Towards Self-Powered Wireless Biomedical Devices

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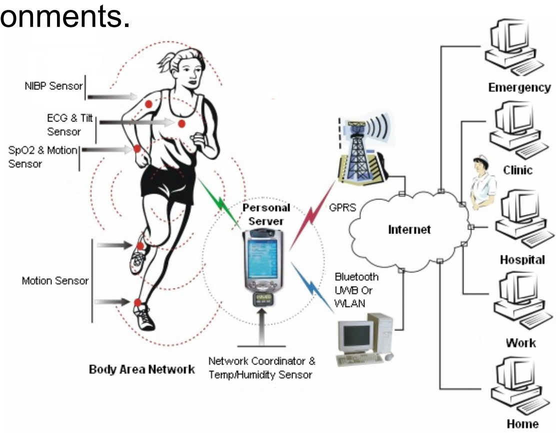
Outlines

- An introduction to Wireless Body Sensor networks
- Self-powered wireless sensor devices: a dream or reality?
- Challenges in the design of self-powered sensors and possible solutions
- Some design examples of low power wireless biomedical sensors
- Conclusions

Wireless Body Sensor Networks

- A latest evolution of healthcare system.
- Seamless integration with home, working, and hospital environments.



E. Jovanov et al., “A wireless body area network of intelligent motion sensors for computer assisted physical rehabilitation”, *Journal of NueroEngineering and Rehabilitation, 2 (2005):6.*

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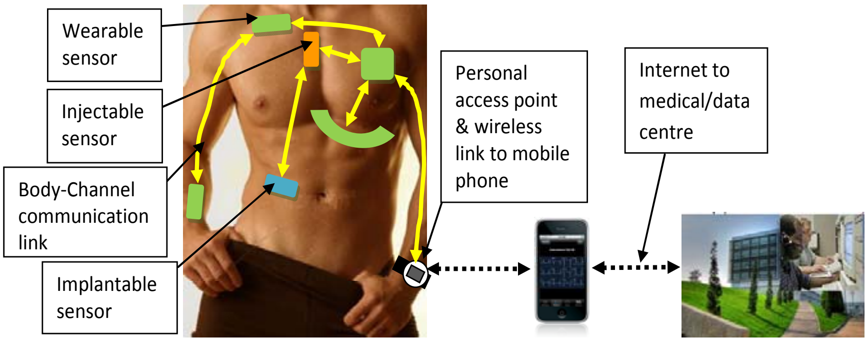
Wireless Biomedical Sensors(WBS)

- Sensor types: wearable/injectable/ingestible/implantable
- Function: context-sensitive measurement of parameters leading to faster acquisition of accurate and actionable information



Wearable sensor

Injectable sensor

Body-Channel communication link

Implantable sensor

Personal access point & wireless link to mobile phone

Internet to medical/data centre

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Wireless Health

- The use of body sensor networks to facilitate personalized and prevention-oriented healthcare
- Reducing healthcare cost in ageing society
- Improving productivities for healthcare providers, patients, and payers.
- Huge market size and potential new market segment in wireless health

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Estimated Market Size for Wireless Health

- Current wireless home health market: around $304 million
- Expected to grow to: $4.4 billion in 2013 with estimated growth rates of 96% in 2010, 126% in 2011, 95% in 2012 according to CTIA(The Wireless Association)
- Expected wireless wearable sensors: more than 400 million devices by 2014 and revenue around $5 billion according ABI Research.

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Self-Powered Wireless Biomedical Sensor: a Dream or Reality?

- Available commercial wireless sensors

Platform	Power(Rx/Tx)	Sleep power
TelosB	18.8/17.4 mA	0.02-426 μA
MicaZ	18.8/17.4 mA	0.02-426 μA
SHIMMER	40/60 mA	50-1400 μA
IRIS	15.5/16.5 mA	20 nA
Sun SPOT	18.8/17.4 mA	0.02-426 μA

Two key limitations:
- Size and capacity
- Lifetime

Energy Harvesting

- Energy harvesting options

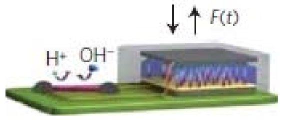
Type	Energy sources	Power density
Radiant	Photovoltaic	12000μW/cm^2
Mechanical	Electrostatic, piezoelectric	3.89μ-830μW/cm^3
Thermal	Thermoelectric	2000μW/cm^2@12°C gradient
Magnetic	Electromagnetic	0.01μ-0.3μW/cm^2
Chemical	Glucose	2-4mW/cm^2

