The Design of ECG-on-Chip

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Outlines

- Personalized healthcare.
- Why Electrocardiogram(ECG)-on-Chip?
- Low power techniques for wearable biomedical devices
- Design examples
- Conclusion

Wireless Healthcare

- New trends in healthcare: personalized and prevention-oriented healthcare
- Overburdened healthcare system in ageing society
- Improving productivities and cost saving for healthcare providers, patients, and payers.
- Huge market size and potential new market segment in wireless health

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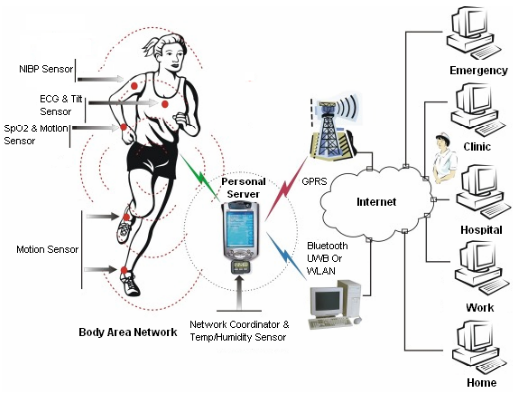
Personalized Healthcare



Body Area Networks

- A latest evolution of healthcare providing healthcare-on-demand service
- Body area networks facilitate:
  - Monitoring patients with chronic disease
  - Monitoring hospital patients
  - Monitoring elderly patients at home
  - 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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Why ECG-on-Chip?

- Cardiovascular diseases are the leading cause of deaths globally
- The direct costs of heart diseases was USD 190b in USA alone[1]
- Prevalence will increase with global aging population and affluence
  - Atrial fibrillation (AF), a common arrhythmia, afflicts nearly 9% of persons over 80 years old[2]

[1]Heart Disease and Stroke Statistics, American Heart Association, 2010
[2]Alan S Go, et al. Prevalence of diagnosed atrial fibrillation in adults, *JAMA,* 2001.

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Idea ECG Device

- Full 12-lead measurement
- Early warning of abnormal ECG
- Wireless connection to remote doctor
- Large memory to record raw ECG data
- Long battery life: more than 7 days
- Easy to use: can be operated by anyone
- Small size, light, comfortable to wear, and waterproof

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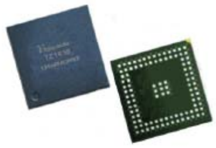
Wearable ECG Devices: Available Products

VitalJacket (Biodevices)
- Disposable electrodes embedded in T-shirt
- Bluetooth transmission, software package provides on-line visualization

VitalJacket T-Shirt And Software Package

Sensium (Toumaz)
- Low-power wireless sensor interface platform
- Uses proprietary wireless link
- Limited number of input channels and low data rate (50kb/s)

Toumaz – Sensium chip



Zio patch (iRhythm)
- Fully recyclable and disposable cardiac monitoring patch
- Off-line recording only, no real-time wireless transmission
- Requires manual event recording and transmission to technical operator via phone line

iRhythm – Zio patch

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What are the Gaps?

- Available multi-channel ECG recording chip
  - TI ADS1298: 0.75mW per channel
- 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

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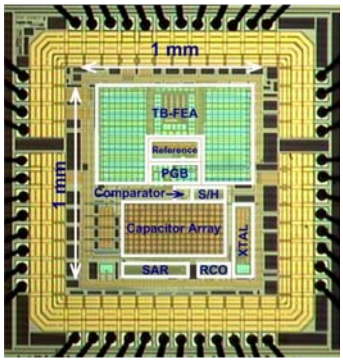
NUS Solution: NanoWatt ECG-on-Chip

- Fully integrated and 450-900nW
- Patented low voltage on-chip tunable band-pass filter(4.5mHz-290Hz)
- Programmable gain(45/ 50 / 54 / 60 dB)
- 12-bit ADC
- On-chip oscillator



