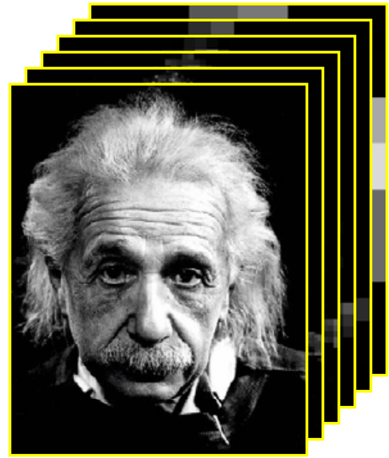
Advanced Bionics Inc.

- Commercially available since early 80's.
- More than 90,000 children and adults use cochlear implants.
- 30,000 auditory nerves.
- A minimum of 6 ~ 8 stimulating sites needed to converse on the phone.
- Currently under development. First chronic human trial in 2002.
- 1.2 Million optic nerves.
- A minimum of 800 ~ 1000 sites needed to read large fonts.

University of Southern California

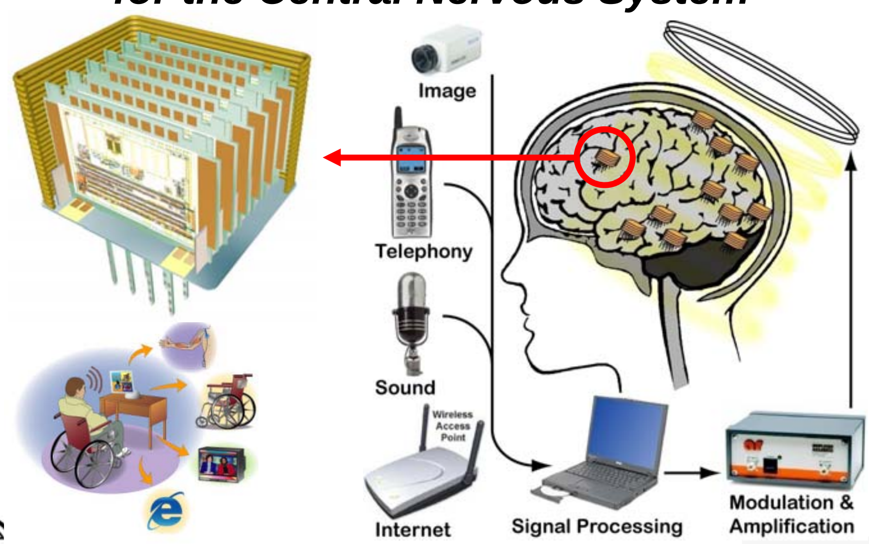
Major Challenges in Visual Prostheses

- **Number of stimulating sites**
  A minimum of 625 pixels are needed to restore a functional sensation.
- **Stimulation strategy**
  Provide maximum flexibility to support future advanced strategies.
- **High Bandwidth**
  Transmit maximum data volume with minimum number of carrier cycles.
- **Low Power consumption**
  Minimize the implant temperature rise and tissue exposure to EM field.
- **Implant size, assembly, and packaging**
  From the size of a matchbox to a button.



