Design for dependability of Wireless Sensor Networks

La conception pour la dependabilité des réseaux de capteurs

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Réseaux de Capteurs: Impacts et Défis pour la Société
École d’Été – Université de Bejâia
- Engineering students
  - Undergraduate – ~ 6200
  - PhD – 754
- Teaching staff – 604

- Students/teaching staff ratio – 14.5

- International students on PhD programmes – 139

- Cooperation with international universities – 526

- Dissertations undertaken within mobility programs (2009/2010) – 40
Critical infrastructures require monitoring mechanisms that enable us to detect failures and attacks as early as possible.
the usefulness of WSNs to monitor critical infrastructures is primarily determined by the dependability of the WSN itself.
Outline

- Introduction to dependability
- Aspects and characteristics of WSN to be addressed to improve their dependability
- Example of faults detection in WSN
- Test of a pressure sensor in an abdominal aortic stent-graft
Dependability

Attributes analysis
- Availability
- Security
- Reliability
- Maintainability

Risks
- Defects
- Failures
- Errors

Means to achieve dependability
- Prevention
- Detection
- Fault tolerance

Techniques to be employed
- Built-In-Self-Test (BIST)
- Built-In-Self-Repair (BISR)
- Reconfiguration
- Data Fusion
Failures may happen and attacks may be targeted at any layer of the WSN architecture from the node hardware and operating system, through the networking protocol stack, up to the middleware and service layers.
Design for Dependability of WSN

Challenges to achieving reliability

- wireless communication
- constrained resources
  - Available power resources;
  - processing speed;
  - storage capacity;
  - communication bandwidth;
  - harsh environment

Making systems long-lived

- Allow reconfiguration
- Localized algorithms used to prevent single points of failure
- Low duty cycle operation designs
Design for Dependability of WSN

- Long lifetimes - Energy efficiency
- Low and predictable Delay
  - Tens of ms for discrete manufacturing
  - Seconds for process control
  - Tens of seconds to minutes for asset monitoring
- Scalability — Up to 100 sensors/actuators in areas of few m²
- Robustness — A large WSN, with sufficient node capacity, admits losing nodes to hardware failure without the entire system failing by means of redundancy, re-routing and preventive maintenance.
  - requires information on the probable node failure rates at field conditions
  - sensor devices are planned to be unattended for long periods without maintenance
  - design for testability of the nodes’ hardware
Design for Dependability of WSN

- Many sensor networks have mission-critical tasks; reliability needs to be taken into account at design time.
  - safety, secrecy, security
    - deducing information from surroundings is possible
    - information leakage results in privacy breaches
    - wireless communication facilitates packet sneaking in by an adversary.

- Reliability in message delivery
  - Lost messages may compromise the correct behavior of the monitoring system

\[
\text{No. packets received} = P_{\text{success}} \times \text{No. packets sent}
\]
Errors may result from the interaction of hardware, software and the environment – sensor node electronics are subject to stress

- environmental contaminants and conditions (temperature, temperature changes, and humidity, vibration) ripple voltage, and overvoltage.
- Power-up (heat) and shutdown (cool) generate thermo-mechanical stresses.

Quality and reliability are not free

- but poor quality and reliability usually cost more than good quality and reliability.
Resistance of individual nodes against failures and attacks
- intrusion detection and prevention,
- separation of critical parts of the system,
- software-based remote code attestation.

Dependability of the networking layer
- robust network topologies,
- secure and reliable transport of data,
- prevention of traffic analysis.

Dependable and persistent distributed data storage service within the network
- network-failure and attack resistant.
Sensor node architecture abilities

- **Features**
  - Self-calibration
  - Self-diagnostics
  - Ability to compensate for variations and ambient conditions

- **Monitor**
  - Events
  - Interaction

- **Intelligent sensors**
  - Having adequate information from which the sensor can assure the validity of the measurement and the ability to communicate with the other intelligent devices in the system

- **Information redundancy (retransmission, erasure codes), route fix**
Energy Conservation in WSNs

- Task level
  - trade-off functionality for reduced computations
- Algorithm level
  - collaborative signal processing and coordinated communications
- Protocol level
  - power aware routing and selective multicasting
- Physical level
  - radio power control and dynamic bandwidth management

Energy Conservation in WSNs

- Event triggered activity
  1. Microphones detect bird call
  2. Algorithms estimate bird location
  3. Camera with bird in field of view captures photograph

- Communication - the most energy demanding component on a typical sensor node

- Processing vs. communication
  - Compute an 8-bit 1024 FFT 80 nJ [Wang JSSC05]
  - RF Tx/Rx of an 8 bit sample (20 m) 32 nJ [Cook ISSCC06]
Wireless protocols efficiency

A Comparative Study of Wireless Protocols: Bluetooth, UWB, ZigBee, and Wi-Fi
The 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON), 2007
Wireless protocols efficiency

- **802.15.4**
  - low-power consumption / low data rate (979 nJ/bit)

- **802.11b**
  - high-power consumption / high data rate (112 nJ/bit)

- Use multiple radios to implement “wake-on-wireless”, where a low power radio is used to wake up a high power radio.
Wireless link

- Received signal strength

\[ PER = 1 - (1 - BER)^n \]

“... up to 90% of all innovations are driven by electronics and software”.

