Ultra-Low Power Computing Systems for Bio-Signals Monitoring

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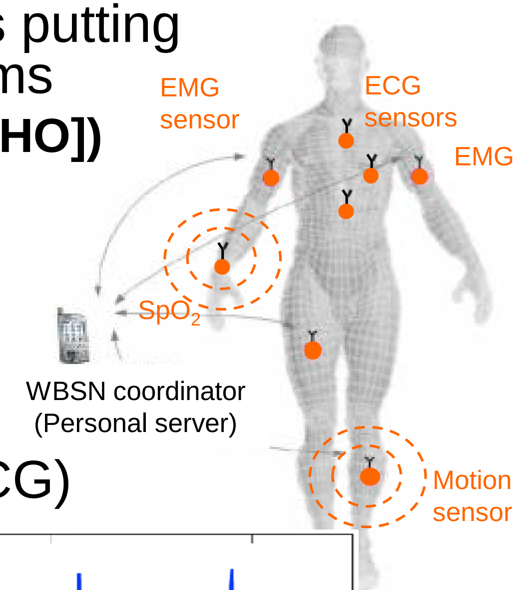
PHIDIAS - NiPS Summer School 2014
Perugia, Italy (July 17th, 2014)

Design of Wireless Body Area Sensor Nodes (WBSN)

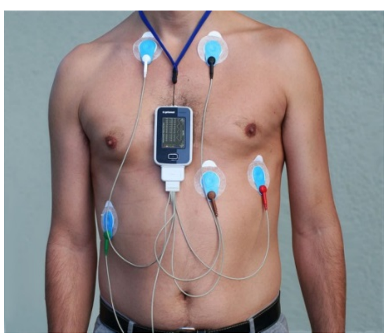
- Alarming rise of lifestyle-induced chronic diseases is putting unsustainable pressure on current healthcare systems
  - 50% of all deaths worldwide in 2006 **(55% in 2012 [WHO])**



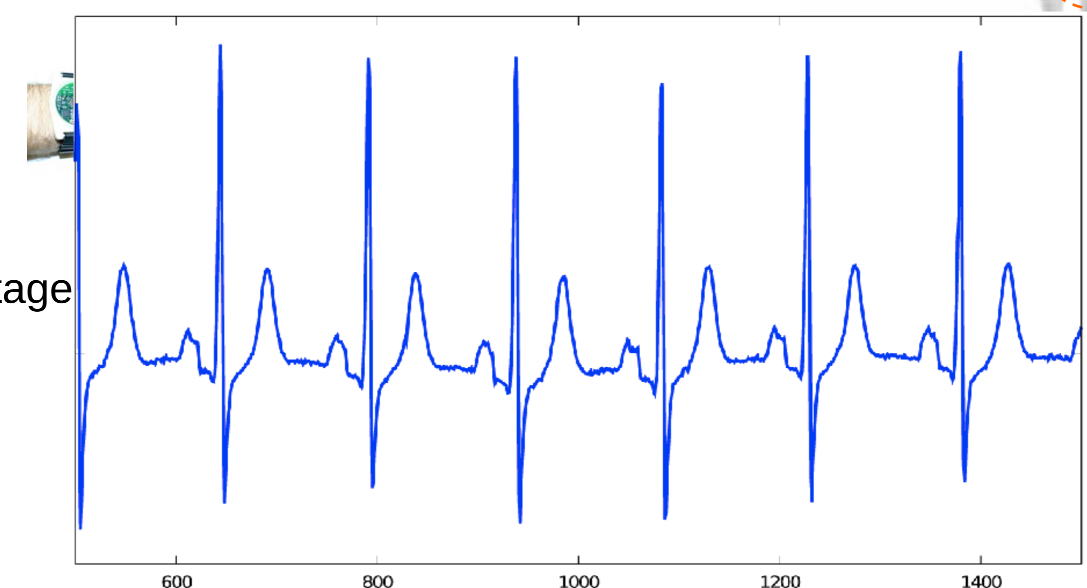
- A two-fold paradigm shift is anticipated:

Symptom-based	➔	**Preventive healthcare**
Hospital-centered sickcare	➔	**Person-centered healthcare**

- WBSN are key for this shift: Electrocardiogram (ECG)



ECG Holter data logger (clinical practice)



to
2-3
SN
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?

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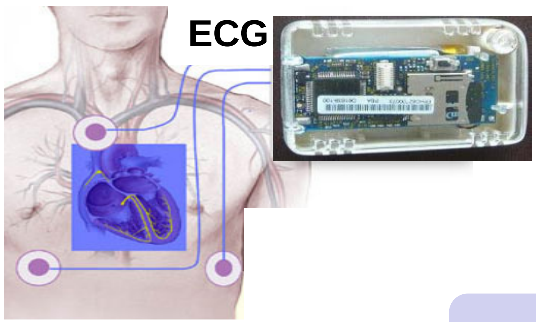
The Shimmer™ WBSN platform

- **TI MSP430 microcontroller**
  - 16-bit, 8MHz, 10KB RAM, 48KB Flash
  - ADC converters, DMA, HW multiplier
- **CC2420 radio**
  - 250 Kbps, ZigBee compliant
- **Sensors**
  - 3-channel ECG
  - Accerelometers and gyroscopes

- **CONSTRAINTS:**
  - No floating point operation
  - No hardware division
  - Limited memory
  - Limited computing power
  - Limited autonomy (rechargeable Li-polymer battery of 250 mAh)

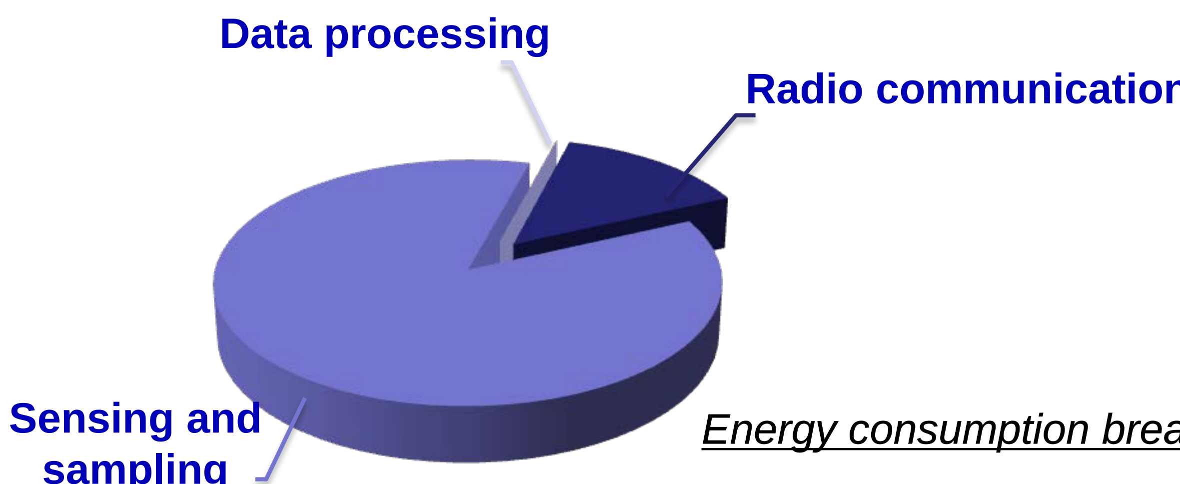
Long-lived wireless ECG monitoring require a major breakthrough in the energy efficiency of WBSN nodes



1. **Can we reduce the data sensing/sampling cost and the amount of streamed data?**
2. **Can we embed automated analysis without compromising the system lifetime?**

Under stringent processing and memory constraints!

- This wireless 1-lead ECG streaming monitor **lasts 134.6 h.**

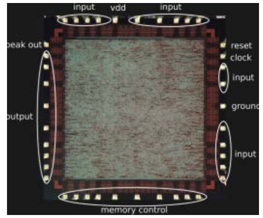


Energy consumption breakdown

[Rincon et al., DATE '08 and TITB '11]

State-of-the-Art Smart WBSN: Embedded Processing

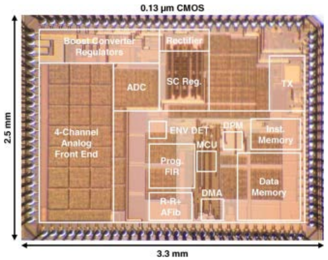
Shimmer (shimmerresearch, 2010-13)



Heart Rate Monitoring (Massagram, 2010)

Corventis's PiiX (Corventis MCT systems, 2011-13)

Toumaz's Sensium Life (Wong,2009)



Zhang (2012)

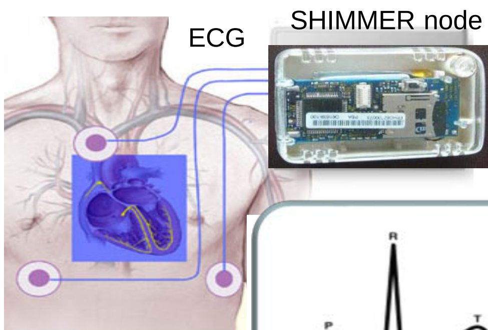
IMEC cardiac patch (Yazicioglu,2009)

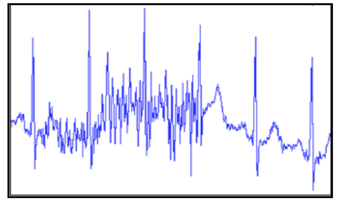
Holst Centre (Masse, 2010-13)

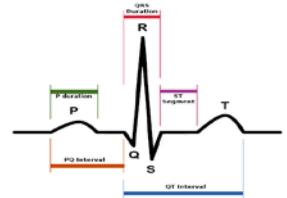
Only simple filtering and one-lead input

The goal from an ULP system-level perspective is to design:
(1) Long-lived and accurate multi-lead ECG monitoring
(2) Smart wireless personal health analysis systems

Our smart ECG sensor node concept for WBSN will capitalize on all 3 automatic processing algorithms