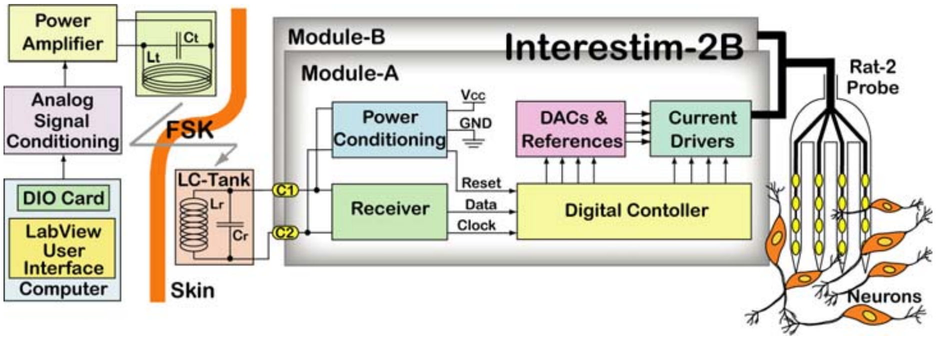
480 × 384
184,320 Pixels

A Distributed Network of Wireless Implants for the Central Nervous System



Ghovanloo, and Najafi JSSC 2004

A Wireless Stimulating System with Modular Architecture

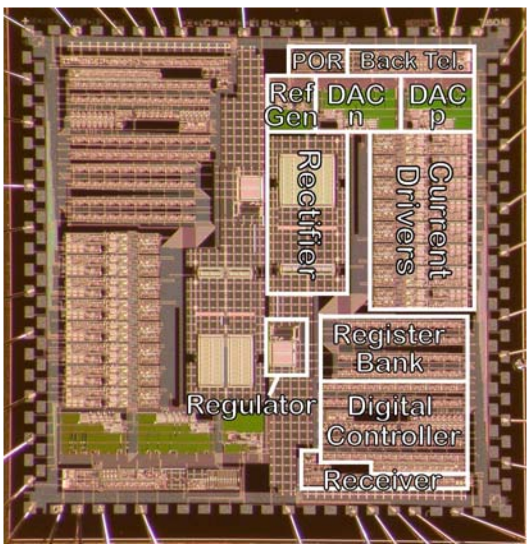


A modular 32-site wireless microstimulating system to stimulate the neural tissue through passive probes

Up to 64 modules can be used in parallel
Driving a total of 2048 stimulating sites

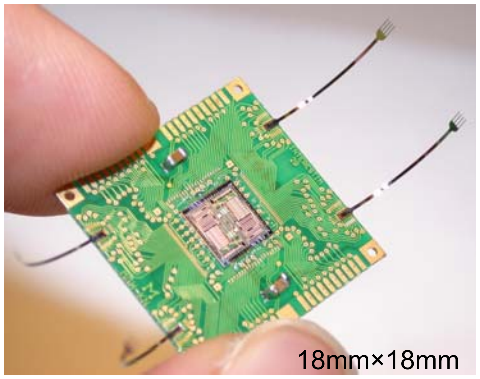
Interestim-2B Chip

- AMI 1.5-μm 2M/2P n-well Std.-CMOS
- Die 4.6×4.6 mm^2
- Active area 10 mm^2
- 2 Modules/chip
- 8 Drivers/module
- 4 Sites/driver
- 64 Sites/chip
- 6500 Transistors per module

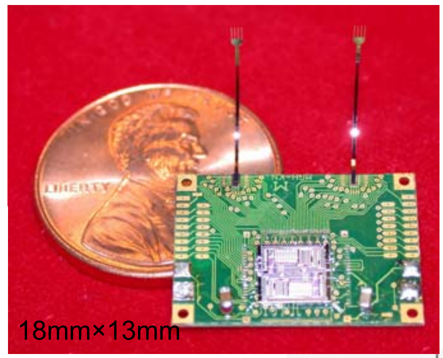


Ghovanloo and Najafi, ISSCC 2004

Interestim-2B with Micromachined Silicon Microelectrodes



- 64 sites per Interestim-2B chip
- 16 sites per silicon probe
- Fully integrated except for the receiver LC-Tank

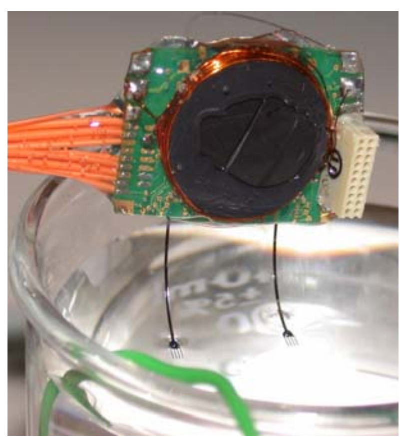


- 2.5 Mbps data rate with 5/10MHz FSK
- 7.6 µs Minimum pulse width
- 65,800 Pulses/sec
- >100MΩ Output impedance