- The ISO 26262 standard for functional safety in automotive electronics highly recommends that fault injection be included as part of the dependability analysis of critical systems.
Testability of WSN

- The errors induced by faults form identifiable patterns.
- Error patterns
  - corresponding to faults are evident in, and can be derived from, system metrics.
  - allow faults to be distinguished by type, persistence, etc.
- Controllability – able to define experimental parameters accurately, in time (e.g., fault activation-trigger and duration), space (e.g., fault location) and value (e.g., fault type).
- Observability – The effect(s) of a fault should be readily apparent. Observations must be made at each node and compared with respect to the time, space and value domains.
- Repeatability
Testability of WSN

- Failure of WSN modules (such as communication and sensing module) due to (fault dictionary)
  - fabrication process problems,
  - environmental factors, enemy attacks and so on;
  - battery power depletion;
  - out of the communication range

- Faulty nodes
  - permanente: remain faulty until being replaced,
  - static: new faults are generated during fault detection.
Fault detection in WSN

- Self-detection / passive detection
  - Sensor nodes run their own fault detection operations (e.g. remaining energy; status of sensor)
  - Eventually communication is not used

- Active detection
  - Fault detection run at the network level – in-cell update cycle
  - Communication between cell manager and cell members
  - E.g., if a cell does not send an acknowledge in given time it is declared faulty
Fault detection in WSN

- **Hard fault** – sensor node cannot communicate with other nodes because of the failure of a certain module.
- **Soft fault** – the failed node can continue to work and communicate with other nodes but the data sensed/transmitted is not correct.

**Fault detection:**
- Good node is considered good – $P_{GG}$
- Faulty node is considered faulty – $P_{FF}$
- Faulty node is considered good – $P_{FG}$
- Good node is considered faulty – $P_{GF}$

**Fault detection accuracy** = $P_{GG} + P_{FF}$

$p$ – the probability of a node’s failure
Fault detection in WSN

Fault recovery

- Awake sleeping sensor nodes or introduce new sensor nodes to replace the faulty ones
- A sensor node may be appointed as a backup cell manager to replace this one in case it fails
  - E.g. if the manager detects a fault in itself (passive detection) it sends a message to communicate that it is going down
  - The backup manager assumes management and the other sensor nodes communicate with this new manager
Fault detection in WSN

- Neighbor nodes: two nodes within a single hop’s communication scope.

- $\text{Neighbor}(Si)$, $\text{Nb}(Si)$ - The set of all neighbours of node $Si$

- $\text{Num}(\text{Nb}(Si))$ - the total number of neighbors of node $Si$
Fault detection in WSN

- $m_t^i$: measure of $S_i$ at instant $t$
- $\theta_1, \theta_2$: predefined threshold levels
- $c_{ij}=\{0/$good$, 1/$faulty$\}$: test between $S_i$ and $S_j$
- $\Delta m_{ij} = m_t^i - m_t^j \leq \theta_1 \rightarrow c_{ij} = 0$
- $\Delta \Delta m_{ij} = \Delta m_{ij}^{t+1} - \Delta m_{ij}^t \leq \theta_2 \rightarrow c_{ij} = 0$
- $\Delta t_i = t_{i+1} - t_i$
- $c_{ij} = c_{ji}$

Fault detection in WSN

for Nb(Si)
  set cij=0;
for s=1:N
  if |dmijt| > θ₁
      cij=1,
  else
      if |∆dmijt| > θ₂
          cij=1,
      endif
  endif
next

- Ti: ={LG, LF, AG, AF}
  - LG, likely good if
    \[
    \sum_{S_j \in Nb(S_i)} c_{ij} < \sum_{S_j \in Nb(S_i)} \frac{Num(Nb(S_i))}{2}
    \]
  - LF, probably faulty otherwise
  - AG, actual good if
    \[
    \sum_{S_j \in Nb(S_i) \land T_j=LG} c_{ij} < \sum_{S_j \in Nb(S_i) \land T_j=LG} \frac{Num(Nb(S_i))_{T_j=LG}}{2}
    \]
  - AF, actual faulty otherwise