ThermoLife® (5 °C gradient: 30 μW),

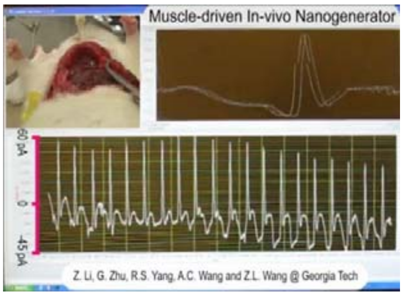
IMEC Wrist TEG(300μW at 22°C),

Human Energy Scavenging

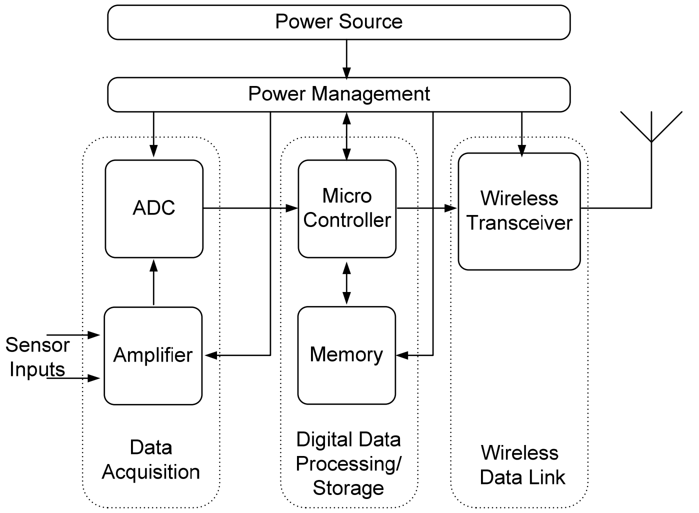
- Wearable devices can generate 0.3mW – 8 W from breathing, finger motion, blood pressure, body heat, walking.
- Implantable nanowire devices:
  - Current density: ~8.9nA/ cm^2
  - Output voltage: ~96mV
  - Power density: 2.7mW/ cm^3



Z.L. Wang, *et al* "Self-powered nanowire devices", *Nature Nanotechnology,* Mar 2010.



Challenges in Designing of Self-Powered WBS


Power Source

Power Management

ADC

Micro Controller

Wireless Transceiver

Sensor Inputs

Amplifier

Memory

Data Acquisition

Digital Data Processing/ Storage

Wireless Data Link

Challenges in Designing of Self-Powered WBS

- Complicated system contains analog, mixed-signal, digital, RF, and power blocks.
- Energy scavenging from body and ambient are unstable.
- Limited power budget
  - Less than few mW for wearable devices.
  - Less than 1 mW for implants

Possible Solutions

- Asynchronous architecture.
- Sub-threshold circuits.
- Wireless communication using human body – intra body communication.
- Exploring new signal processing flow: continuous-in-time and discrete-in-amplitude.
  - Event driven ADC with continuous-time digital signal processing achieves upto 80% dynamic power saving in terms of number digital outputs for audio signals.

M. Kurchuk and Y Tsividis, “Signal-dependent variable-resolution clockless A/D conversion with application to continuous-time digital signal processing”, IEEE Trans. on CAS I, May 2010 .

Design Examples

- 1-V 450nW programmable ECG sensor interface
- 1-V 2.3μW ECG-on-Chip
- 1-V 22μW 32-channel ECoG chip
- 0.5V 18μW 16-channel neural recording chip
- 250mV digital filter for QRS detection

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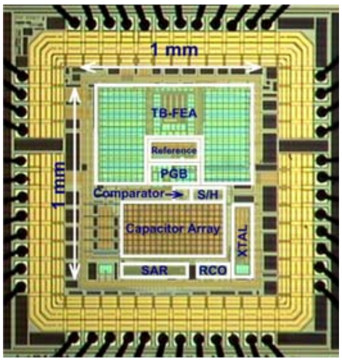
NanoWatt ECG Recording Chip

- Fully integrated, configurable chip for ECG recording
- 450 to 900nW
- Low voltage on-chip tunable band-pass filter(4.5mHz-290Hz)
- Programmable
- 12-bit ADC
- On-chip oscillator



