System Level Design of Smart Wireless Body Sensor Networks

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Technion, Israel (Oct. 2, 2013)
Pressing changes in healthcare landscape and economics call for personalized healthcare

- The burden of disease is shifting from diseases caused by infectious organisms to disorders with behavioral causes
- 50% of all deaths worldwide in 2006 and economic fallout in billions... expected to be 75% of gross domestic product by 2030

This calls for a two-fold paradigm shift in health delivery:

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

Determinants of health issues
(source: Institute for the future, Center for disease control and prevention, 2006)
Limits in Personalized IT Healthcare Systems: Wireless Body Sensor Networks (WBSNs)

- Collect unprecedented longitudinal patient data
- Improve the effectiveness of therapeutic intervention and the science of health promotion
- Support clinical decision making

Multi-parametric biosignals analysis with feature extraction after appropriate noise filtering:

How to design a WBSN?
We focus on the electrocardiogram (ECG) signal as it is an indispensable clinical tool in most WBSNs.

- Electrical activity of the heart recorded by electrodes placed on the body surface

- Useful to diagnose ailments reflected by disturbances of the heart’s electrical activity
State-of-the-Art WBSN: Option 1 - Streaming of Raw Data

Long-term ECG monitor (Holter or event recorder)

Streaming of only raw biosignal data

Since the WBSN nodes do not do any processing, how much can they last?
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
  - Accelerometers 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 BIODEVICES ‘09]
State-of-the-Art WBSN: Option 2 - Embedded Processing

The goal from an IT systems perspective is to design:

1. Long-lived and accurate multi-lead ECG monitoring
2. Smart wireless personal health analysis systems

Only simple filtering and one-lead input
Key elements to develop smart WBSN for automatic ECG monitoring

- Noise and artifact removal in ambulatory conditions
- ECG wave delineation
- ECG signal compression

Resting ECG

ECG corrupted by baseline wander

ECG corrupted by muscle noise
Our smart ECG sensor node concept for WBSN will capitalize on all 3 automatic processing algorithms:

1. **Noise filtering**
2. **ECG delineation**
3. **Feature Analysis (arrhythmia diagnosis)**

These algorithms are applied to the received data, which is then displayed on the device.
Selecting ECG filtering algorithms

- Baseline wander and muscular noise removal
  1. Cubic spline
     - 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 the possible noise sources, possible to correct then with few sensors locations 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 (√)

[Boichat et al., BSN’09]

[Rincon et al., TITB’11]
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

\[
\begin{align*}
[\text{QRS}_{\text{on}}, \text{QRS}_{\text{end}}] & \leq 0.10 \text{s} \\
0.12 \text{s} & \leq [P_{\text{on}}, \text{QRS}_{\text{on}}] \leq 0.20 \text{s} \\
T_{\text{peak}} & > 0 \\
[\text{QRS}_{\text{on}}, R_{\text{peak}}] & < 0.03 \text{s} \\
\text{QT interval rule} & \\
\text{HBR variability} & \\
\text{Atrial activity} &
\end{align*}
\]

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!
Personal arrhythmia detection WBSN system


Automated ECG-based Diagnosis for a Wireless Body Sensor Platform

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Implementation results on the Shimmer node as WBSN system

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

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>RAM usage</th>
<th>Buffers length</th>
<th>Execution time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-lead WT delineator</td>
<td>6.8 kBytes</td>
<td>512 elements</td>
<td>5%</td>
</tr>
<tr>
<td>Multi-lead WT delineator</td>
<td>5.5 kBytes</td>
<td>256 elements</td>
<td>30.5% total (23% filtering, 2.5% multi-lead merging, 5% delineation)</td>
</tr>
</tbody>
</table>

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

But can we create a “universally optimal” compression scheme at design time 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) in a Measurement/Sensing matrix (Gaussian random matrix): $y_{M \times 1} = \Phi_{M \times N} \cdot x_{N \times 1}$,

- Then, the measurement vector can be recovered by solving the convex optimization problem:

$$\begin{align*}
\min_{\tilde{\alpha} \in \mathbb{R}^N} & \| \tilde{\alpha} \|_1 \\
\text{Subject to:} & \quad \| \Phi \Psi \tilde{\alpha} - y \|_2 \leq \sigma
\end{align*}$$

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

- Minimal area/power for biosignals processing
  - Less than 5% of an embedded platform (< 10 kGE)
  - Near-VT computing: 2-4 MHz (180MHz@1V)

[Diagram of FIRAT/TamaRISC architecture]

Firat (umcL 90nm)

Dicle (umcL 180nm)

Firat ASIC vs. 1chf coin

… And vs. my finger!