- If Ti=LG and Tj is not LG, for all j, then:
  - Ti = AG; Ti = AF, otherwise
Fault detection in WSN

- $k$ average number of neighbors of each node

\[
P_{\text{ff}} = p \sum_{i=0}^{m-1} c_k^i (1 - p)^{k-i} p^i
\]

\[
P_{\text{glf}} = (1 - p) \sum_{j=0}^{m-1} c_k^j (1 - p)^j p^{k-j}
\]

\[
m = \begin{cases} 
\frac{k}{2} + 1, & k \text{ even} \\
\frac{(k+1)}{2}, & k \text{ odd}
\end{cases}
\]

\[
P_{\text{fg}} = p \sum_{j=0}^{m-1} c_k^j (1 - p)^j p^{k-j}
\]

\[
P_{\text{glg}} = (1 - p) \sum_{j=0}^{m-1} c_k^j (1 - p)^{k-i} p^i
\]
Fault detection in WSN

- $x = \text{Num}(\text{Nb}(Si))$ initially diagnosed as possibly normal (LG).
- $y$ is the number of AG nodes initially diagnosed as (LG) in $x$ nodes.

\[
\begin{align*}
\frac{x}{2} + 1, & \quad x \text{ even} \\
\frac{x + 1}{2}, & \quad x \text{ odd}
\end{align*}
\]

\[
P_{FG} = p \sum_{x=1}^{k} c_k^x \left( \sum_{y=0}^{n-1} c_k^x P_{y}^{y} P_{x-y}^{x-y} \right) \left( \sum_{a=0}^{k-x} c_{k-x}^{a} P_{a}^{a} P_{k-x-a}^{k-x-a} \right) + P_{f \text {fl}} \left( \sum_{a=0}^{k} c_k^a P_{a}^{a} P_{k-a}^{k-a} \right)
\]

\[
P_{GF} = (1-p) \sum_{x=1}^{k} c_k^x \left( \sum_{y=0}^{n-1} c_k^x P_{y}^{y} P_{x-y}^{x-y} \right) \left( \sum_{a=0}^{k-x} c_{k-x}^{a} P_{a}^{a} P_{k-x-a}^{k-x-a} \right) + P_{g \text{fl}} \left( \sum_{a=0}^{k} c_k^a P_{a}^{a} P_{k-a}^{k-a} \right)
\]

\[
P_{GG} = (1-p) \sum_{x=1}^{k} c_k^x \left( \sum_{z=0}^{n-1} c_k^x P_{z}^{z} P_{x-z}^{x-z} \right) \left( \sum_{a=0}^{k-x} c_{k-x}^{a} P_{a}^{a} P_{k-x-a}^{k-x-a} \right) + P_{g \text{ff}} \left( \sum_{a=0}^{k} c_k^a P_{a}^{a} P_{k-a}^{k-a} \right)
\]

\[
P_{FF} = p \sum_{x=1}^{k} c_k^x \left( \sum_{z=0}^{n-1} c_k^x P_{z}^{z} P_{x-z}^{x-z} \right) \left( \sum_{a=0}^{k-x} c_{k-x}^{a} P_{a}^{a} P_{k-x-a}^{k-x-a} \right) + P_{f \text{ff}} \left( \sum_{a=0}^{k} c_k^a P_{a}^{a} P_{k-a}^{k-a} \right)
\]
Reliable vital signals monitoring

- results from a clinical trial indicate that sensing is the primary source of unreliability
  - patient movement, improper sensor placement, sensor disconnections


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Smart cardiovascular medical device

Cluster of capacitive pressure sensors
Maximizes the system sensitivity to leakages

Sensor
LC resonant circuit with oscillating frequency sensitive to pressure variations

Receiver
Delivers energy and detects sensors’ resonance frequencies through an inductive coupling link

Frequency band
12.5 MHz to 20.0 MHz (allocated for medical applications)
Smart cardiovascular medical device

Readout Stimulus

Square wave (100 kHz)

Sensor’s response

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Detecting multiple sensors

<table>
<thead>
<tr>
<th>Sensor</th>
<th>$L_s$ (μH)</th>
<th>$C_s$ (pF)</th>
<th>$f_{calc}$</th>
<th>$f_{meas}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>5.42</td>
<td>22</td>
<td>15.1</td>
<td>14.7</td>
</tr>
<tr>
<td>2</td>
<td>3.85</td>
<td>27</td>
<td>16.2</td>
<td>16.2</td>
</tr>
</tbody>
</table>