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Measured Performance of ECG Chip

Parameter	Measurement results
Core Voltage	1 V
Core Current	450 nA (QRS mode)
3 dB Bandwidth	4.5 mHz ~ 292 Hz (Tunable)
Mid-band Gain	45.6 / 49 / 53.5 / 60 dB
Input Referred Noise	2.04 μV_{rms} (0.05 ~ 300 Hz)
Amplifier THD	< 0.6% (@ full output swing)
CMRR	> 71.2 dB
PSRR	> 84 dB
ADC Resolution	12 bits
ADC Sampling Rate	1 KS/s
ADC DNL	< ±0.8 LSB
ADC INL	< ±1.4 LSB
ADC SFDR	74 dB
ADC SNDR	63 dB

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Performance Comparison

Parameter	Yin'07	Wattanapanitch'07	Wu'06	NUS ECG Chip
Supply Voltage	±1.7 V	2.8 V	1 V	1 V
Process Technology	1.5 µm CMOS	0.5 µm CMOS	0.35 µm CMOS	0.35 µm CMOS
Current (TB-FEA)	8 µA	743 nA	330 nA	337 nA
Mid-band Gain	39.3 / 45.6 dB	40.9 dB	40.2 dB	45.6 / 49 / 53.5 / 60 dB
–3 dB BPF Bandwidth	0.015 Hz – 4 kHz (Tunable)	0.392 Hz – 295 Hz (Fixed)	0.003 Hz – 245 Hz (Fixed)	0.0045 Hz – 292 Hz (Tunable)
Input Referred Noise	3.6 μV_{rms}	1.66 μV_{rms}	2.7 μV_{rms}	2.04 μV_{rms}
Noise Efficiency Factor	4.9	3.21	3.8	2.66
Output @ 1% THD	~ 48% Full Swing	~ 29% Full Swing	~ 85% Full Swing	100% Full Swing
CMRR	N/A	66 dB	64 dB	≥ 71.2 dB
PSRR	N/A	75 dB	62 ~ 63 dB	≥ 84 dB
ADC Resolution	N/A	N/A	11-bit	12-bit
ADC Sampling Rate	N/A	N/A	1 KS/s	1 KS/s
ADC DNL	N/A	N/A	< ±1.5 LSB	< ±0.8 LSB
ADC INL	N/A	N/A	< ±2 LSB	< ±1.4 LSB
Total Power	27.2 µW (Amplifier)	2.08 µW (Amplifier)	2.3 µW	445 nW ~ 895 nW

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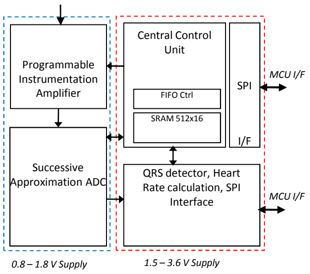
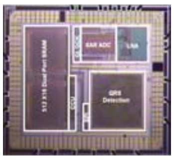
ECG-on-Chip

- 2.3 μW fully integrated programmable ECG chip for signal conditioning, ADC, QRS detection, memory, and MCU interface

Analog Frontend	Supply Voltage	1.0 V
	Pass-band	0.05 ~ 100 Hz
	Gain	46 ~ 60 dB programmable
	Input-referred Noise	2.5 μV$_{rms}$ (0.05 ~ 460 Hz)
	THD @ FS Output	< 0.6%
	Sampling Freq	256 Hz
	ADC ENOB	> 10.2
	Power @ 1.0 V	0.75 μW
QRS + FIFO + CCU + SPI + I/O	Supply Voltage	1.5V
	Internal SRAM	2 Kb
	Interface	SPI slave & master
	Power @ 1.5 V	1.5 μW