Ghovanloo and Najafi, TNSRE 2007

In Vitro Experiments

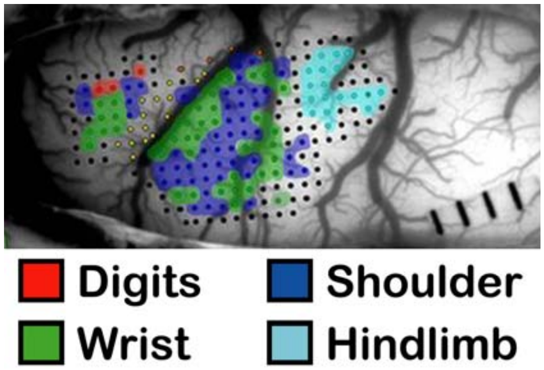
- Testing hardwired and wireless operation after assembly/coating
- Measuring site impedance



- Activating sites to decrease their impedance (10~100 kΩ)

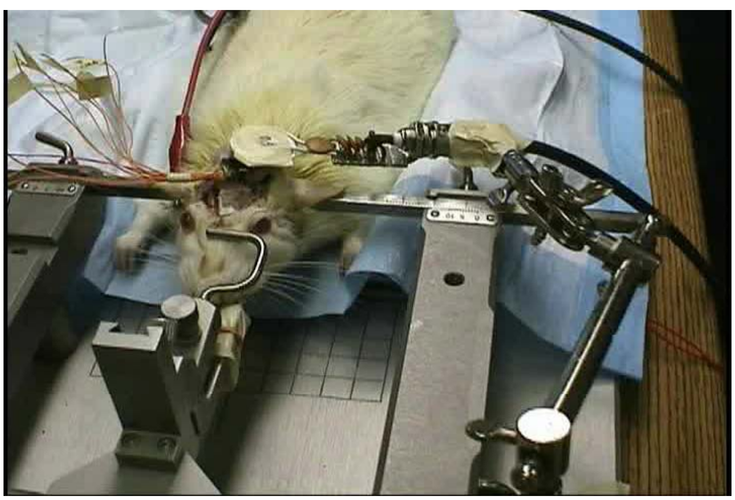
In Vivo Experiments

Functional organization of the rat motor cortex as defined by intracortical stimulation.



Kleim et al. The American Neurophysiological Society 1998

In Vivo Experiments

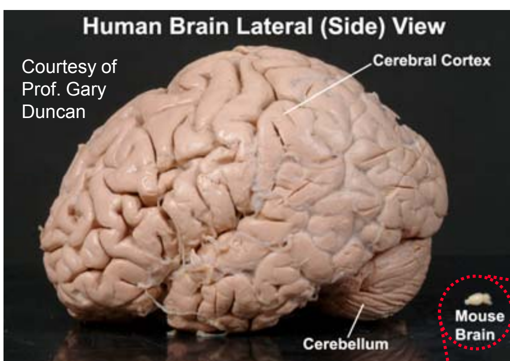


Wireless stimulation of the rat motor cortex in the wrist area

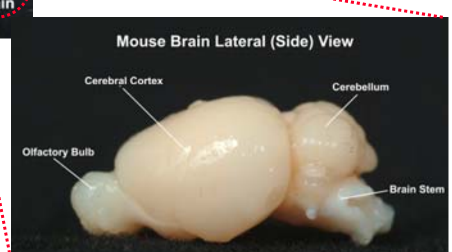
Ghovanloo and Najafi, TNSRE 2007

A Multichannel Wireless Neural Recording System for Brain-Computer Interfacing and Neuroscience Research Applications

Multichannel *Neural Recording*

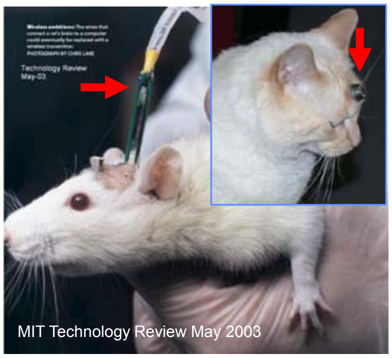


- Brain has **10^9 to 10^{12}** neurons depending on the species.
- Human brain is the most **complex** living structure in the universe (so far).
- Human brain has as many as **10^{14} synapses**.