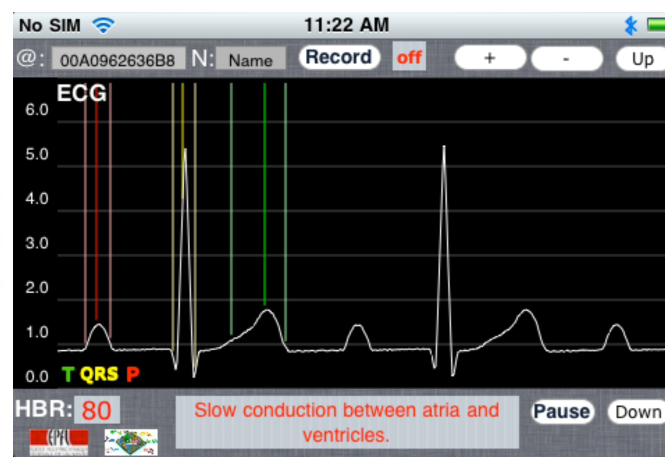




Noise filtering → ECG delineation → Feature Analysis (arrhythmia diagnosis) →

Compression →

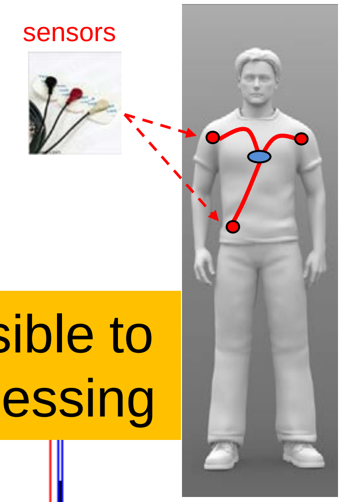
Displays the received data

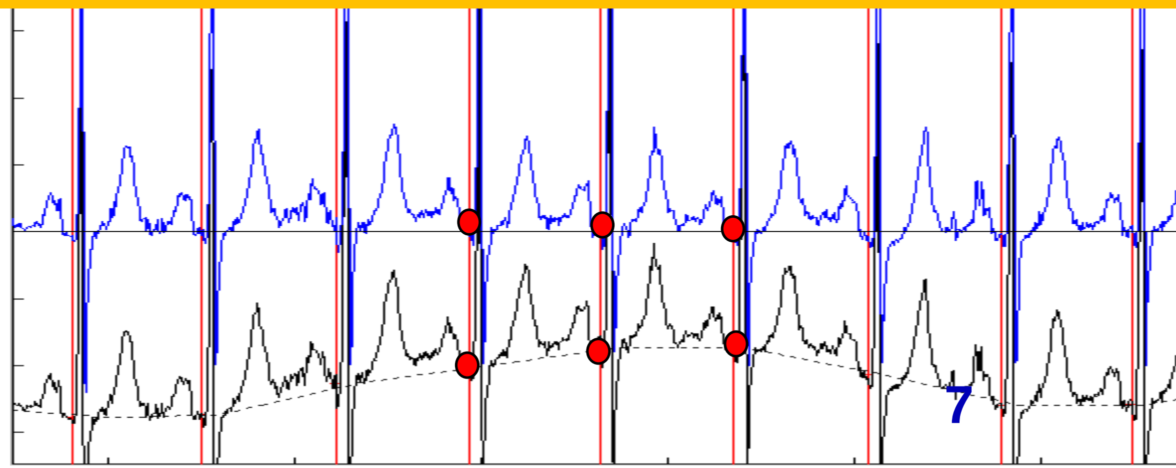


Selecting ECG filtering algorithms

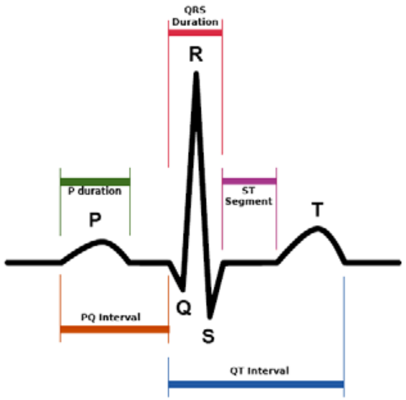
- Baseline wander and muscular noise removal
  1. Cubic spline **[Rincon et al., TITB'11]**
     - Detect the knot of 3 consecutive beats
     - The curve fitting the 3 knots is the baseline wander
  2. Morphological filtering
     - Based on erosion and dilation operations
     - Baseline correction + noise reduction

Moral of the story: knowing possible noise sources, possible to correct them with few sensors and "simple" signal processing



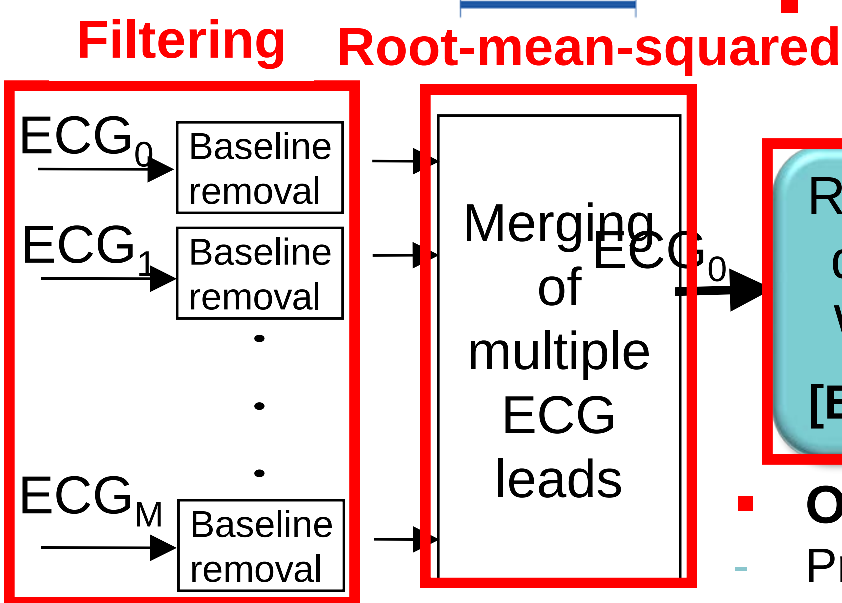


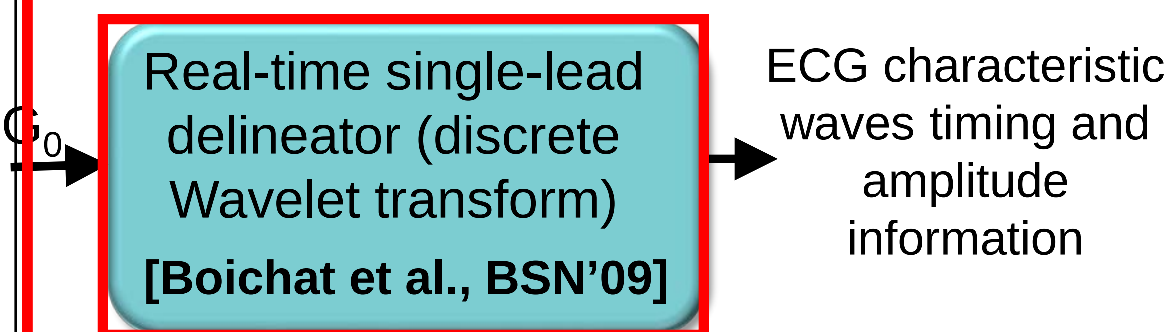
Embedded delineation of ECG characteristic waves



- Delineation is either done manually (by a cardiologist) or automatically (either by a bulky bedside equipment or offline on a PC)

- Delineation can be either based on a single lead or multiple leads



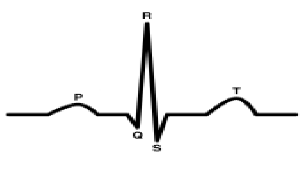


- **Optimizations for online operation:**
  - Processing of short blocks of ECG samples
  - Dynamically adapting underlying signal thresholds
  - Integer operations for fast implementation of complex functions (√)

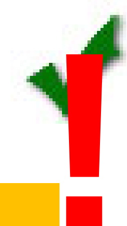
Arrhythmia detection in WBSN systems

- Database of pathologies based on delineated points and thresholds
  - Defined at design time with doctors (few 100s of bytes of memory)
  - Applied at run-time by using a **simple look-up table**

$\boxed{[QRS_{on}, QRS_{end}] \leq 0.10s}$
$0.12s \leq [P_{on}, QRS_{on}] \leq 0.20s$
$T_{peak} > 0$
$[QRS_{on}, R_{peak}] < 0.03s$
QT interval rule
HBR variability
Atrial activity



Filtering → **ECG delineation** → **Arrhythmia diagnosis** →



No issues of complexity or memory requirements, but need to develop **new adaptive classifiers** for each type of person

Biggest issue: Achieve efficient interaction with doctors!

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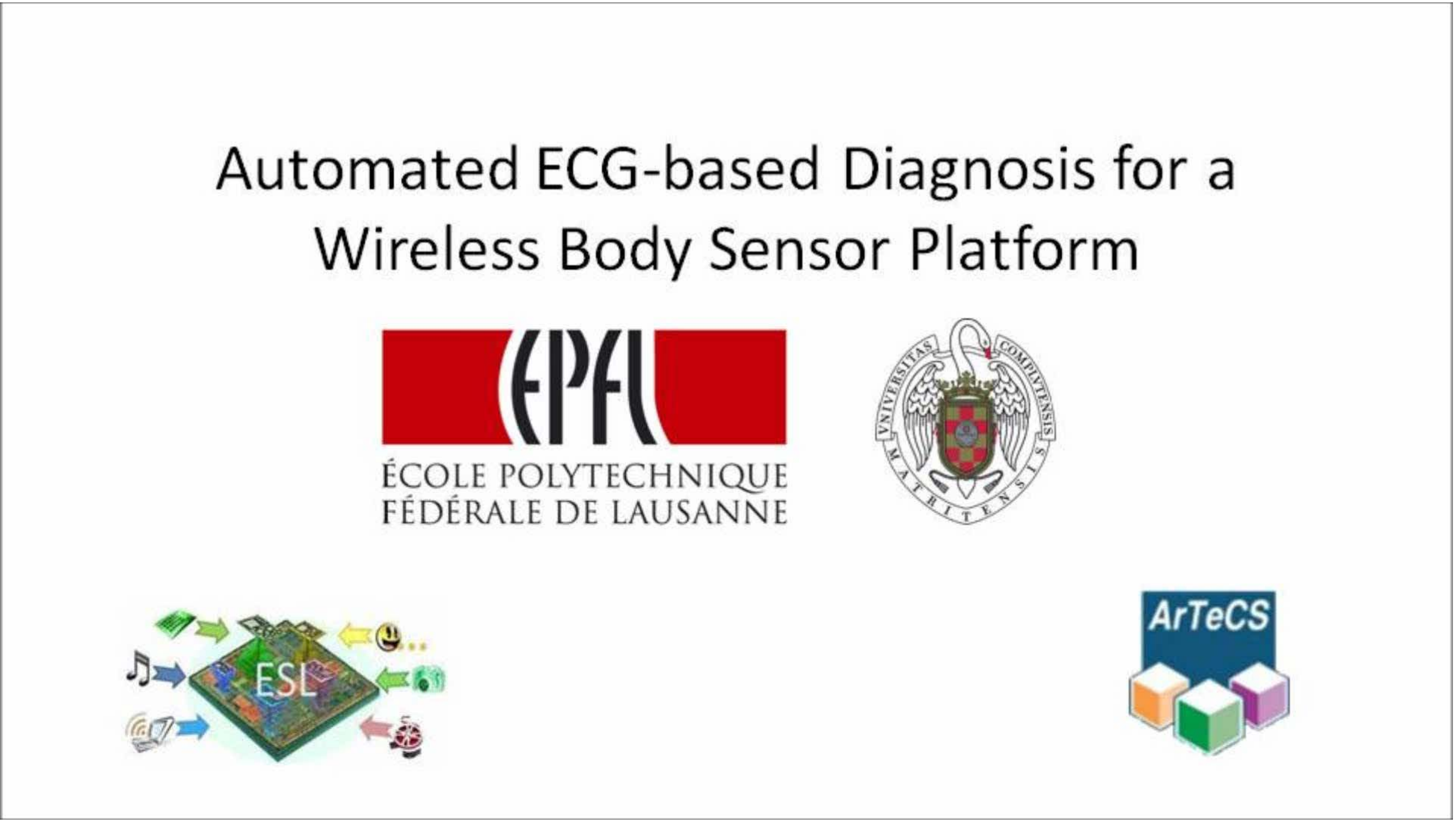
Personal arrhythmia detection WBSN system

See video at: http://esl.epfl.ch/cms/lang/en/pid/46016



Implementation results on the Shimmer node as WBSN system

- Real-time delineation demands limited requirements after careful algorithm optimization (computational load and memory footprint)

Algorithm	RAM usage	Buffers length	Execution time
Single-lead WT delineator	6.8 kBytes	512 elements	5%
Multi-lead WT delineator (morphological filter of baseline removal)	5.5 kBytes	256 elements	30.5% total (23% filtering, 2.5% multi-lead merging, 5% delineation)

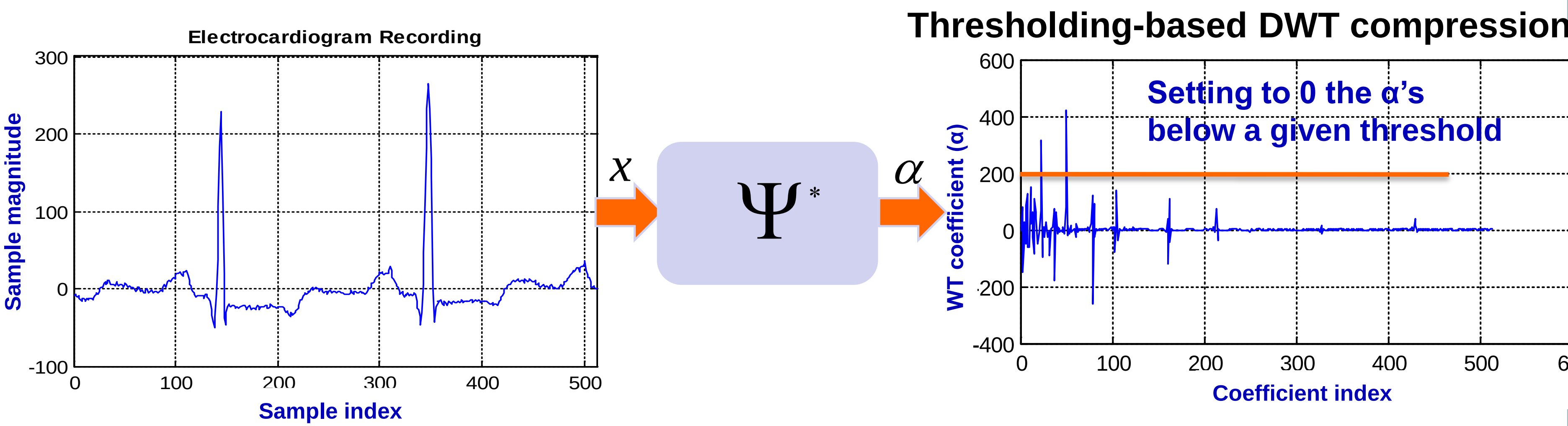
Execution of complex automatic ECG processing algorithms is possible

Small on-chip memory (10 kB) is the current limiting factor

Advanced on-chip processing gives real-time information about heart health with no impact on node lifetime: **more than 139 hours**

The electrocardiogram is a highly compressible signal

- ECG is highly sparse in the wavelet domain



- The Discrete Wavelet Transform (DWT) allows near-optimal compression of ECG signals

Orthogonal wavelet basis

Original ECG vector

$$x_N = \Psi \alpha_N$$

$$\|\alpha\|_0 = K << N$$

Coefficient vector

But can we create a "universally optimal" low-complexity compression scheme for ECG signals that works as well?