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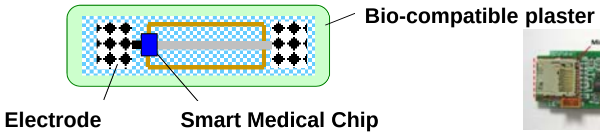
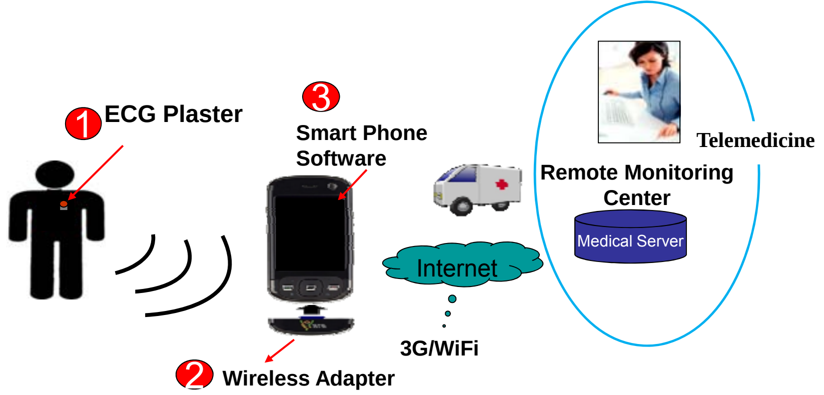
Application (1): Wireless ECG Plaster





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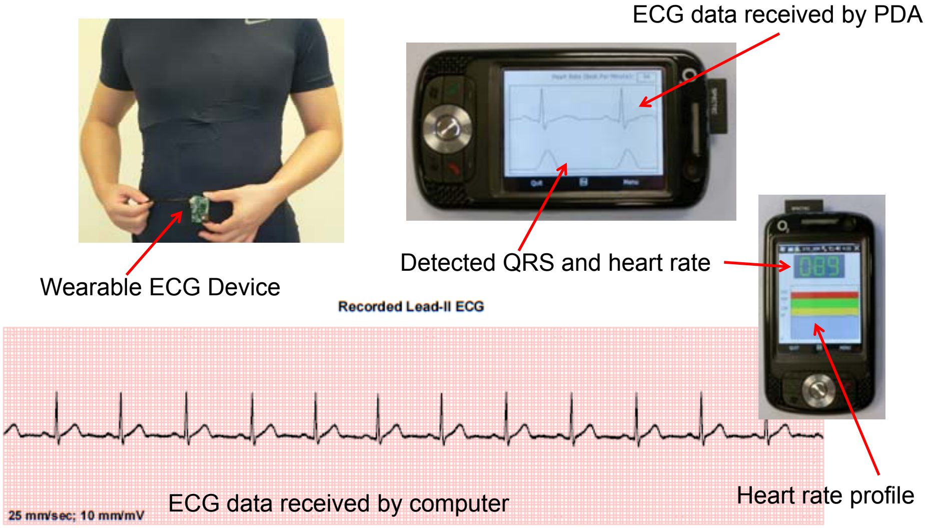
Prototype of NUS ECG Sensor


ECG data received by PDA

Detected QRS and heart rate

Wearable ECG Device

Recorded Lead-II ECG

ECG data received by computer

Heart rate profile

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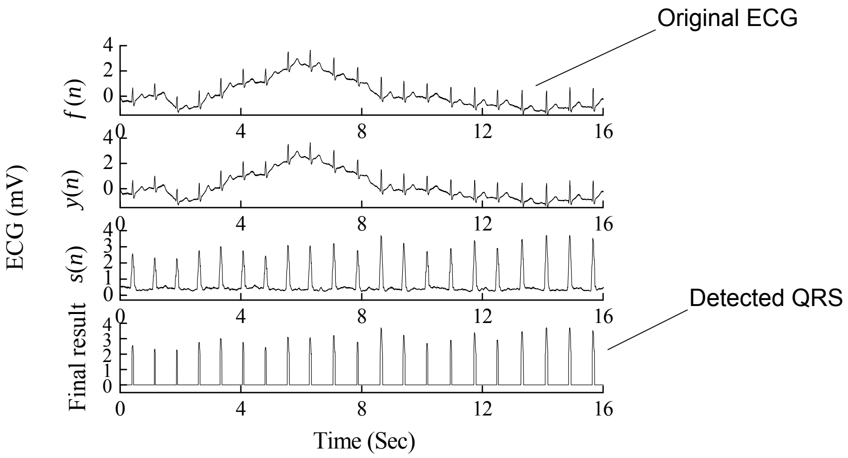
Detection of QRS for Exercise ECG under Running by NUS Algorithm (NanoWatt)