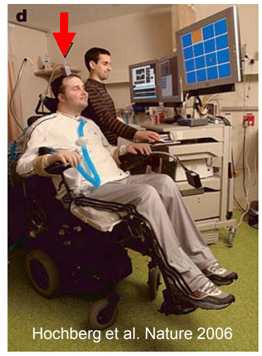


- Neuroscientists are interested in understand the relationship between **large populations** of neurons.
- For this purpose, they need to record **simultaneously** from a large number of **recording channels**.

Multichannel Wireless Neural Recording



MIT Technology Review May 2003



Hochberg et al. Nature 2006

In animal experiments:

1. Improve SNR.
2. Reduce motion artifacts.
3. Eliminate the tethering effect, which can bias the animal behavior.

In human applications:

1. Reduce the risk of infection.
2. Reduce the risk of damage.
3. Improve user's comfort level.
4. Increase mobility.
5. More aesthetically acceptable.

Yin and Ghovanloo, EMBS 2008

Design Challenges

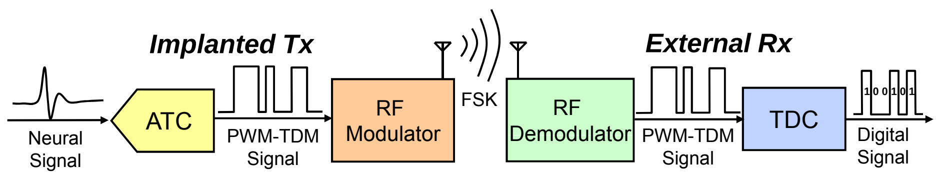
- Neural signals conditioning
  - Peak to peak amplitude: 20 ~ 500 μV → Low noise and interference
  - Frequency content: 0.1 Hz ~ 10 kHz → 20 kS/ch at Nyquist rate
- Internal power dissipation
  - Heat → tissue damage → Power dissipation < ~80 mW/cm^2
  - Rechargeable battery lifetime
- Dimensions
  - < ~1 cc depending on the position of implantation → Full integration
- Evaluation and safety
- **Wireless bandwidth** → @ low carrier frequency

Number of Channels	1	10	32	100	1000
Sampling Rate (kSps)	20	200	640	2000	20,000
Data Rate (Mbps)	0.16	1.6	5.12	16	160

PWM-Based Wireless Neural Recording System

Pulse Width Modulation (PWM) technique:

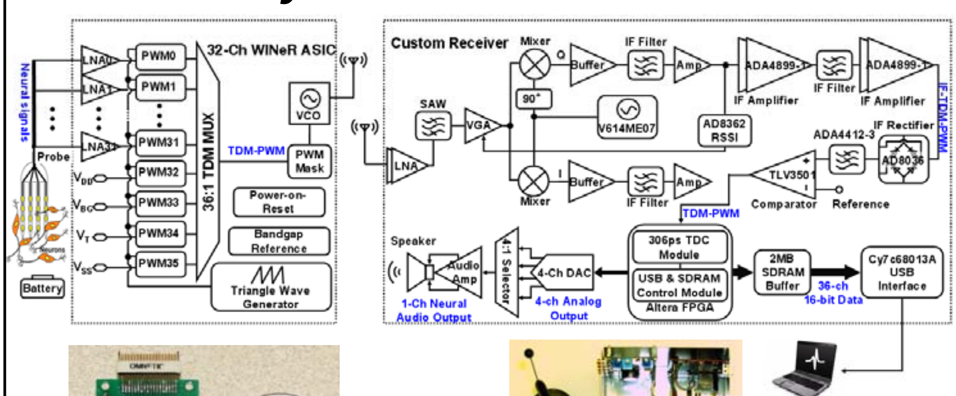
- Wireless single-slope ADC architecture
  - A. Analog-to-Time Converter (ATC) → Generating a PWM-TDM signal
  - B. Wireless link: Wideband RF modulator and demodulator based on FSK
  - C. Time-to-Digital Converter (TDC) → Measuring the PWM pulse width
- Less complexity, smaller size, and less power for the implantable unit
- Immune to amplitude noise and interference (pseudo-digital)
- No need for transmitter-receiver synchronization