Compressed sensing (CS) is a new low-complexity sensing and compression paradigm for sparse signals

- Using CS it is sufficient to collect *M* (<<*N*) linear random measurements (samples)

Measurement/Sensing matrix (Gaussian random matrix)

$$\boxed{y_{M\times 1} = \Phi_{M\times N} \cdot x_{N\times 1}}$$

Measurement vector **Original ECG vector**

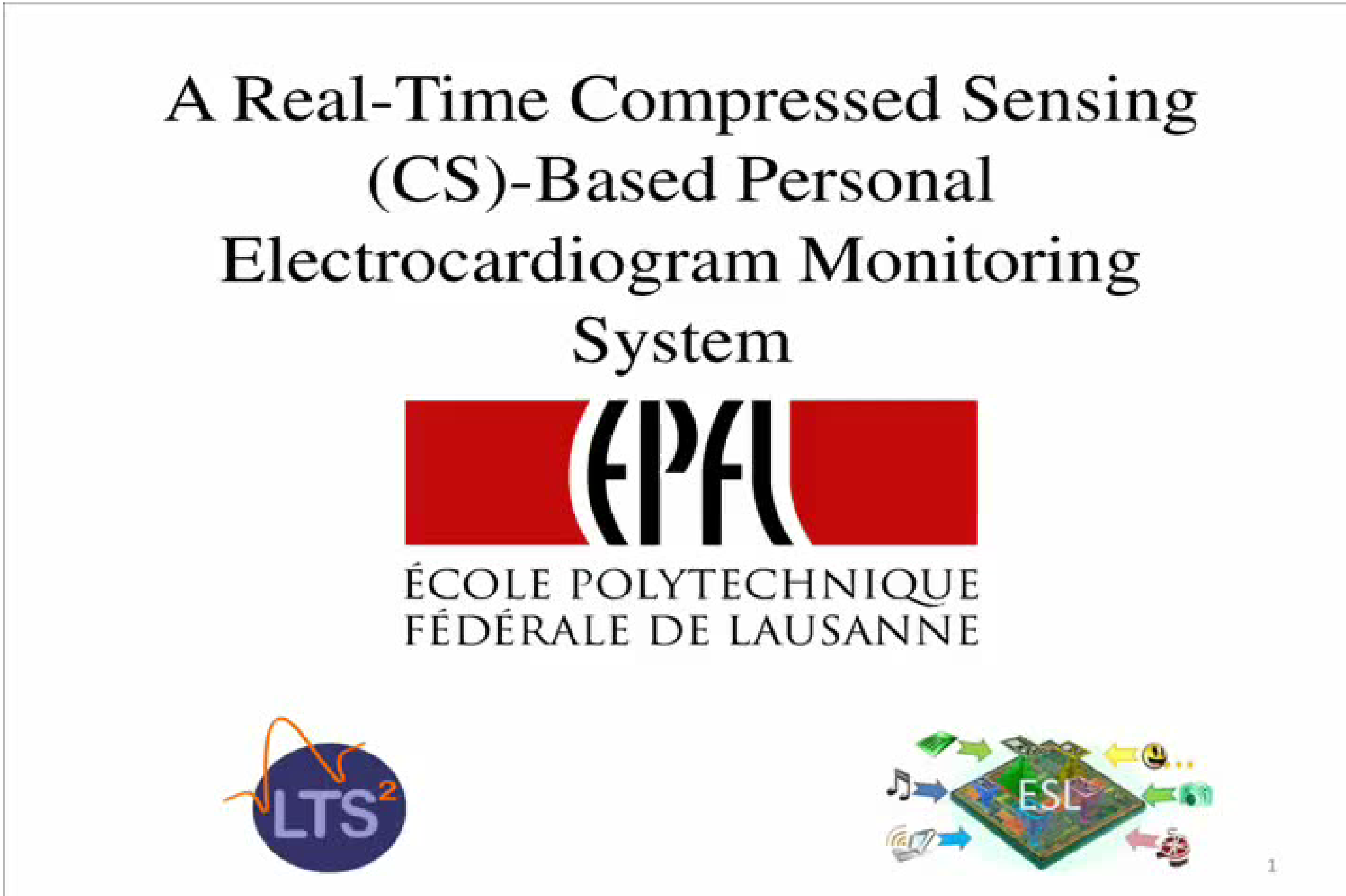
- Ther
prob

CS is attractive for real-time ECG compression on resource-constrained WBSN, but what about biosignal degradation due to CS reconstruction (in real-time)?

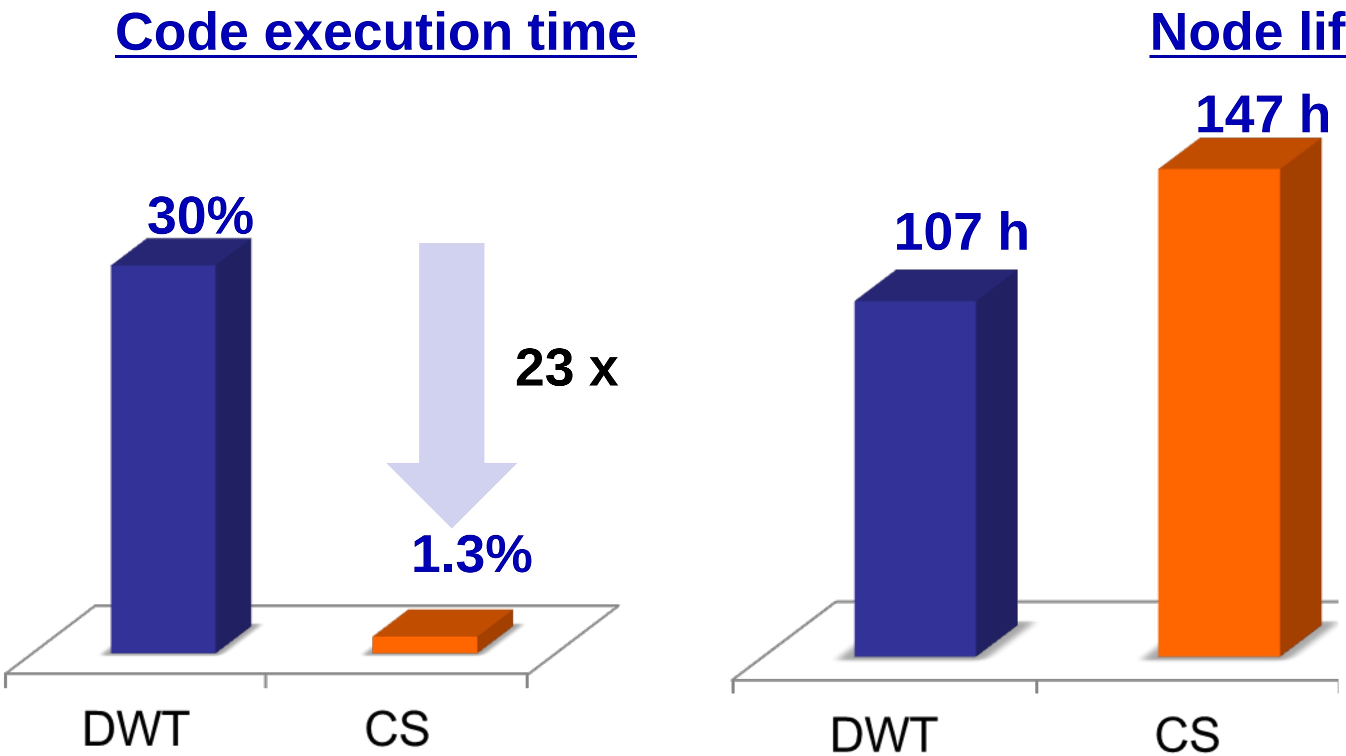
$$\boxed{\min_{\tilde{\alpha}\in\Re^N} \left\|\tilde{\alpha}\right\|_1 \quad \textbf{Subject to: } \left\|\Phi\Psi\tilde{\alpha} - y\right\|_2 \le \sigma}$$

CS-based ECG WBSN (only 30% of ECG data kept)

See video at: http://esl.epfl.ch/page-42817.html



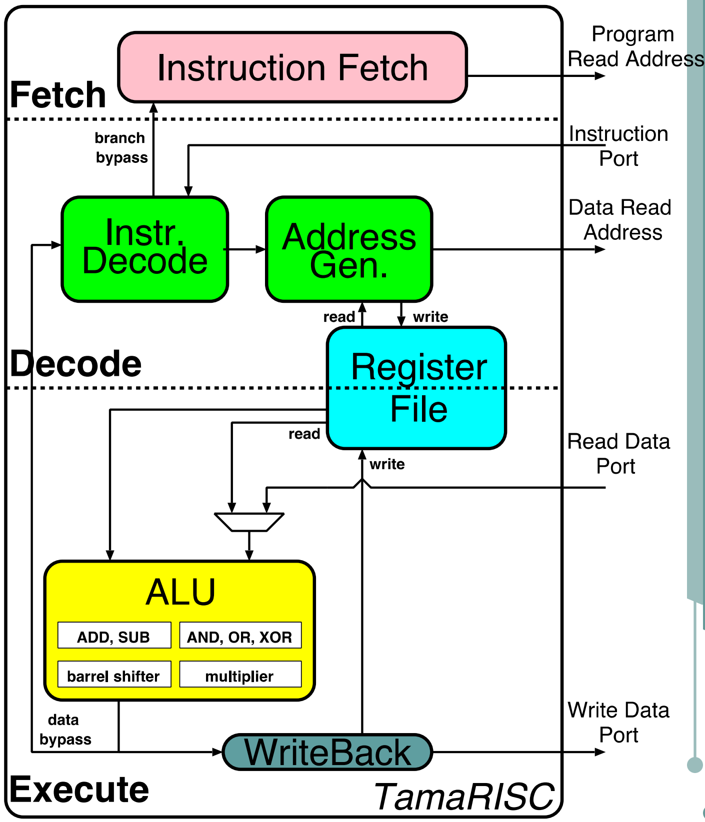
CS provides over a 23-fold reduction in execution time, but only 10% node lifetime extension



Limited gains because the used generic microcontroller is not optimized for ultra-low-power **DSP and CS-based operations in biological signals**

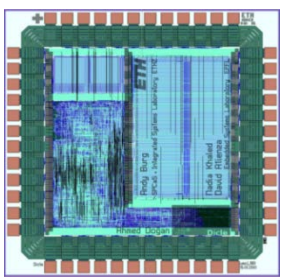
Simplicity is the key: A new generation of ultra-low-power processing cores for WBSNs

- FIRAT/TamaRISC: Inspired on PIC24
  - 16-bit RISC, simple 3-stage pipeline
  - Drastically reduced to 15 types of instructions (added CS execution support)
  - 1 cycle/inst., Immediate branch, full data bypass
  - Minimal ALU: ADD, SUB, AND, OR, XOR, Shift, Mult.