Original ECG

Detected QRS

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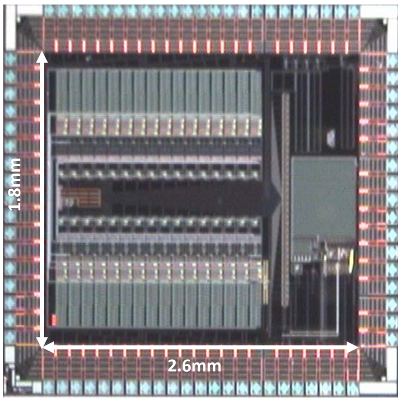
32-Channel EEG Chip

- 32-channel EEG recording chip (lowest power consumption < 20μW)
- Reconfigurable with amplifiers, filters, 10-bit ADC
- Intracranial EEG recording (ECoG)



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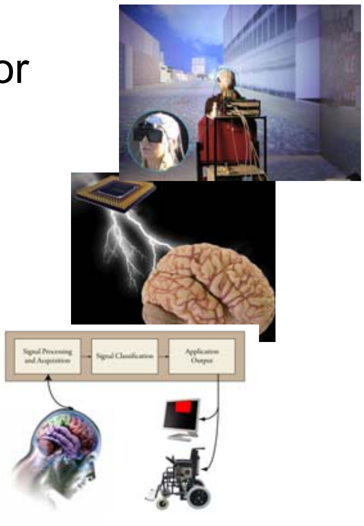
Applications: Wearable EEG Sensor

- Wearable wireless EEG for seizure detection, brain-computer-interface, gaming, education, cognitive enhancement.



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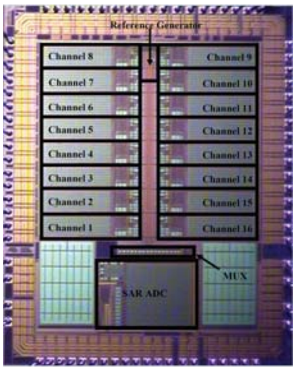
Multi-Channel Neural Recording Chip

- 0.5V 18-μW 16-Channel chip for implantable neural recording
- 10kHz bandwidth with on-chip filter, programmable gain, and 10-bit ADC
- Power consumption: 30 times less than current state of the art.



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A Design Example: Sub-1 mW Wireless ECoG Sensor

- Applications
  - Prediction of seizure and monitoring of epilepsy patients, deep brain stimulation, and Brain-Computer-Interface
- Implantable ECoG requirements:
  - Low noise(<1.5μV_{rms}) and low power
  - Multiple channels: at least 32-channel
  - Small chip area and long battery life

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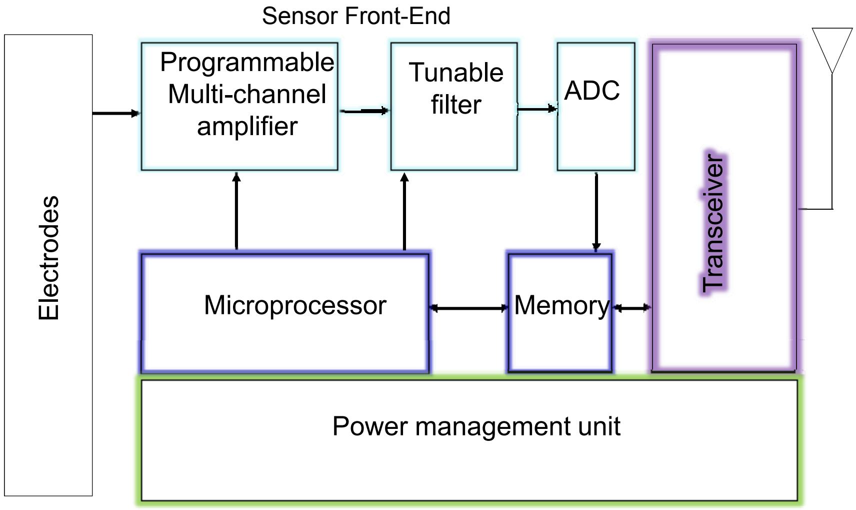
Wireless ECoG Sensor