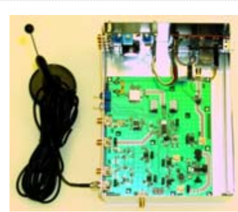


Asynchronous/Clockless design for the ASIC (Yin and Ghovanloo, ISCAS'08)

- Simplicity
- No on-chip clock interference

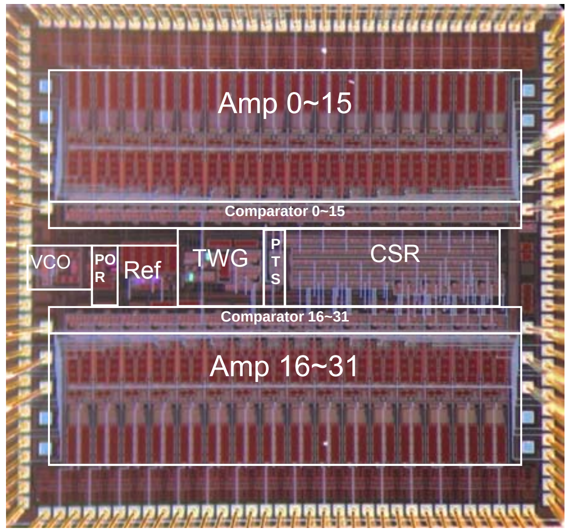
Wireless Integrated Neural Recording System Architecture



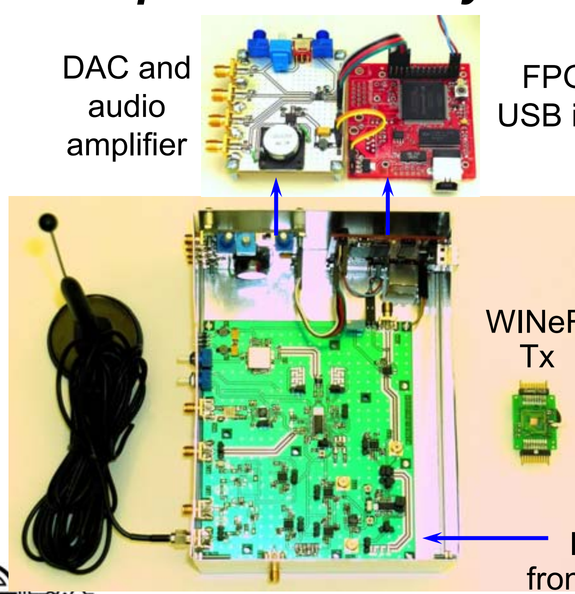


32 Channel WINeR SoC

- System-on-a-Chip (SoC)
- 32 neural recording + 4 monitoring channels
- Sampling rate: 640 kHz
- 8.8 bit resolution
- Programmable bandwidth
- Programmable gain
- Process: AMI 0.5-μm, Std. CMOS
- Size: 3.3 mm × 3 mm
- Supply: ± 1.5 V
- FSK Transmitter: 890 ~ 915 MHz
- Power : 5.6 mW