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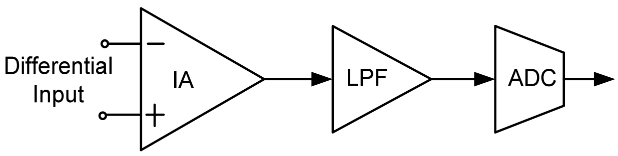
Conventional Low Power Techniques(1)

- Conventional approach for ECG front-end
  - Instrumentation Amplifier (IA): low noise
  - Low pass filter (LPF): cut-off around 100Hz
  - High pass filter (HPF): cut-off < 100mHz
  - Programmable gain
  - Analog to Digital Conversion (ADC)



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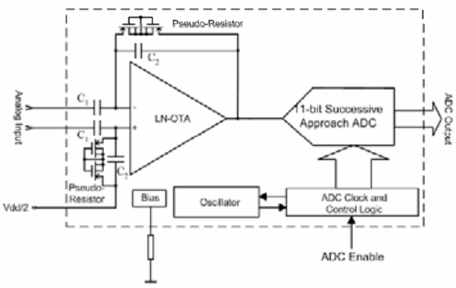
Conventional Low Power Techniques(2)

- A 2.3µW ECG chip



Honglei Wu and Yong Ping Xu, "A 1V 2.3µW Biomedical Signal Acquisition IC", ISSCC, 2006

- Dense integration
  - Amplification
  - Band Pass Filter (BPF)
  - Sample/Hold (S/H)
  - 11-bit ADC
- Issue
  - Narrow bandwidth (<250Hz) and large capacitive load (128pF) require long settling time

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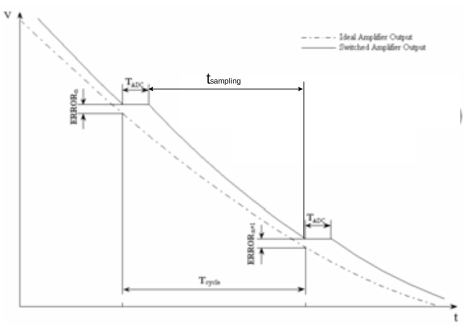
Conventional Low Power Techniques(3)

- Address the problem
  - Increase the sampling time, i.e. shortening hold time.
- Drawbacks
  - All conversion activities take place during TADC
  - High conversion clock frequency (20MHz)
  - High power consumption for ADC block and clock gen



$$Err = V_o \cdot e^{-t_{sampling}/\tau} = \left|\frac{dV_{out}}{dt}\right|_{\max} \cdot t_{hold} \cdot e^{-t_{sampling}/\tau}$$

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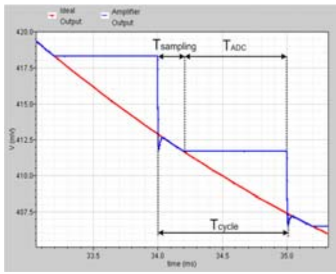
Cross-Domain Optimization

- Optimization done in analog and digital domains
  - Inserting a unity gain buffer between LNA and S/H circuit
  - Increasing hold time leading to low clock frequency for ADC, i.e. 16kHz versus 20MHz.
- Result: 40% reduction in power



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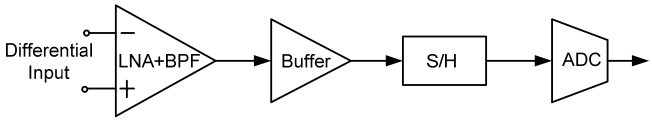