Sensor Front-End

Electrodes

Programmable Multi-channel amplifier

Tunable filter

ADC

Transceiver

Microprocessor

Memory

Power management unit

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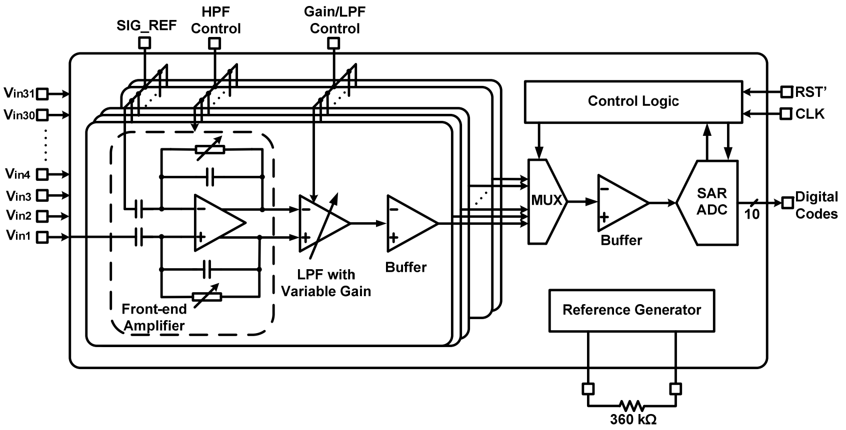
Front-End Architecture



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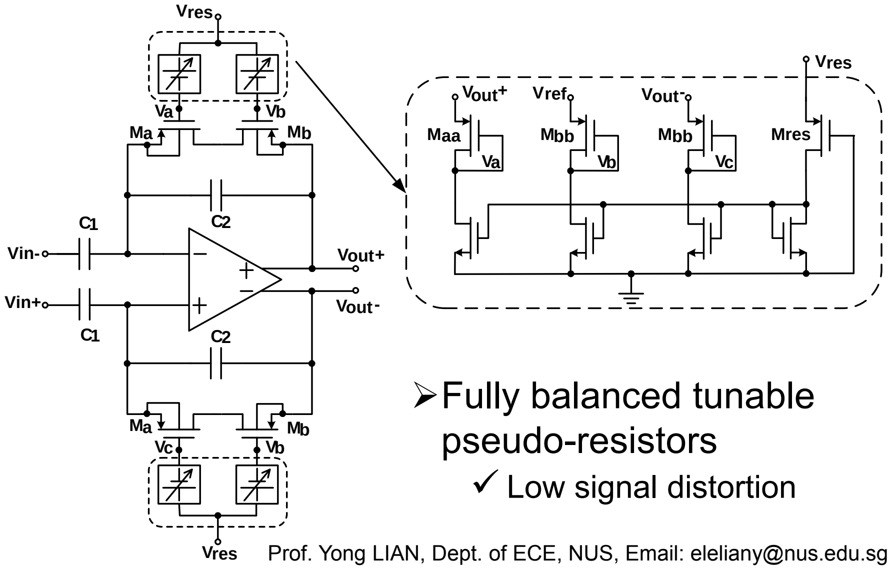
Low Power Low Noise Preamplifier

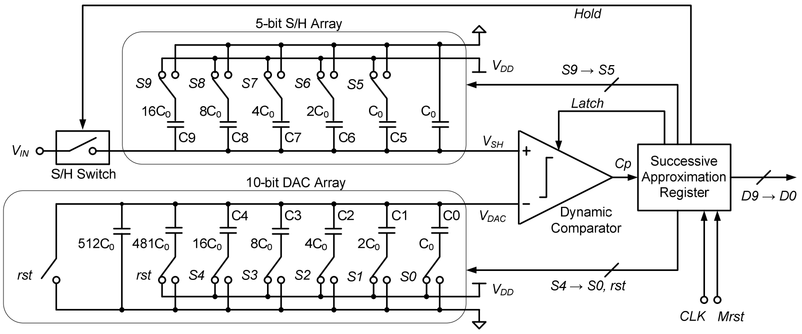


- ➢Fully balanced tunable pseudo-resistors
  - ✓ Low signal distortion

Challenges on SAR ADC

- Low supply voltage → rail-to-rail range to boost SNDR.
- To support multiple channels → sufficient input BW.
- Power limited application → energy efficient.