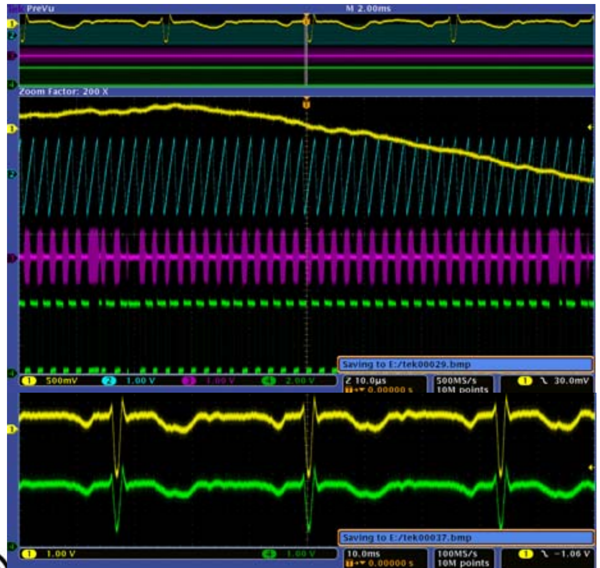


Complete WINeR System Prototype



- Bandwidth: 18 MHz
- Noise Contrib.: 2.9 μV_{rms} (1Hz~8.8kHz)
- Power: 1.9 W from ±5 V
- Dimensions: 17 × 14 × 7 cm^3

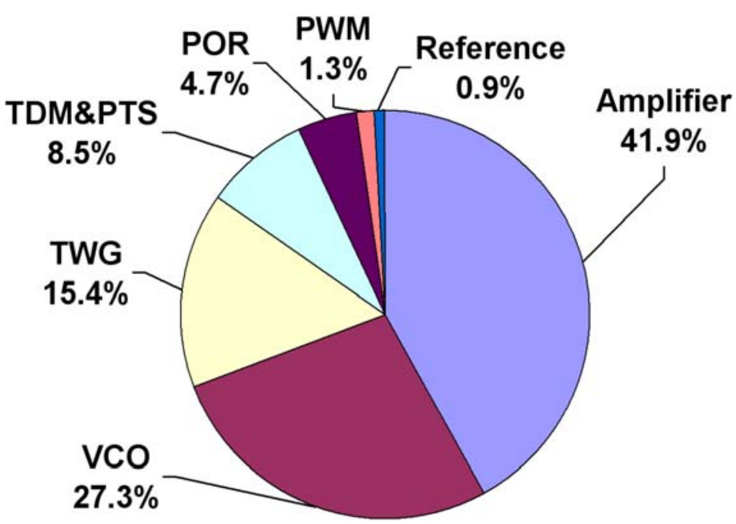
Key Measured Waveforms



Input: 1.3 mV ECG signal at 30 Hz

1. LNA Output
2. TWG Output
3. IF-TDM-PWM
4. Demodulated TDM-PWM
5. Tx LNA Output
6. Rx DAC Output

Power Chart



Total: 5.6 mW @ ±1.5 V

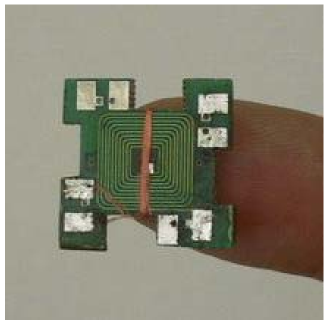
WINeR System Performance Summary

Fabrication technology	AMI-0.5 µm 3M2P CMOS
Die size	3.3 mm × 3 mm
Number of channels	32 recording + 4 monitoring
LNA gain	67.7 dB / 77.1 dB
LNA input ref. noise	3.9 µVrms (10 Hz ~ 10 kHz)
LNA low cutoff	0.1 Hz ~ 1 kHz
LNA high cutoff	700 Hz ~ 10 kHz
Sampling rate	58 ~ 680 kSps
FSK carrier frequency	898 / 926 MHz
System resolution	8.8 bits @ 1 m receiving distance
INL / DNL	(1.56, -1.22) / (0.53, -0.37)
System input referred noise	4.9 µVrms @ 1 m distance
Total power dissipation	5.6 mW

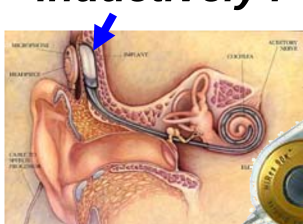
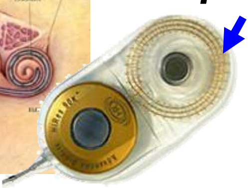
In Vivo Experiments on Freely Moving Rats

Ongoing….

A Multiband Wireless Link for High Performance Implantable Microelectronic Devices



Inductively Powered vs. Battery Powered Implants

Advanced Bionics Inc.