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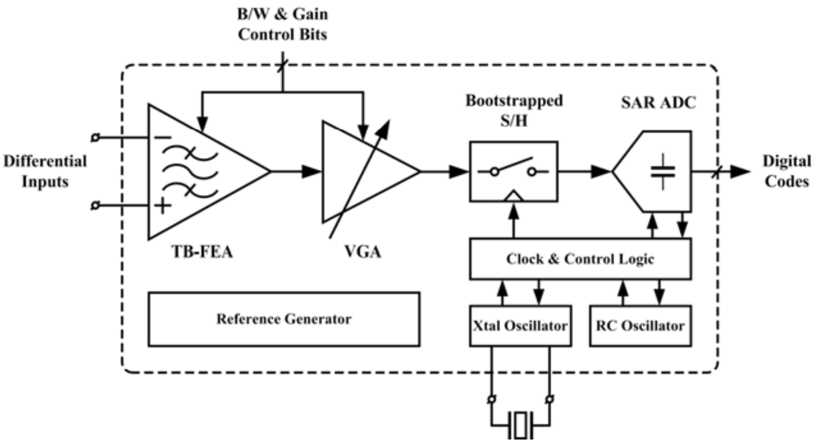
Proposed System Architecture



XD Zou, XY Xu, LB Yao, and Y Lian, "A 1-V 450-nW fully integrated programmable biomedical sensor interface system," *IEEE Journal of Solid-State Circuits*, vol.44, No. 4, pp.1067-1077, April 2009.

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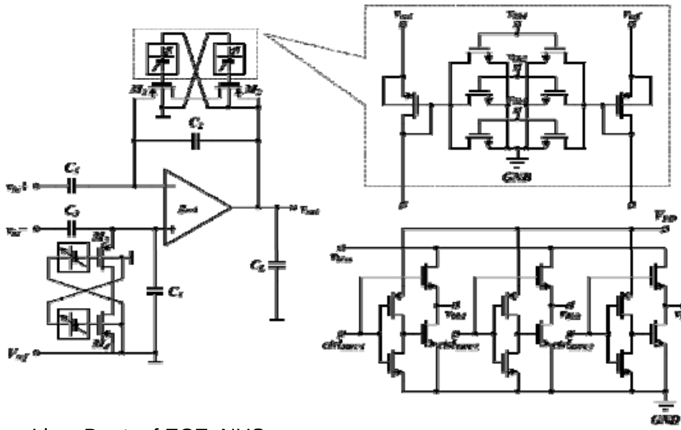
Front-end Amplifier

- Balanced tunable active resistor structure
- 3-bit current-controlled HPF



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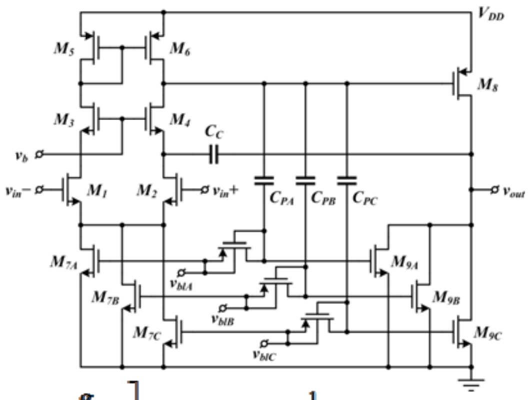
Low-power Low-noise OTA

- Push-pull output
- M3 & M4 for freq compensation
- 3-bit current-controlled LPF
- Input-referred thermal noise



$$\overline{v_n^2} = 4kT\frac{1}{g_{m1,2}}\left[1+\frac{2r_{O5}^2}{g_{m1,2}g_{m3,4}r_{O1}^2R_{O1}^2}+\frac{g_{m5,6}}{g_{m1,2}}\right]+2kT\frac{1}{(g_{m8}+g_{m9})(g_{m1,2}R_{O1})^2}$$

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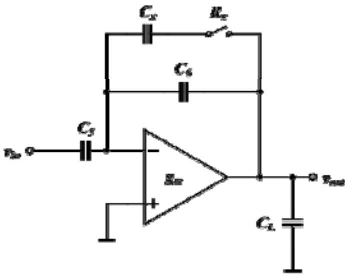
Programmable Gain Buffer