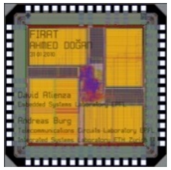


[Dogan et al., DATE 2012]

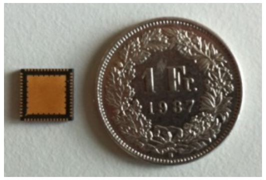
- Minimal area/power for biosignals processing
  - Less than 5% of an embedded platform (< 10 kGE)
  - Near-VT computing: ~10 MHz (180MHz@1V)



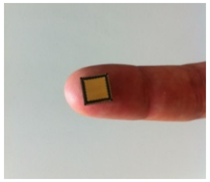
Dicle (umcL 180nm)



Firat (umcL 90nm)



Firat ASIC vs. 1chf coin



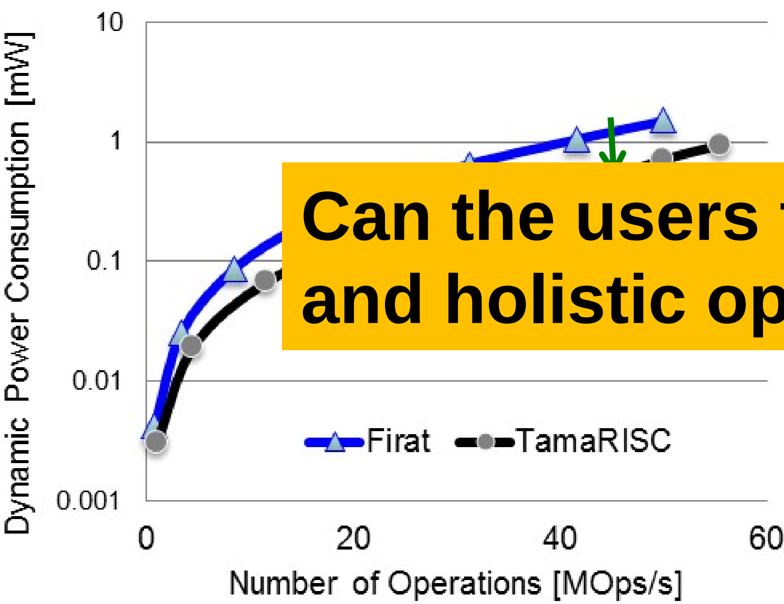
… And vs. my finger!

TamaRISC: Experimental results

	Number of Clock Cycles(*)		
	FIRAT	TamaRISC	MSP430
Filtering-DWT	1.85M K	1.81M	4.7M
Compression	114K	90K	800K

(*) 1-package compression (512 samples)

TamaRISC only 38% of MSP430 cycles due to architecture specialization and low voltage operation



TamaRISC vs Firat: Faster and 30% extra power savings due to full data bypass, CS support and low-power encoding

Can the users finally see the benefit of CS and holistic optimization at system-level?

		logy
TamaRISC	12.1 pJ	90 nm
16-bit [Kwong,2011]	> 47 pJ	130 nm
32-bit [Ickes,2011]	19.7 pJ-27 pJ	65 nm

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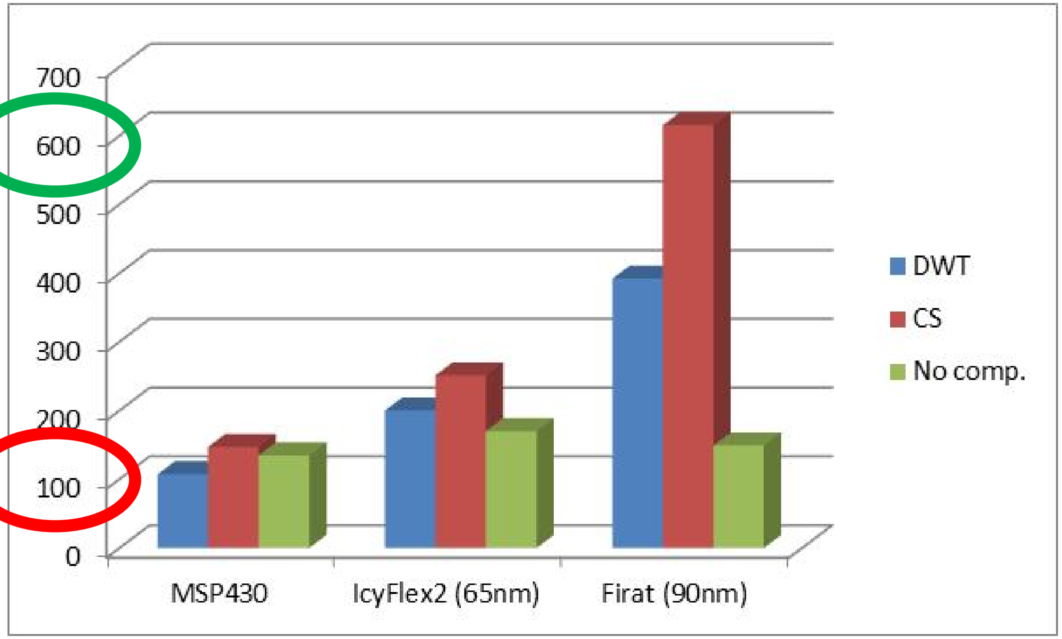
CS and biosignals algorithms analysis show true advantages on ultra-low-power (ULP) processors

Lifetime (in hours)



- Feasible to develop long-lasting smart WBSN nodes that interact with smartphones
  - Adapts at run-time to patient's heart
  - Automatic detection of arrhythmias
  - Real-time notification to doctors

SmartCardia

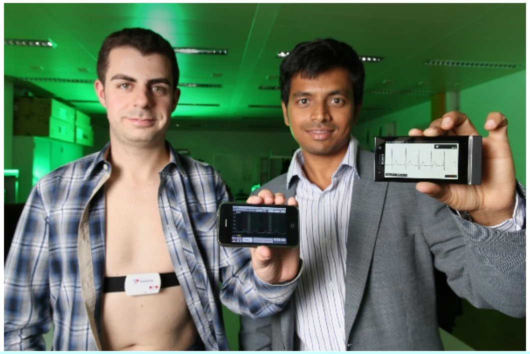
CS and biosignals algorithms analysis show true advantages on ultra-low-power (ULP) processors

See video at: http://www.smartcardia.com

Smart ULP WBSN designs can reach resonance in the media, but also impact in medical community!

18 octobre 2011

Le résumé de l'actualité romande



Date: 19.10.2011

LE TEMPS

Santé

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Part of complete coverage on

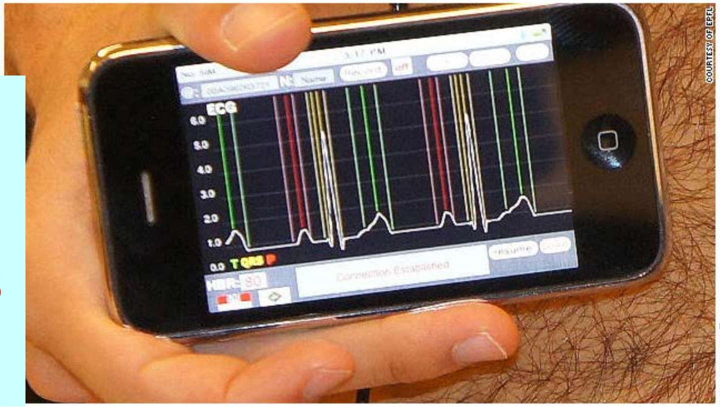
CNN Labs

CNN LABS

Smartphone detects danger in a heartbeat

By **Matthew Knight,** CNN

October 24, 2011 -- Updated 1614 GMT (0014 HKT) | Filed under: Mobile



Date: 19.10.2011

Blick

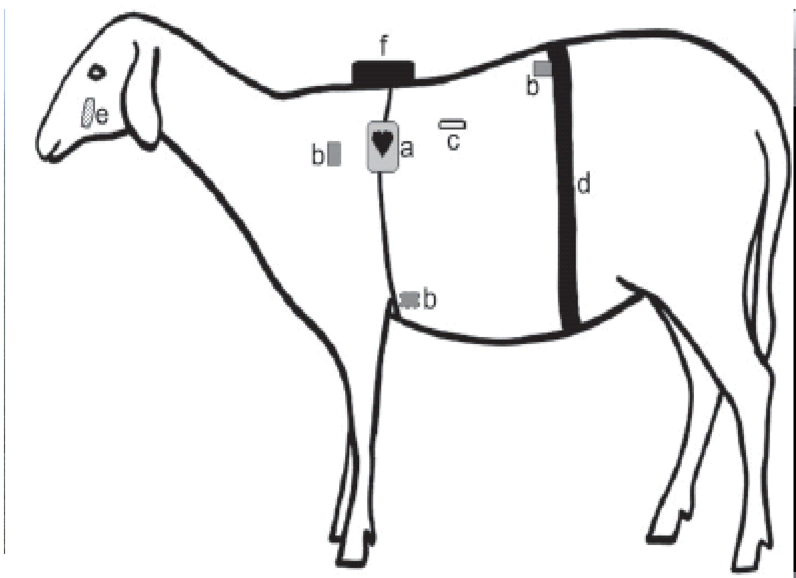
Ein SMS vom Herz

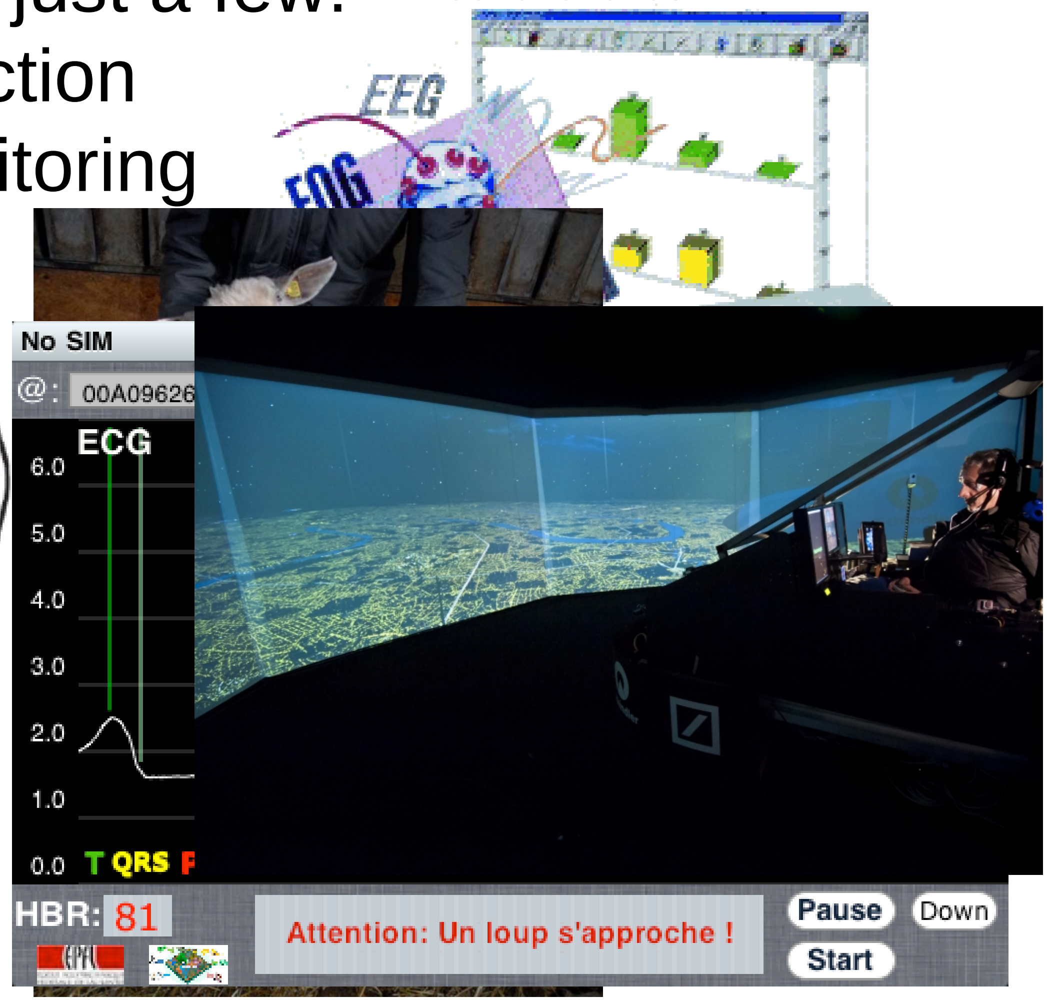
Lausanne – Diagnose: Herzinfarkt. Der häufigsten Todesursache der Welt wird der Kampf angesagt, und zwar mit Schweizer Technik. Forscher der ETH Lausanne haben ein Gerät entwickelt, das den Herzrhythmus konstant überwachen kann. Falls eine Rhythmusstörung auftritt, **sendet das Gerät an Patient und Arzt per SMS oder E-Mail eine Warnung.** «Das System liefert sehr präzise Daten und verfügt über einen leistungsfähigen Akku mit einer Laufzeit von drei bis vier Wochen», sagt Forscher David Atienza.