Dual-Capacitive-Array SAR ADC



- A hybrid between the two conventional designs.
- Additional S/H array for quantization.
  - First 5 bits (MSB) are obtained from 5-bit S/H array
  - Remaining 5 bits from 10-bit DAC array

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Performance Comparison

Parameter	Dension’07	Yazicioglu’08	Zou’08	This work*
Supply voltage	1.8 V	3 V	1 V	1 V
Process	0.8 µm CMOS	0.5 µm CMOS	0.35 µm CMOS	0.35 µm CMOS
Current (front-end amplifier)	1.2 µA	2.3 µA	337 nA	385 nA
Input referred noise	0.93 µV (0.5~100 Hz)	0.57 µV (0.5~100 Hz)	2.04 µV (0.05~ 300 Hz)	1.15 µV (0.5~150 Hz)
NEF	4.9	4.1	2.66	2.24
ADC resolution/ Sampling rate	--	11-bit / 8 kS/s	12-bit / 1 kS/s	10-bit / 10 kS/s
Total power	2.2 µW	198 µW	0.9 µW	22 µW
No. of channel	1	8	1	32
Average power per channel	2.2 µW (amplifier)	24.75 µW	0.9 µW	0.69 µW
Area per channel (analog part only)	1.4 mm^2	0.45 mm^2	0.64 mm^2	0.08 mm^2

*ISSCC2010

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Sub-mW Wireless Transceiver

- ECoG front-end consumes only 22μW (NanoWatt per channel)
- Most power goes to wireless transceiver, e.g. 20mW++ for commercially available wireless transceiver(ZigBee).
- Sub-mW wireless transceiver is necessary for implantable solution → reduced battery size or extended battery life.

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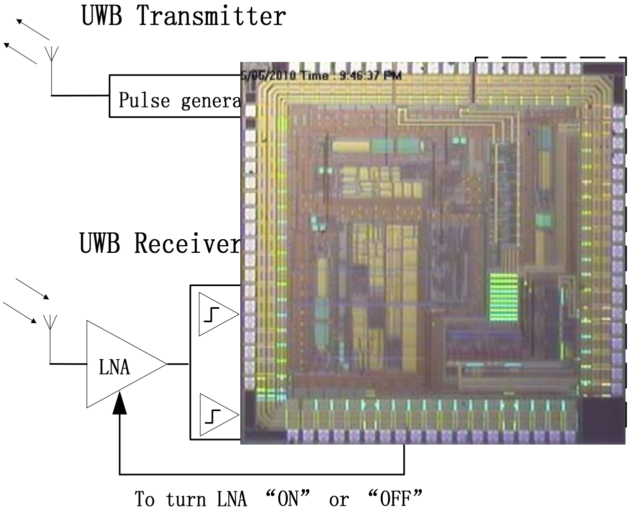
Proposed Pulse-Based Ultra-Wideband Transceiver



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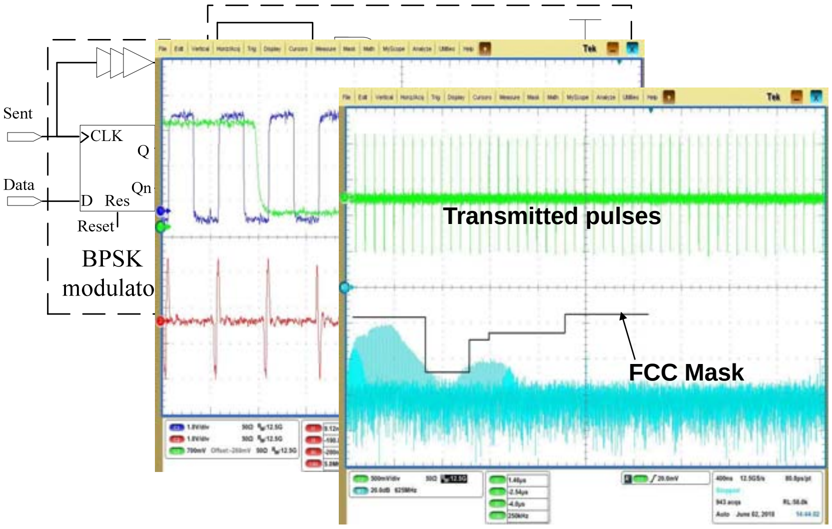
Simplified All Digital Transmitter



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Conclusions

- It is possible to design self-powered wireless biomedical sensors for both wearable and implantable applications
- Many challenges in system architecture, low voltage circuit techniques.
- Call for revolutionary signal processing flow that improves energy efficiency.
- Be aware of challenges beyond CMOS: system integration, packaging, etc.

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