- Over 15 kHz bandwidth for faster S/H tracking
- 2-bit gain tuning
- "Flip-over-capacitor" scheme to avoid Rx in the feedback path



$$G = \frac{C_5}{C_6} \bullet \frac{sC_xR_x + 1}{sC_xR_x + 1 + C_x/C_6}$$

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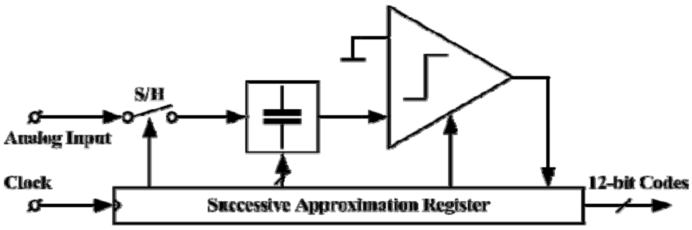
12-bit SAR ADC

- **Passive S/H to reserve power**
- **Constant comparator reference to avoid dynamic offset**



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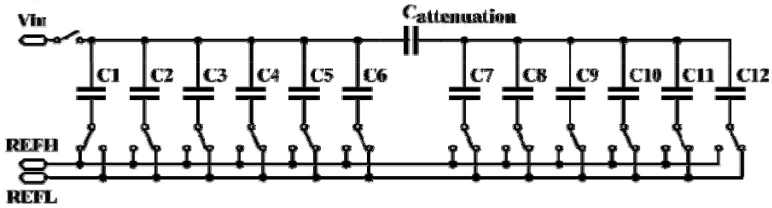
12-bit Binary Search Array

- $C_{attenuation}$ chosen to be equal to C_{unit} to compensate the input and bottom plate parasitic capacitances



$$err \approx \frac{V_{FS}}{2^{m+n}}\left[(p_{CMP}-1)\left(\frac{1}{2}-\frac{1}{2^m}\right)+p_{PIP}\left(1-\frac{1}{2^n}\right)\right]$$

$$\approx 1LSB\left[\frac{1}{2}(p_{CMP}-1)+p_{PIP}\right]\approx 0.7LSB$$

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32 kHz Low-power RC Oscillator

- Active-load-capacitor oscillator for further power saving
- < 60 nA operating power
- < 3 μs_{rms} measured jitter
- > 9-bit accuracy
- Sufficient for QRS detection

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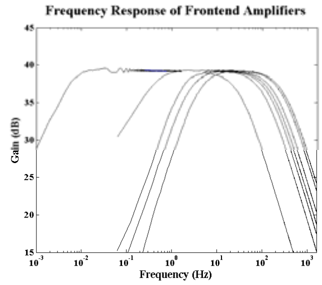
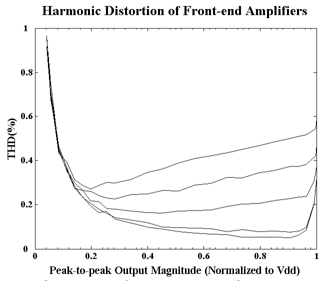
Front-end Measurement Results





- High-pass cutoff freq
  - 4.5 mHz ~ 3.5 Hz
- Low-pass cutoff freq
  - 30 Hz ~ 292 Hz
- Mid-band gain
  - 45.6 / 49 / 53.5 / 60 dB
- Input-referred noise
  - 2.04 μV_{rms}
- THD
  - < 0.6% @ full swing

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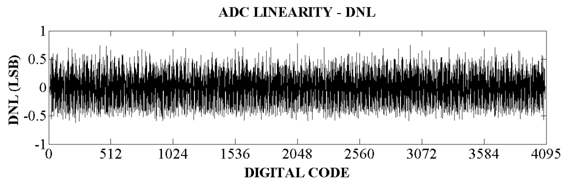
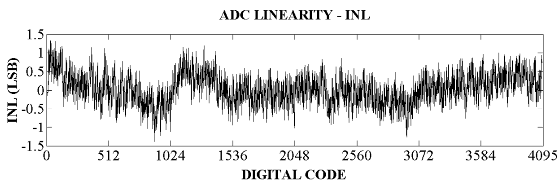
12-bit SAR ADC