Non-intrusive, light and can reduce visits by 50-60% for patients (4-week test)

New smart ULP WBSN systems open up a new dimension of possibilities

- Multiple applications, just a few:
  - Sleep apnea detection
  - Sheep stress monitoring
  - Pilot monitoring





New smart ULP WBSN systems open up a new dimension of possibilities

See video at: http://www.youtube.com/watch?v=X1jQH8D8vJM

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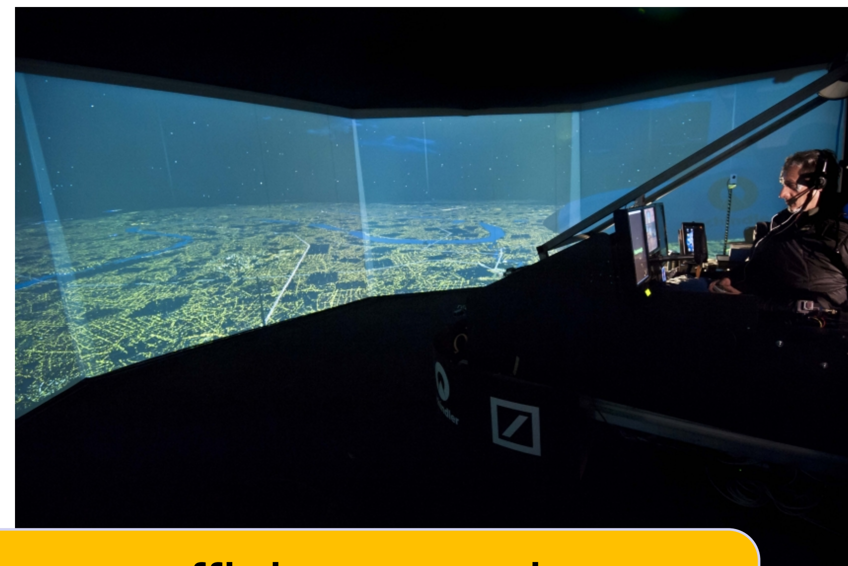
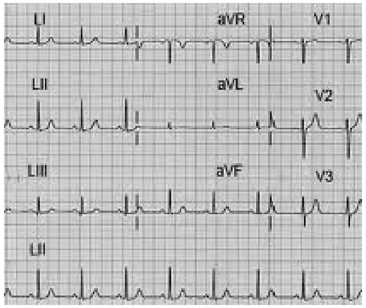


But can we get even better energy efficiency and target more complex medical applications (still on-line)?

Multiple-input bio-signal analysis seems well suited for multi-core platforms

- Multiple-input ECG analysis is **<u>parallel-friendly</u>**, similar processing in each lead:
  - Filtering, baseline removal
  - Features extraction
  - Data compression

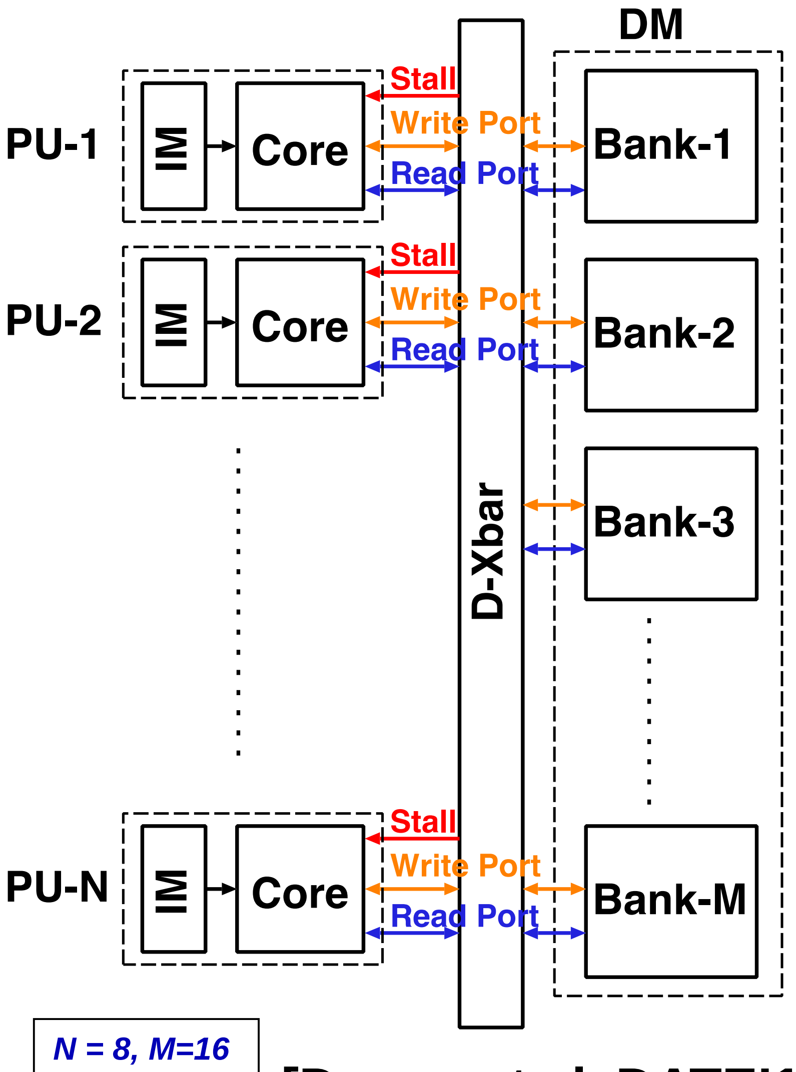


- Applications theoretically suited for multi-core as many algorithms process each bio-signal separately
  - Very limited (and predictable) shared data

- **Opportunity:** low-power design in high-performance via parallel processing enables aggressive voltage-frequency scaling (near-threshold)

Are multi-core architectures more power efficient than single-core for ULP biosignal analysis?

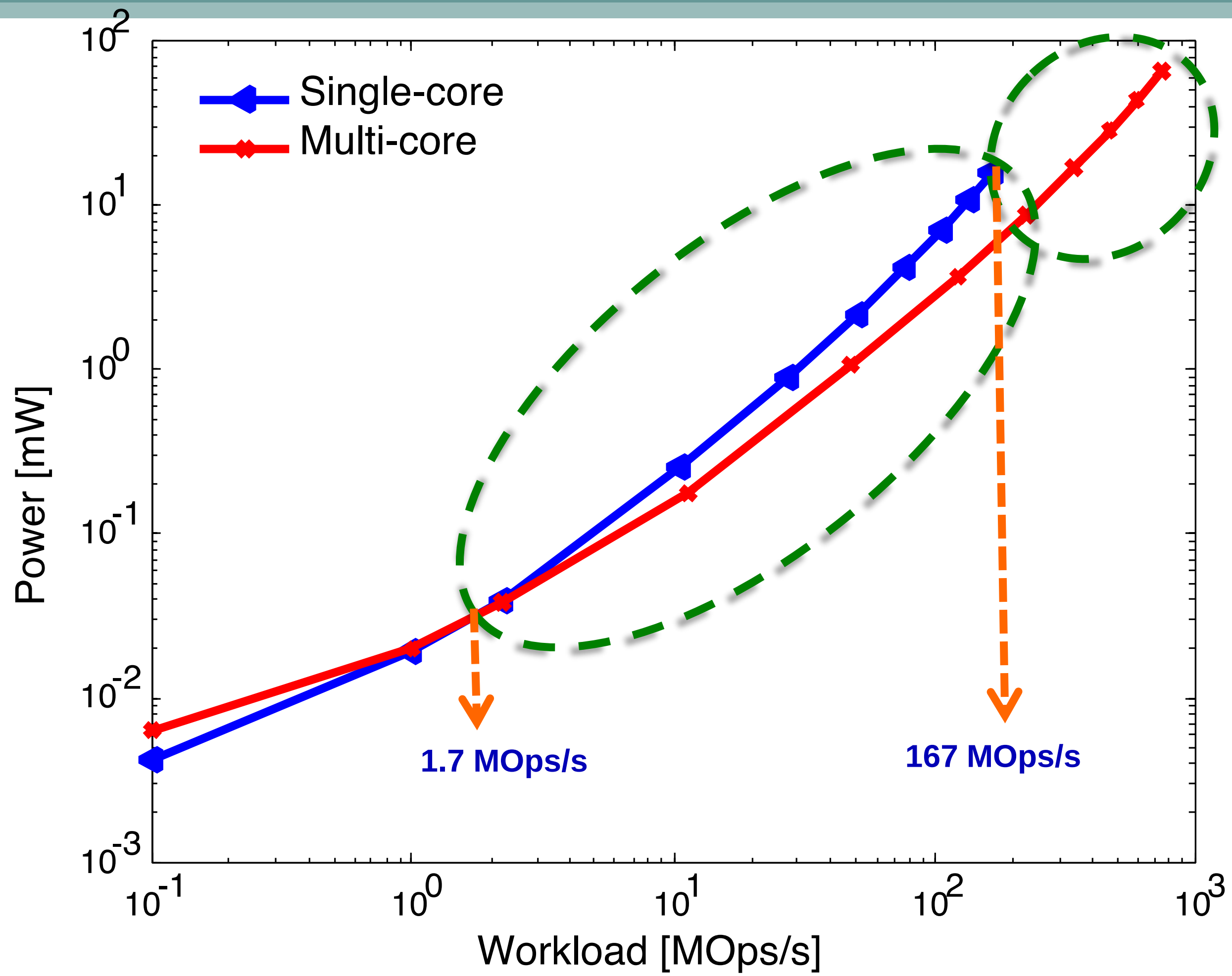
ULP Multi-Core WBSN architecture with tightly coupled memories



[Dogan et al, DATE'13]