[Dogan et al., DATE 2012]
TamaRISC: Experimental results

<table>
<thead>
<tr>
<th></th>
<th>Number of Clock Cycles(*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIRAT</td>
<td>TamaRISC</td>
</tr>
<tr>
<td>Filtering-DWT</td>
<td>1.85M K</td>
</tr>
<tr>
<td>Compression</td>
<td>114K</td>
</tr>
</tbody>
</table>

(*): 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.

Higher efficiency compared to state-of-the-art processing cores.

<table>
<thead>
<tr>
<th></th>
<th>Energy per Ops @ 1.0 V</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>TamaRISC</td>
<td>12.1 pJ</td>
<td>90 nm</td>
</tr>
<tr>
<td>16-bit [Kwong,2011]</td>
<td>&gt; 47 pJ</td>
<td>130 nm</td>
</tr>
</tbody>
</table>
Single-Core ULP WBSN Node: Power/Performance Results

- Single-input ECG applications
  - > 20 kOps/s and < 4.1 MOps/s
  - Benefits from voltage scaling
- Multiple-input (i.e., 8 leads) ECG
  - > 175 kOps/s and < 33 MOps/s
  - Limited voltage scaling, but still able to do 9-lead ECG processing

Can the users finally see the benefit of CS and holistic optimization at system-level?
CS and biosignals algorithms analysis show true advantages on ultra-low-power (ULP) processors

- 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

Lifetime (in hours)
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!

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 monitoring
  - Pilot monitoring
New smart WBSN systems open up a new dimension of possibilities

See video at: http://www.youtube.com/watch?v=X1jQH8D8vJM
New smart WBSN systems open up a new dimension of possibilities

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

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 **parallel-friendly**, 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: parallel processing enables more aggressive voltage-frequency scaling

Are multi-core architectures more power efficient than single-core for ULP biosignal analysis?
ULP Multi-Core WBSN architecture with tightly coupled memories

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

N = 8, M=16

[Dogan et al, DATE’12]
Power/Performance comparisons

Between 1.7–167 MOps/s workloads multi-core is more power efficient, up to 62%
The power consumptions become equal at 1.7 MOps/s. Multi-core has reached the lowest voltage at 10.9 MOps/s. Single-core is more power efficient for workloads lower than 1.7 MOps/s.

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
  - Instruction memory 54%
  - Clock tree 5%
  - Cores 27%
  - Data memory 11%
  - Data crossbar 3%

- Low workloads: > 90% of the power due to leakage in memories
  - Instruction memory 47%
  - Data memory 46%
  - Logics 7%

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

- Reduce number of memory accesses by exploiting application characteristics
- Reduce amount of (active) memory
ULP Multi-Core WBSN architecture with Single-Instruction Multiple-Data (SIMD) extensions

- Fully shared data and instr. memories
- Enhanced logarith. 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

[Dogan et al, DATE’ 13]
Breakdown of Dynamic Power in ULP Multi-Core WBSN architecture

- 86% power savings on instruction fetch accesses
- Broadcasting entails no noticeable power overhead
- Xbars consume less than 8% of the total power

Yes, multi-core architectures are more power efficient for ULP biosignal analysis (45.7% overall)
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
  - Hybrid ULP processing: SIMD + MIMD mode for active power saving
  - Broadcasting/synchronization Support + power gating for low leakage

- A plethora of possible applications: even not expected ones…
  - A lot of research to be done: both in multi-core *hardware and software* for ultra-low power WBSN! Let’s go for it!
Key References and Bibliography

- **CS-based ECG delineation and implementation**

- **ULP WBSN computation optimization and ECG application mapping**

- **Single- vs. multi-core WBSN platform design**
Key References and Bibliography

**ULP biosignal analysis and optimization**

**WBSN Technologies and Components**
QUESTIONS?

Acknowledgments:

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