- DNL< ±0.8 LSB
- INL< ±1.4 LSB
- SFDR: 74 dB
- SNDR:63 dB





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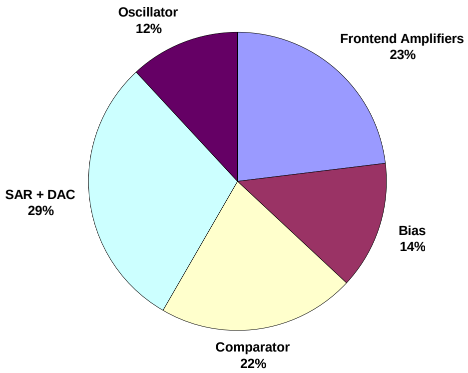
Power Breakdown

- Low-power mode (QRS detection): 445 nW



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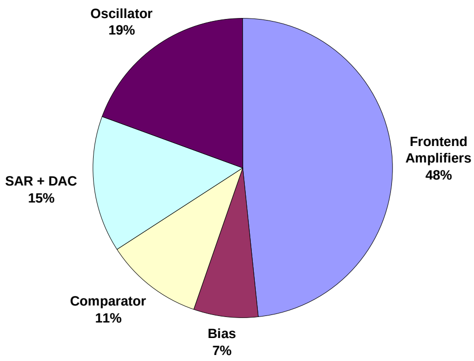
Power Breakdown

- Max power mode (ECG recording): 895 nW



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Performance Comparison

Parameter	Design in [1]	Design in [5]	Design in [2]	This work
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 Bandwidth	0.015 Hz ~ 4 kHz (Tunable)	0.392 ~ 295 Hz	0.003 ~ 245 Hz	4.5 mHz ~ 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

[1] M. Yin and M. Ghovanloo, "A Low-Noise Preamplifier with Adjustable Gain and Bandwidth for Biopotential Recording Applications," Proceedings of IEEE International Symposium on Circuits and Systems, pp. 321-324, May 2007.

[2] W. Wattanapanitch, M. Fee and R. Sarpeshkar, "An Energy-Efficient Micropower Neural Recording Amplifier," IEEE Transactions on Biomedical Circuits and Systems, Vol.1, No.2, June 2007.

[3] H. Wu, Y. P. Xu, "A 1V 2.3µW Biomedical Signal Acquisition IC," Proceedings of the 2006 IEEE International Solid-State Circuit Conference, Feb. 2006, 119-128.

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NUS ECG-on-Chip

- 450 nW fully integrated programmable ECG chip
- 2.3µW ECG recording with on-chip QRS detection, memory, and MCU interface
- 12-lead ECG recording chip
- 32-channel EEG recording chip (lowest power consumption < 20µW)
- Wireless ECG-on-Chip (available soon)

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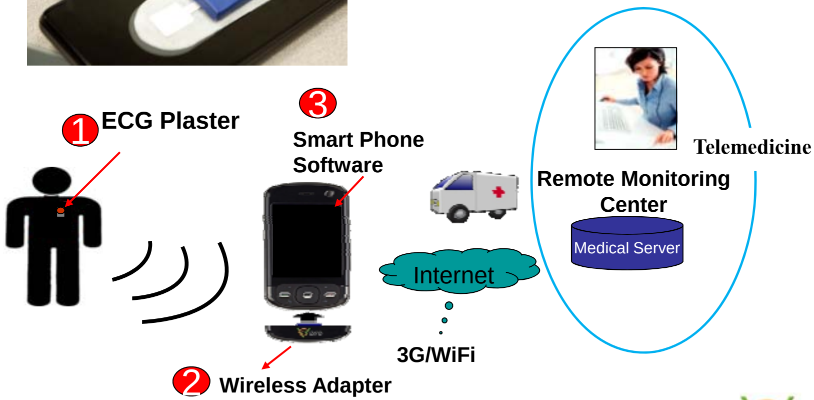
Application (1): Wireless ECG Plaster