Medtronic Corporation

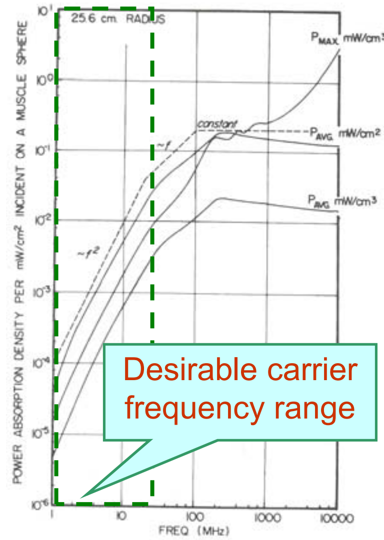
University of Southern California

Alfred Mann Institute - USC

- Battery powered devices:
  - Low stimulus pulse rate
  - Autonomous (after initial adjustments)
  - Small number of stimulating sites
- Inductively powered devices:
  - High current (Neuromuscular stimulators)
  - High stimulus rate (Cochlear implants)
  - Large number of sites (Visual prostheses)
- All implants need wireless data.

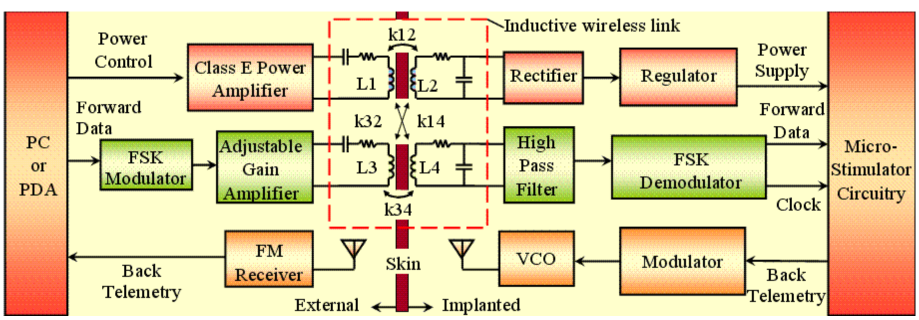
Efficient Power: Carrier Frequency as Low as Possible

- Carrier frequency should be below the coil self resonance frequency.
- More power loss in the power transmission and conditioning circuitry at higher frequencies.
- 1 MHz < Carrier Frequency < 20 MHz
Average density of electromagnetic power absorption in tissue increases as f^2.
- Tissue is more transparent to EM field at lower frequencies.
- Carrier Frequency↑ ⇒ Penetration Depth↓



J. C. Lin, A. W. Guy, and C. C. Johnson
IEEE Trans. Microwave Theor. Tech. 21, 1973

Wireless Link Using Multiple Carrier Frequencies



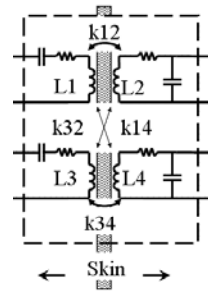
- Low frequency for power transmission (~5 MHz)
- Medium frequency for forward data transmission (~50 MHz)
- High frequency for back telemetry (~1 GHz)

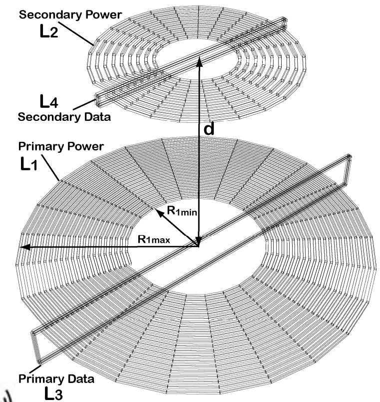
Atluri and Ghovanloo, TCAS-I 2007

Direct and Cross Coupling

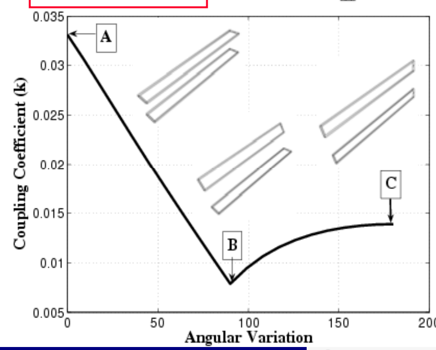
Geometry and orientation of the power and data coils were chosen to:

