Wireless Electronic Systems: Trading off performance, reliability and energy efficiency

Eindhoven University of Technology & TNO Embedded Systems Innovation

Joint work with Marc Geilen, Hailong Jiao, Majid Nabi, José Pineda, and many others

"Knowing is not understanding."
Charles Kettering

Electronic Systems

Mission
- Scientific basis for design trajectories
- From function to realization
- Constructive design

3. Electronic Systems

- POOSL: Fast discrete-event simulation
- Embedded control and signal processing
- Health monitoring
- CompSOC: Predictable multiprocessor platforms
- GPUs and accelerators
- Brain-inspired computing
- Ultra-low power electronics

The Electronic Systems group

partners

Electronic Systems
Wireless Electronic Systems

**Trade-offs**

- Cross-technology interference
- Device density
- Limited transmit power
- Wireless channel behavior

**Reliability**

- Latency and throughput requirements
- Safety-critical real-time applications

**Performance**

- Communication
- Processing

**Energy Efficiency**

- Co-design
- Model-driven development
- Experimental validation

**An integral approach**

- Circuit → PHY
- Application → MAC
- Network → Co-design
- 150 NXP JN5168 dongles
- 130 TI CC2650 SensorTags
- 100 MyriaNed nodes
Approximate computing

Can you see the difference between the two figures?

\[
\begin{array}{c}
10 \\
\times \ 10 \\
= 100
\end{array}
\]

\[
\begin{array}{c}
10 \\
\times \ 10 \\
\approx \ 99
\end{array}
\]

100% accuracy is not always necessary

Trade off between power, performance, area and accuracy

- Approximate data
  - Simplified logic
  - Bit-width representation
- Approximate timing
  - Clock frequency
  - Supply & threshold voltage

Better-Than-Worst-Case Design – Approximate timing

- Enhanced performance
- Lower power consumption
- Smaller silicon area at the cost of
- Reduced reliability
13 Wireless baseband processing in the Internet of Things

- Targeting IEEE 802.15.4 / WiFi standards
- Requires protocol / circuit co-design

QoS-AB project, with NXP

14 Potential approximate modules

<table>
<thead>
<tr>
<th>Protocol accelerator</th>
<th>CCA (various modes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Detection and SNR</td>
<td>Link Quality Indicator</td>
</tr>
<tr>
<td>Slotted/Unslotted CSMA</td>
<td>Beacon Generator</td>
</tr>
<tr>
<td>Backoff Controller</td>
<td>Automatic Acknowledge</td>
</tr>
<tr>
<td>Symbol Counter</td>
<td>Adaptive Channel Quality Estimation for TSCH</td>
</tr>
<tr>
<td>TSCH Accelerator</td>
<td>Security coprocessor AES Encryption / Decryption</td>
</tr>
<tr>
<td>Radio module</td>
<td>Interrupt Generator</td>
</tr>
<tr>
<td>TX modulator</td>
<td>Configuration / Status Registers</td>
</tr>
<tr>
<td>RX demodulator</td>
<td>Protocol Timers</td>
</tr>
<tr>
<td>Checksum generator</td>
<td>DMA Controller</td>
</tr>
<tr>
<td>Checksum verifier</td>
<td>Serialiser</td>
</tr>
<tr>
<td>Deserialiser</td>
<td></td>
</tr>
</tbody>
</table>

QoS-AB project, with NXP

15 Approximate multiplier – Approximate data

A low power accuracy-controllable iterative-approximate multiplier
- Basic idea: piece-wise linear approximation, shift operations
- Low error rate (0.13% NMED, normalized mean error distance)

<table>
<thead>
<tr>
<th>32-bit Approximate Multiplier Based 5th Order FIR Filter</th>
<th>Area savings</th>
<th>Power savings</th>
</tr>
</thead>
<tbody>
<tr>
<td>-26 %</td>
<td>-49 %</td>
<td></td>
</tr>
</tbody>
</table>

Protocol Stacks
**Protocol Stacks**

**WBAN**

**Wireless Body-Area Network (WBAN) communication**

ODLF:
- On-Demand Listening and Forwarding

**WBAN**
- One gateway
- Number of nodes known
- Highly dynamic link quality

**ODLF**
- Hybrid star and gossiping protocol
- Gateway dynamically requests transmission support
- Efficient implementation with a support bitmap

**Trading off performance and energy**

Energy dissipation increases with lower-quality links
Support set \( \Psi \) grows with lower-quality links

**Link Quality Estimation (LQE)**

- Prerequisite for many adaptive mechanisms, many variants
- Typical parameters: window size \( w \) and coefficient \( \alpha \)
- Agility and stability trade-offs

**SECON 2012**
WBAN LQE: Smoothed Link Likelihood Factor (SLLF)

- Prerequisite for many adaptive mechanisms, many variants
- Typical parameters: window size $w$ and coefficient $\alpha$
- Agility and stability trade-offs

Protocol Stacks

IVN

Cross-technology interference – in-vehicle networking

802.15.4 - Time-Slotted Channel Hopping (TSCH)

- Provides guaranteed access to the medium
- Prevents persistent multi-path fading
- Eliminates blocking of wireless links
**Intermezzo: the Environment**

**MoBAN: mobility model for WBANs**

- Reference point group mobility (RPGM)
- Markov chain for posture selection
- Spatial and temporal correlations
- Based on extensive measurements
- Intra-WBAN and ambient network simulation
- Implemented in MiXiM
29. Cross-technology interference in vehicles

- Interference measurements inside a car (bluetooth, wifi)
- Interference from outside (mostly wifi)
- Usable to drive simulations

Networks

30. QoS provisioning in static trees

Wireless sensor network
- 900 nodes
- 27 configurations per node
- 4 quality metrics
- Routing tree to data sink

Problem
How to configure the network?

Approach
Compositional computation following the routing-tree structure

27^{900} configurations in 4D space

Less than 45 seconds …

31. Pareto algebra

Goal: Compositional computation of trade-offs

Fundamenta Informaticae, 2007
**QoS provisioning in dynamic trees**

- 900 node network
- Simulated in the OMNET++ simulator
- Calibrated for TelosB sensor nodes
- 8 Mhz processor
- 250 kbps tranceiver bit rate

*Good quality reconfiguration within one minute*

**Distributed QoS provisioning in dynamic networks**

- Relations network & node parameters – QoS properties
  - $\left(X_{\text{max}}, Y_{\text{min}}\right)$ Actual
  - $\left(X_{\text{max}}, Y_{\text{max}}\right)$ Model
- Model-driven approach
- Impact models with 4 parameters

*End-to-end packet loss stays within a band*

*Outperforms other approaches*
Wrapping up

38 Conclusions – wireless electronic systems

- is all about trade offs
- requires co-design of circuit, protocols and application
- model-driven
- with experimental validation

39 Funding acknowledgement

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40 Thank you!

Questions?

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