Spectrum parameters

$K(\Phi)$ [dB]
## Smart cardiovascular medical device

Likely faults in the pressure sensor

<table>
<thead>
<tr>
<th>Capacitor Defects</th>
<th>Effects on Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stuck capacitor</td>
<td>Leads to a constant resonant frequency measurement</td>
</tr>
<tr>
<td>Reduction of capacitor's nominal measurement range</td>
<td>Allows detecting pressure deviations but in a narrow range, these measurements could still be taken as admissible</td>
</tr>
<tr>
<td>Large deviation of capacitor's nominal value</td>
<td>Could lead to a false defective stent-graft detection (e.g. a leaking stent-graft)</td>
</tr>
<tr>
<td>Collapsed capacitor</td>
<td>Shows no oscillation frequency</td>
</tr>
<tr>
<td>Bending of the structure</td>
<td>Deviation of the inductance and capacitor values</td>
</tr>
<tr>
<td>Aging of the structure</td>
<td>Increase of inductor resistance</td>
</tr>
</tbody>
</table>

![Aortic Blood Pressure (mmHg)](image)

![Oscillating Frequency Distribution](image)
Fault detection

From the transmitted power data the quality factor \((Q)\) can be obtained.

Using the measured \(f_{osc}\) and \(Q\), the \(k\) and \(R_s\) values are estimated.
Smart cardiovascular medical device

Sensor faults detection

\[ l_m = k \sqrt{l_s l_p} \]

\[ \mathcal{R}(Z_L) = R_p + \frac{\omega^4 R_s l_m^2 c_s^2}{1 + \omega^2 (R_s^2 c_s^2 - 2L_s c_s) + \omega^4 L_s^2 c_s^2} \]

\[ \mathcal{I}(Z_L) = \omega (l_p - l_m) + \frac{\omega l_m + \omega^3 (R_s^2 l_m c_s^2 + l_m^2 c_s - 2L_s l_m c_s) + \omega^5 c_s^2 (l_s^2 l_m - l_m^2 l_s)}{1 + \omega^2 (R_s^2 c_s^2 - 2L_s c_s) + \omega^4 L_s^2 c_s^2} \]
Smart cardiovascular medical device

Block Diagram

Telemetry System

Signal Acquisition

Data Modeling

- Frequency sweep after QRS detection
- Measure transmitted power and impedance

Transmitted Power (P) and Impedance (Z_L)

Extraction of sensor’s components nominal values for fault detection
L_s, R_s, C_s

Cristina Oliveira, José Machado da Silva, Fault Detection System for a Stent-Graft Endoleakage Monitor
18th International Mixed-Signals, Sensors and Systems Test Workshop (IMS3TW), 2012
Results

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Calculated [μH]</th>
<th>Extracted [μH]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_s$</td>
<td>22.17</td>
<td>21.90</td>
</tr>
<tr>
<td>$C_s$ [pF]</td>
<td>36.47</td>
<td>44.98</td>
</tr>
<tr>
<td>$R_s$ [Ω]</td>
<td>3.99</td>
<td>20.38</td>
</tr>
</tbody>
</table>

Extracted $R_s$ and $C_s$ are higher than calculations, because during the assembly of the A–CNTs onto the flex PCB using a special conductive glue extra parasitic capacitance and resistance are inserted. The antenna’s inductance measured with a network analyzer prior to the assembly of the A–CNTs is 18.08 μH. The antenna is not purely inductive, since the overlap of the top and bottom coils introduces a significant series capacitance, which causes the difference in the inductance value.
A Textiles Embedded Body Sensor Network

**Objective**

- Sensor modules interconnected with textile conductive yarns capture EMG and kinematic activity signals from the lower limbs.
- Send aggregated information to an external processing unit.

A Textiles Embedded Body Sensor Network

**Characteristics**

- Tx/Rx at 10Mbps;
- Pulse modulation;
- PLC;
- Line fault detection;
- Energy Efficient;
- Line impedance independent functionality.
A Textiles Embedded Body Sensor Network

- Data Acquisition
  - Acceleration
  - Angular rate
  - Surface EMG

- Status
  - First prototypes concluded and validated
  - Second prototypes just received
    - ¼ of PCB Area
    - Stitching PCB

1º Prototype

System Layout

2º Prototype

Sensor V2  EMG V2

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Test and calibration of wired sensors

- A proprietary I2C based test infrastructure

SCPS – Setup, Capture, Process, Scan
Design for dependability of Wireless Sensor Networks

Many steps have been taken, but there’s still a long way to go!
Bibliography