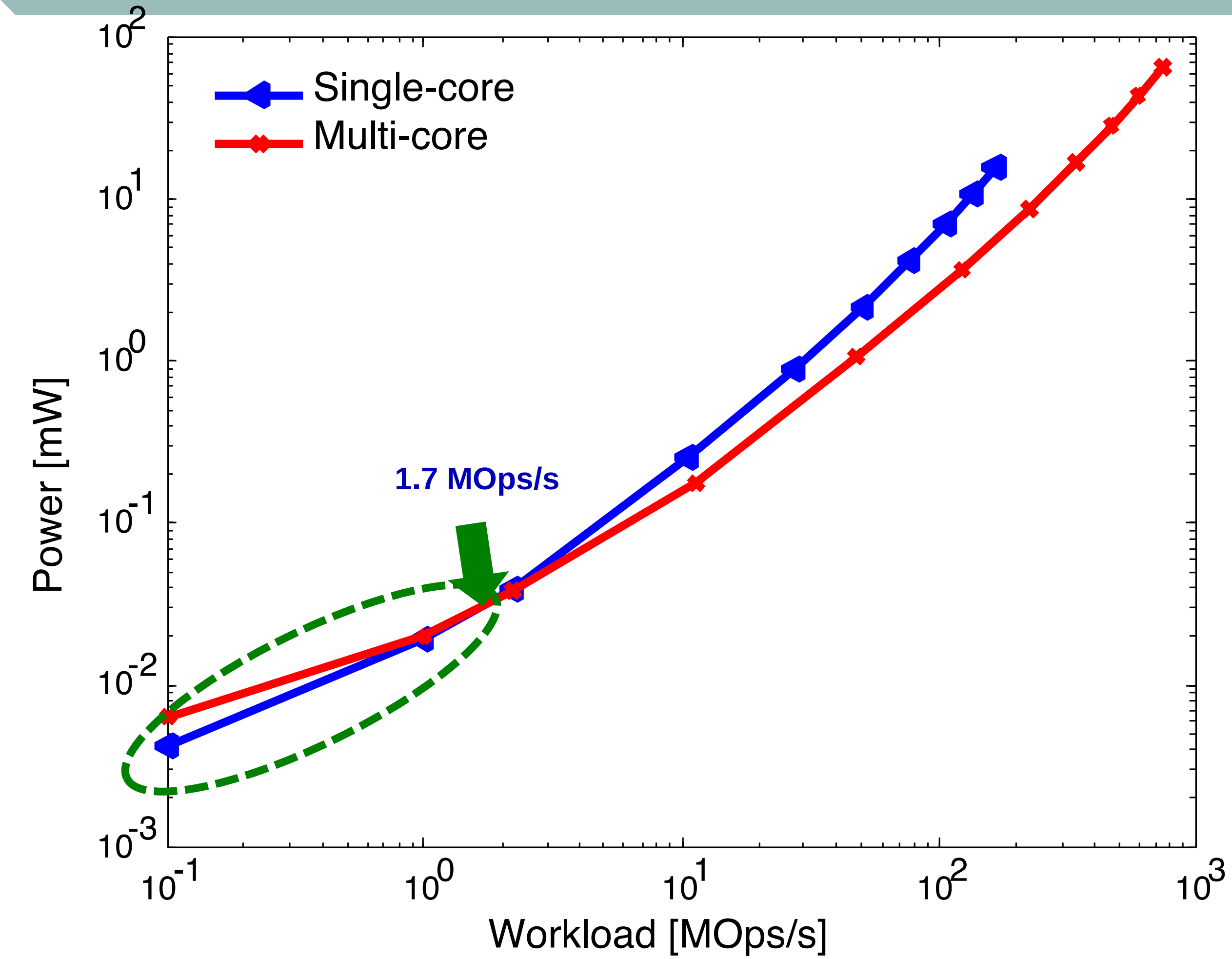
- ULP cores share multi-bank DM
- Multiple instruction, multiple data execution (MIMD) mode
- No need for multi-port DM
  - Low leakage consumption
- Logarithmic interconnect **[Rahimi et al, DATE'11]**
  - Simplified clock network
  - Single supply voltage
- Occasional stalls of cores
  - Clock gating: low active power
  - Interleaved data reduces conflicts

Power/Performance comparisons



Between 1.7–167 MOps/s workloads multi-core is more power efficient, up to 62%

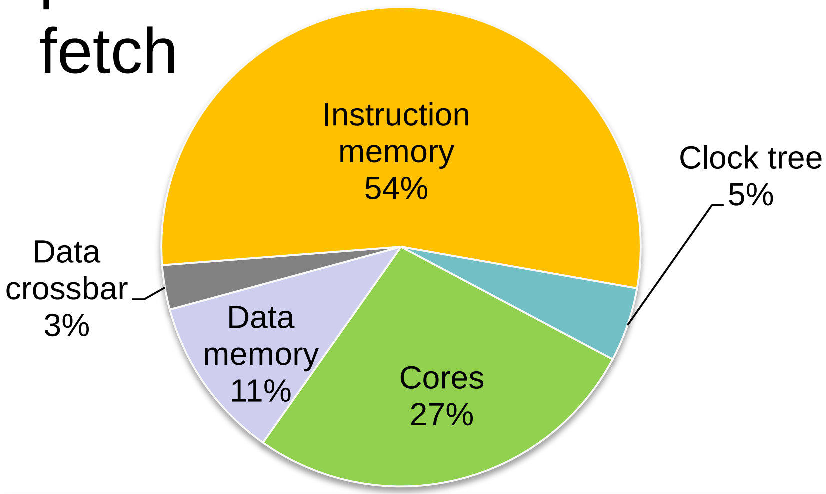
Power/Performance comparisons



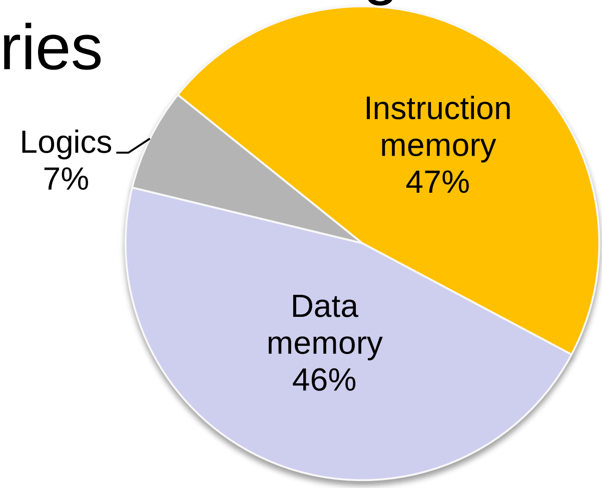
Single-core is more power efficient for workloads lower than 1.7 MOps/s

ULP Multi-Core WBSN architecture power bottleneck analysis

- High workloads: > 50% of power due to instruction fetch



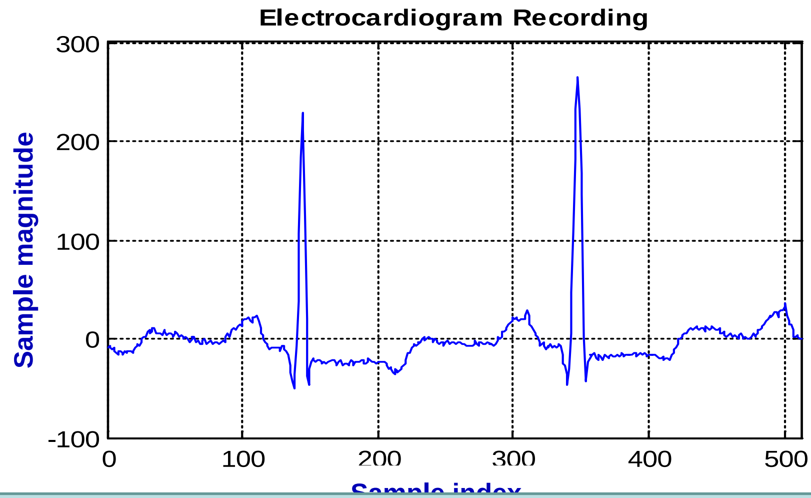
- Low workloads: > 90% of the power due to leakage in memories

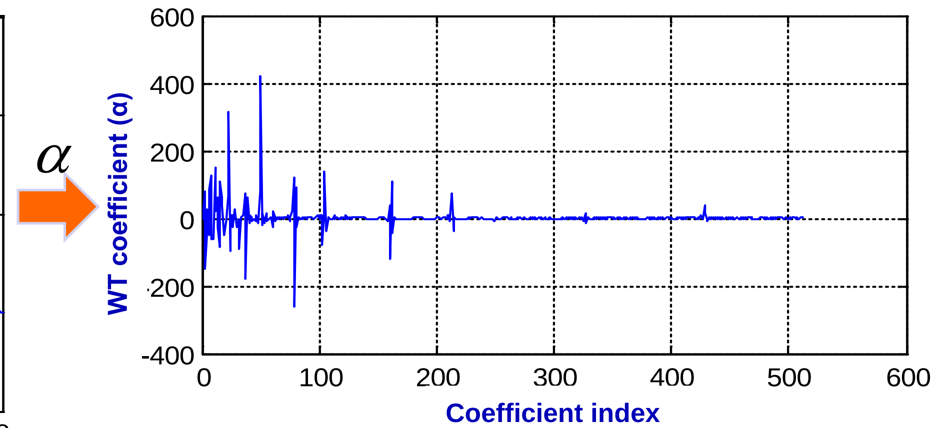


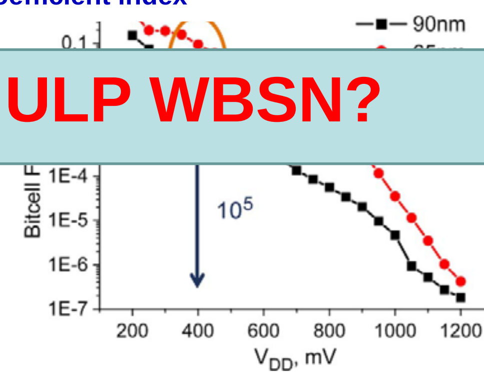
Instruction fetch and instruction memory accesses responsible for largest part of power consumption

- Reduce number of “relevant” memory accesses by exploiting application output characteristics
- Reduce energy / access: **near-threshold computing (NTC)**

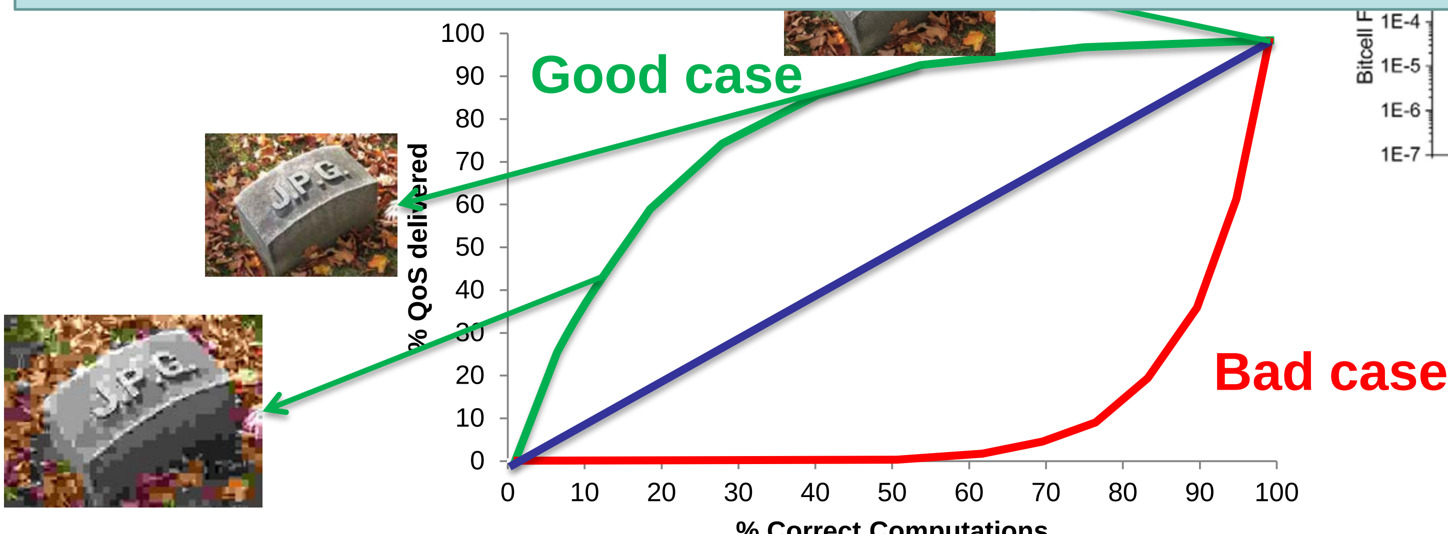
Significance-Driven (SD) Computation at System-Level for WBSN