- Maximize direct coupling coefficients (k_{12}, k_{34})
- Minimize cross coupling coefficients (k_{14}, k_{32})

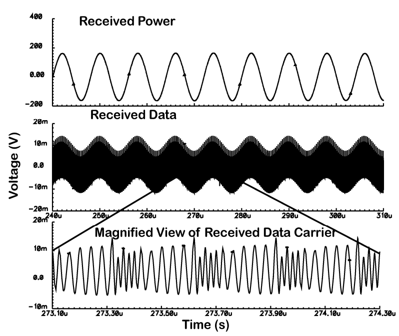


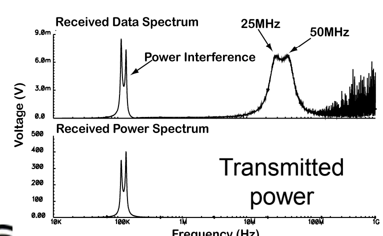


$$k_{ij} \propto \cos\theta$$



Simulation and Measurement Results



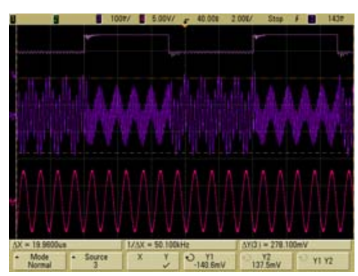


Measurement Setup →

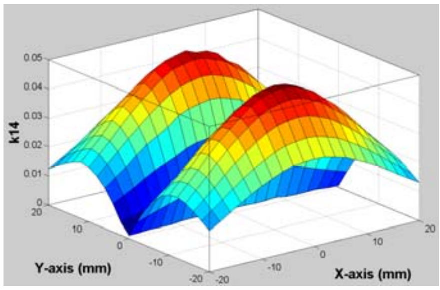
Demodulated Data →

Received Data →

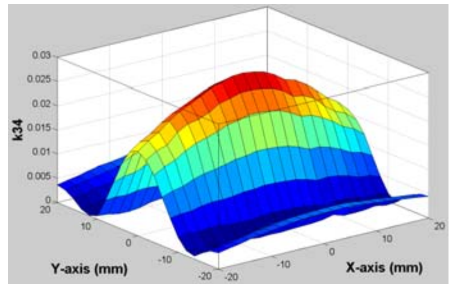
Received power →



Misalignment Analysis for Data Coils

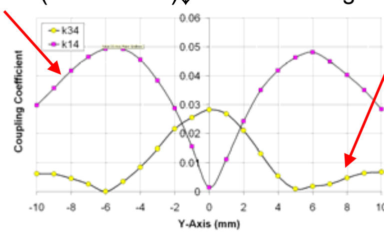


Data-power coils cross coupling k_{14} vs. X-Y misalignments (Undesired)↓



Data coils direct coupling k_{34} vs. X-Y misalignments (Desired)↑

X-misalignments can be easily tolerated.



Y-misalignment can be tolerated as long as $k_{34} > k_{32}$ → $|\Delta Y| < 2mm$

Conclusions

- **Implantable neuroprosthetic devices** can potentially restore sensory or motor functions that might have been damaged as a result of a disease or an accident.
- We have developed a 64 channel **wireless neural stimulating microsystem (Interestim)** with modular architecture, which can be used in neuroprosthetic devices such as cochlear implants or visual prostheses.
- We have developed a 32 channel **wireless implantable neural recording (WINeR)** system for behavioral neuroscience experiments on awake freely moving animal subjects.
- We are working on a **multiband wireless link** to efficiently power high performance implantable neuroprosthetic devices through planar inductively coupled coils and communicate with them though wideband bidirectional wireless links established between orthogonal coils and antennas.

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