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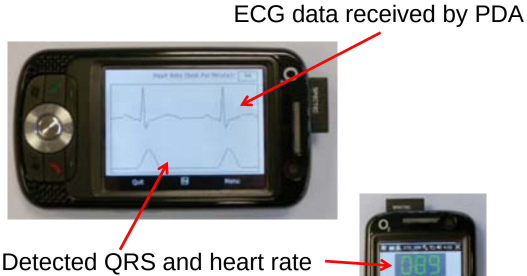
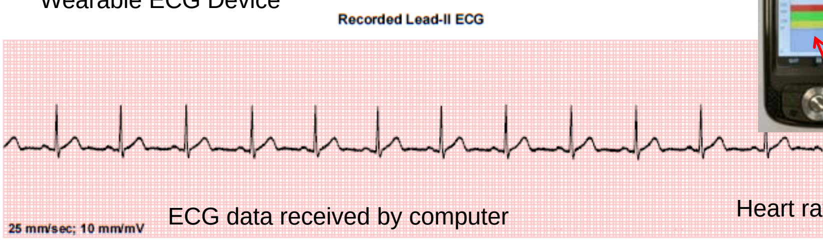
Prototype of NUS ECG Plaster





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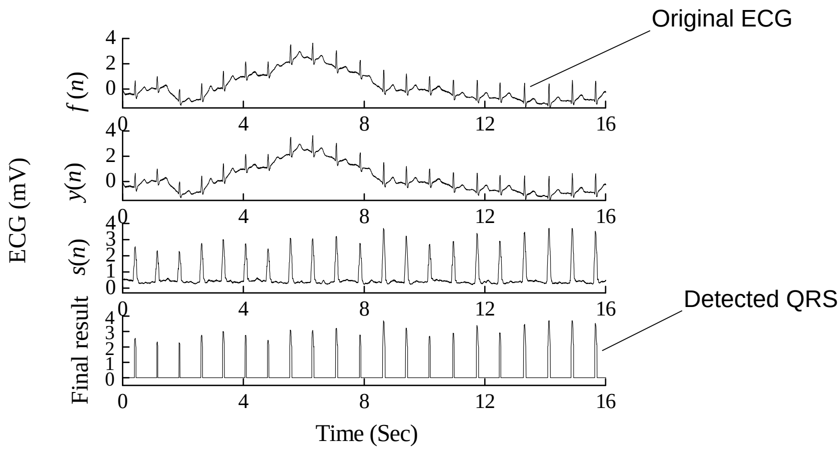
Detection of QRS for Exercise ECG under Running by NUS Algorithm (NanoWatt)



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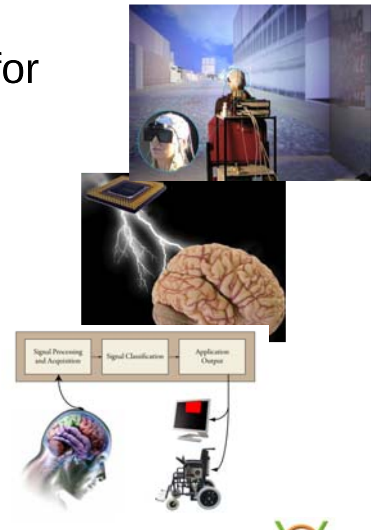
Applications(2): Wearable EEG Sensor

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



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Conclusions

- Wireless wearable ECG devices are essential for personalized healthcare, especially for ageing society
- Very challenging for the design of plaster based ECG device
- Cross domain optimization technique offers better power efficiency

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Acknowledgment

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  - Wen Sin Liew, Xiaodan Zou, Xiaoyuan Xu, Jun Tan, Fei Zhang, Ying Wei, Chacko John Deepu, Lei Wang, Xiaoyang Zhang, Xiaofei Chang, Muhammad Cassim Mahmud Munshi, Zhe Zhang, Chao Xue, Qi Zhang, Daren Zhang.
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Thank You

Q&A

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