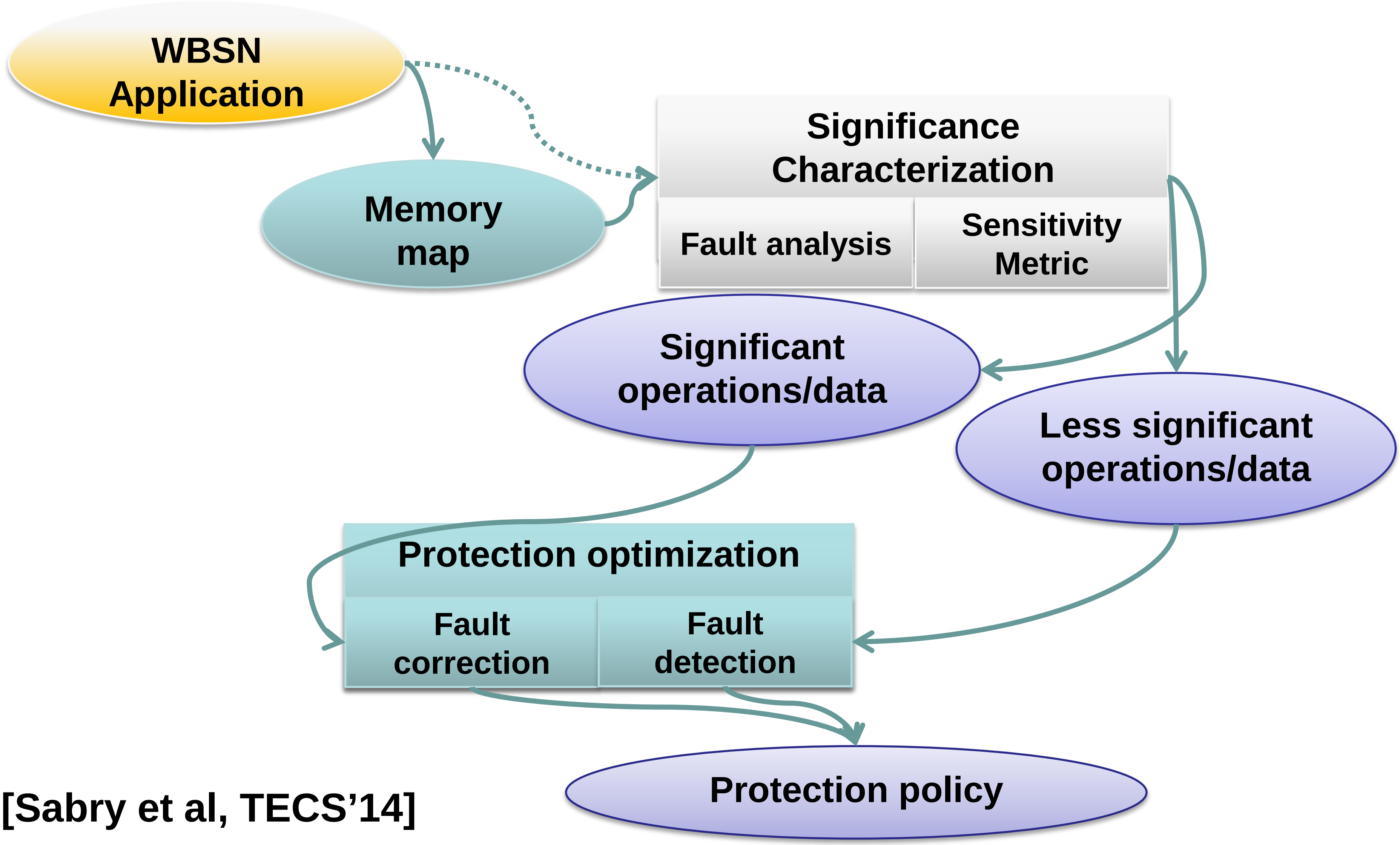




How much can SD computation help in ULP WBSN?



SD Computation: Methodology for Unreliable Memories in WBSN Nodes

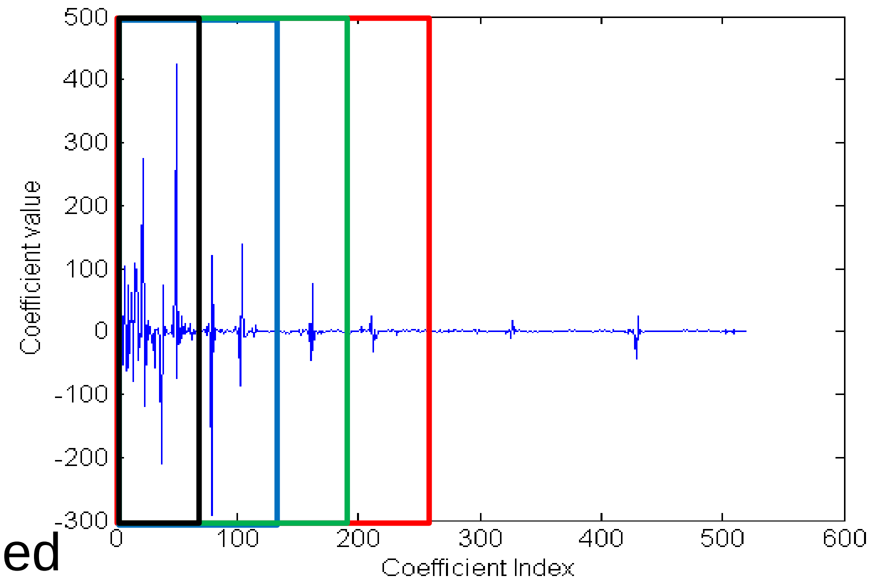


[Sabry et al, TECS'14]

DWT-Based ECG in WBSN: Selected Significance cases

- Significant data: full protection
  - I: 12.5% significant
  - II: 25% significant
  - III: 37.5% significant
  - IV:50% significant
- Significance sensitivity analysis
  - Black box approach: output based
  - Inject error (k) and observe faulty output ($\overline{Y}_k$)
- Sensitivity metric: % root-mean square diff.:

$$PRD(k) = \frac{\left\| Y - \overline{Y}_k \right\|_2}{\left\| Y \right\|_2}$$



Case	PRD
I	63%
II	32%
III	18%
IV	9%

Only little data percentage is really "significant"

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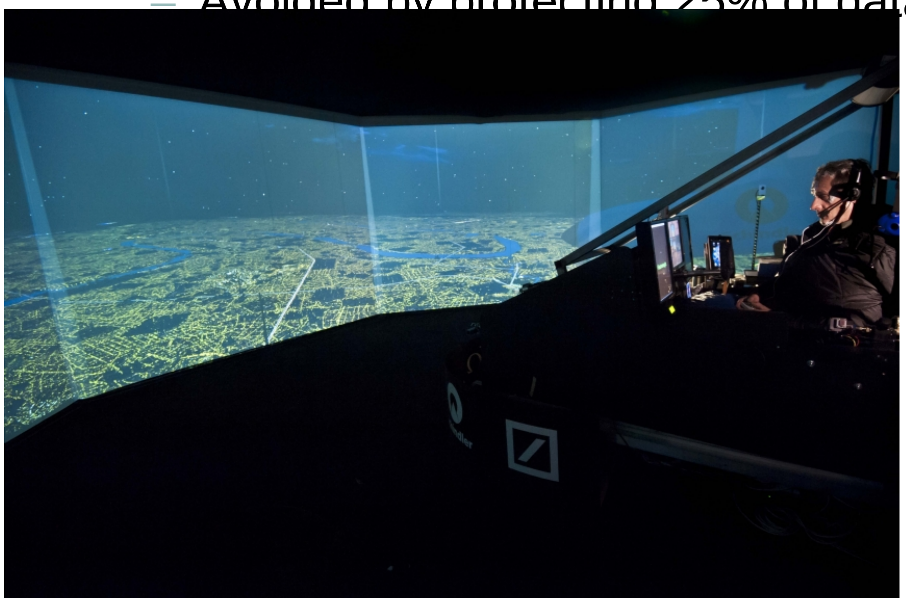
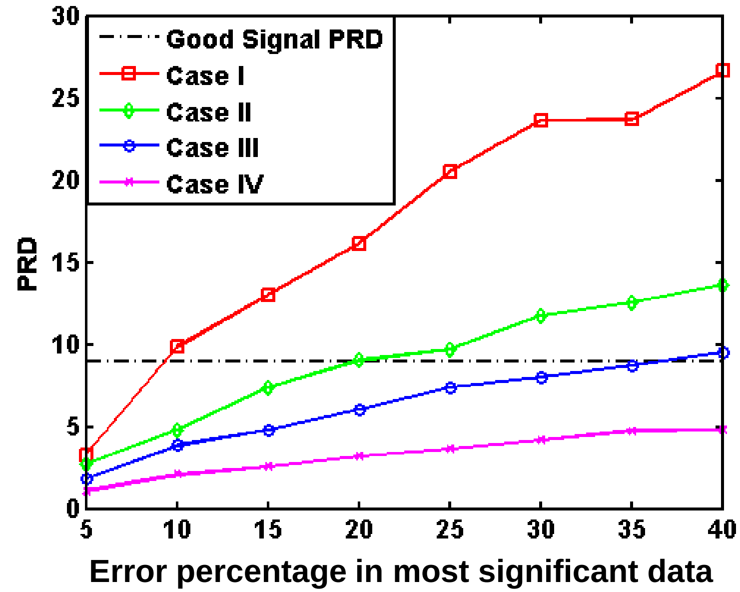
ECG-Based Experimental Evaluation: Solar Impulse Pilots

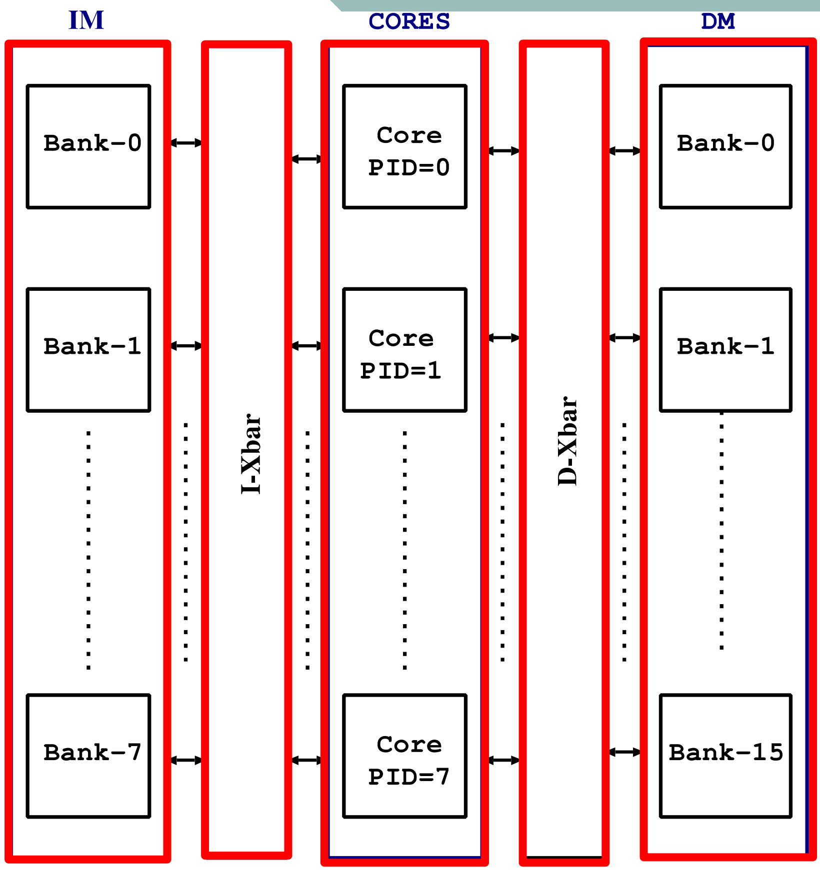
- Error injection (**with IMEC Memory Design Group**)
  - Tested different rates: 1^{e-6} to 1^{e-9} bit/cycle
  - Effective (practical) error occurrence: less than 20% time
    - Avoided by protecting 25% of data





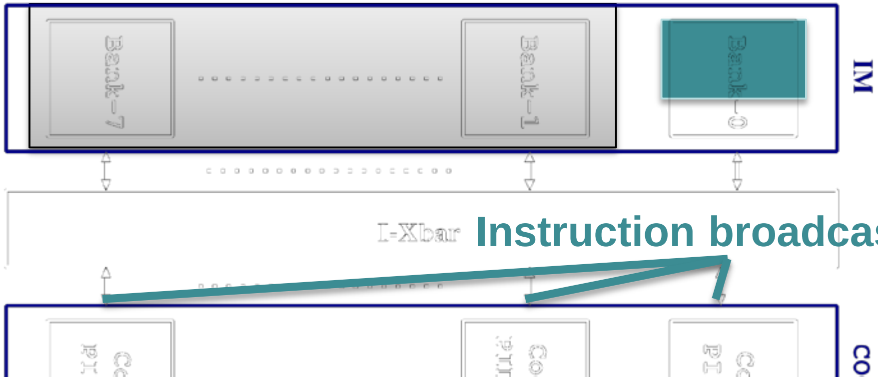
SD computation achieves ~50% lower energy in memories… Doctors did not notice anything!

ULP Multi-Core WBSN architecture with Single-Instruction Multiple-Data (SIMD) extensions



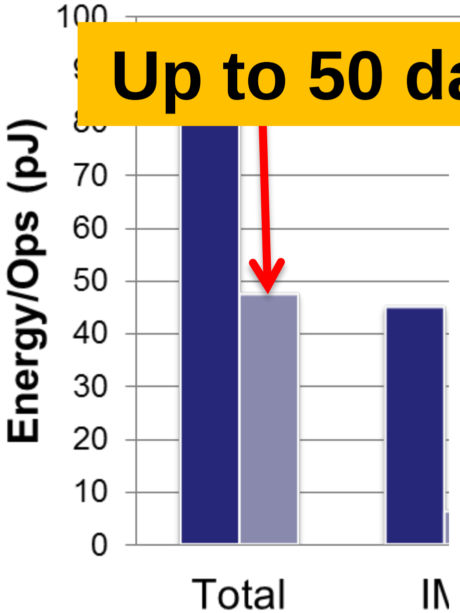
[Braojos et al, DATE' 14]

- Fully shared data and instr. memories
- Enhanced logarit. interconnect with broadcast support (**with U. Bologna**)
  - Coordinated memory accesses
- Extended TamaRISC cores
  - Virtual-physical mem. address trans.
- Supports SIMD mode (and MIMD)
  - Instructions broadcasting for lower memory access power
  - Power gating of unused memory banks



Breakdown of Dynamic Power in ULP Multi-Core WBSN architecture

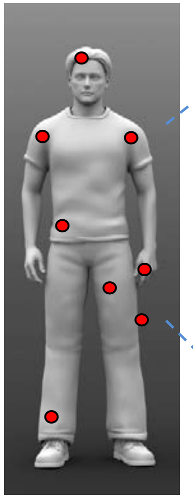
Up to 50 days of operating time (1200 hours)!



- 86% power sav
- Broadcasting e
- Xbars consume

Yes, multi-core architectures are really power efficient for ULP biosignal analysis (45.7% overall)

Next-Generation: "Really Smart" (or just Smarter) WBSN for Healthcare



Bio-signals
- ECG
- Blood pres.
- EEG
- Respiration
- Movements

Sensing → **Processing** → **Transmit**

Instruction memory — **Core** **Core** / **Core** **Core** / **Core** **Core** — **Data memory**

Peripherals

WBSN

Output:
Diagnose,
Abnormality,
Analysis
…

CAN WE DO BETTER?

SW
- **Embedded DSP**
- **On-board diagnosis**
- **Selective DSP (Classification)**

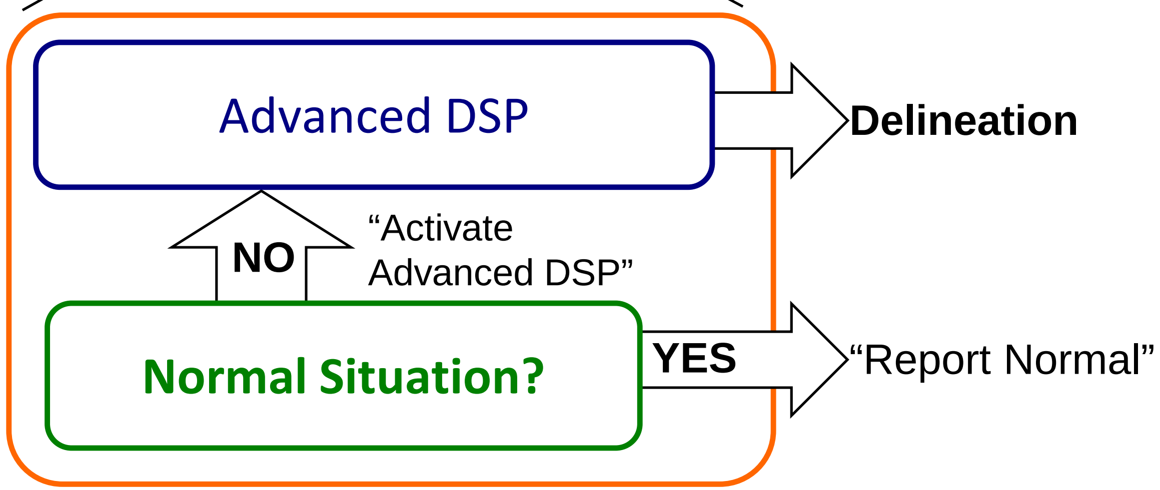
HW
- **Ultra-low Power (ULP) architectures**
- **Hardware accelerators**
- **ULP Multi-core WBSN**

Let's exploit BIG DATA!

Selective advance ECG analysis

WBSN Example:
- TamaRISC µC
  - 8 MHz
  - 16-bit
  - 128 KB
  - Flash
- CC240 radio
  - Zigbee
  - Bluetooth
- 480 mAh Battery

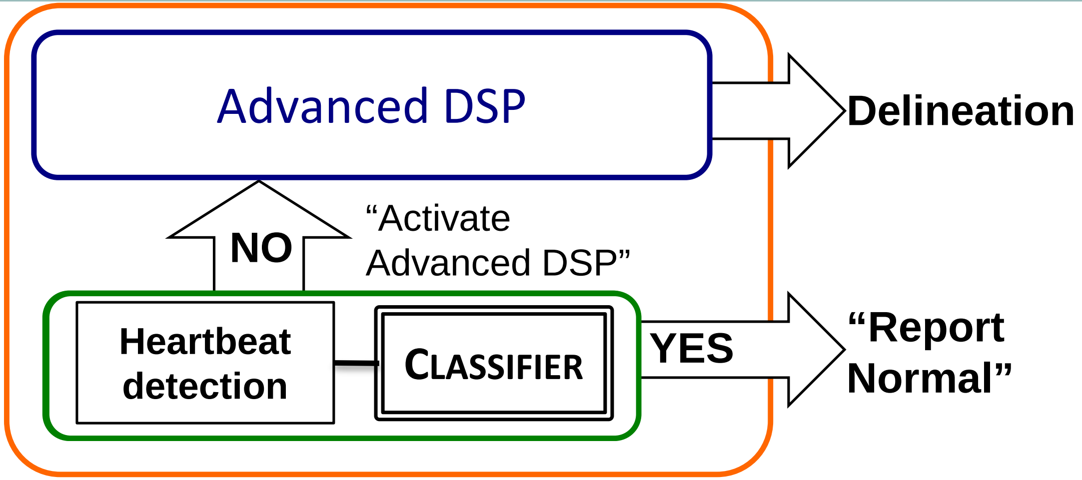
→1200h running



<u>Possible Selective Activation?</u>

Classification of Heartbeats

- Normal condition
  - Normal heartbeat morphology
- Classif. heartbeats
  - Problem dimensionality
  - Very complex existing algorithms



Light-weight embedded heartbeat classifier

1. Random Projection (RP) dimensionality reduction
2. Embedded Neuro-fuzzy classifier (NFC)

Proposed framework for next-generation WBSN designs

training sets of beats to classify

Training

(floating point precision)

PC

RP Matrix / NFC - MFs

Adaptations / Optimizations

→ Precision change
→ Computational complexity reduction
→ Memory footprint contention

Optimized RP-NFC

Real-Time Execut.

(integer arithmetic)

WBSN

Advanced DSP (multi-core TamaRISC)

Delineation

“Activate Advanced DSP”

NO

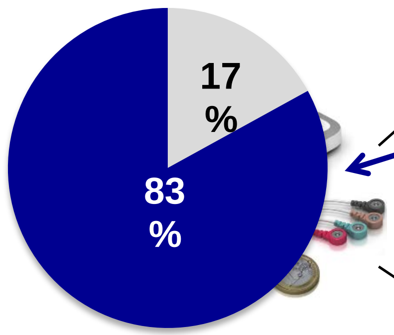
Heartbeat detection

RP-NFC

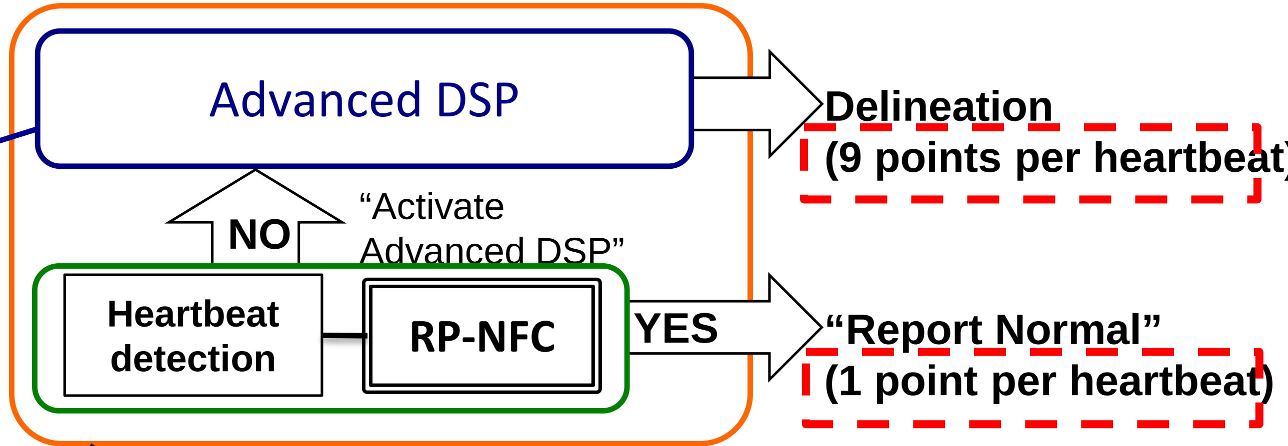
YES

“Report Normal”

Initial Case study: Smarter ECG Monitor



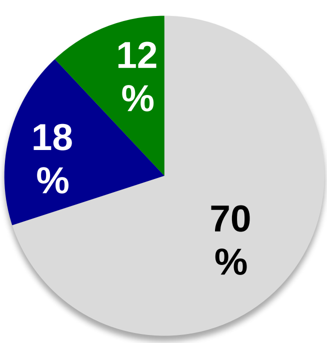
Typical ECG Monitor



Duty Cycle
- Advanced DSP
- Extension
- Idle Time

- Duty cycle reduction of 65% for MIT-BIH DB
- Transmission or storage reduction of 68%

- In a real test with multi-core WBSN node
  → Energy savings of 23%



Smarter ECG Monitor

Up to 61.5 days of operation (~1476 hours), finally we got our ULP WBSN!

Conclusions

- Smart ULP WBSN nodes: novel system-level (HW/SW) design
  - Feasible to do real-time automated biosignals analysis
  - Communication not always the worst part: sensing and processing
- Knowledge about target bio-signals not to overdesign WBSNs
  - Compressed sensing very powerful approach (if used with care)
  - Removes need for complex instructions sets and limits memory use
- New ULP WBSN multi-core architectures are coming up
  - Enable scalability of biosignals processing
  - Significance-driven computing = hardware/software link saves power
- Novel field: SD computing research for biomedical signals …
  - Lots to do in *HW/SW* for ultimate ULP WBSN nodes! **Let's go for it!**

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Thank You

QUESTIONS?

Acknowledgments:

PHIDIAS and SCoRPiO FP7 Project

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FNSNF

ObeSense, BodyPowerSense, BioCS Projects in Nano-Tera.ch

Nestlé

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