Dependable Internet of Things in Adverse Environments

Prof. Dr. Kay Römer
Graz University of Technology, Austria
roemer@tugraz.at
50 Billion connected things by 2020
Critical Applications
Make the IoT as dependable as the power grid

Provable performance guarantees
Dependable Internet of Things for Critical Applications

- Safety-critical applications
  - Smart factories, connected cars, smart health, ...
- Dependability
  - Performance guarantees (latency, loss, lifetime)
- Threats to dependability
  - Harsh environments (temperature, interference)
Building Integrity Monitoring

- Detection of hazards (tiles fall off from façade)
- Test deployment in Madrid
- Significant impact of sunshine on wireless network performance
Real-World Temperature Variations

- October 2014: on-board temperatures between 8 and 62 °C
- Nodes on the South façade experienced the highest fluctuations
Performance of State-of-the-Art Protocols

- Network setup
  - ContikiMAC as radio duty cycling protocol
  - Carrier Sense Multiple Access (CSMA)

- Insufficient network performance
  - PRR ~60%
  - Cause: Temperature variations!

<table>
<thead>
<tr>
<th>Node ID</th>
<th>Average PRR</th>
<th>Minimum PRR</th>
</tr>
</thead>
<tbody>
<tr>
<td>102</td>
<td>91.14%</td>
<td>42.42%</td>
</tr>
<tr>
<td>105</td>
<td>59.73%</td>
<td>3.63%</td>
</tr>
<tr>
<td>106</td>
<td>19.90%</td>
<td>3.77%</td>
</tr>
<tr>
<td>107</td>
<td>74.70%</td>
<td>7.04%</td>
</tr>
<tr>
<td>Network</td>
<td>61.38%</td>
<td>–</td>
</tr>
</tbody>
</table>
Performance of State-of-the-Art Protocols

- Signal strength attenuation at high temperatures

Goal: Performance guarantees in harsh environments
Experimenting with Temperature in the Lab

- Testbed extension to study the impact of temperature
  - 30 nodes, 8 with heating capabilities
  - Remote access

Carlo Alberto Boano et al: TempLab: a testbed infrastructure to study the impact of temperature on wireless sensor networks. IPSN 2014
Environmental and Platform Models

- Model of attenuation of received signal strength depending on transceiver temperature
  - Transmitted & received power decrease at high temperature
  - Highest impact when both nodes are heated (red)

Environment-Aware Protocols

- CSMA-based duty-cycled MAC protocols (such as ContikiMAC) are highly susceptible to temperature variations!
  - They rely on clear channel assessment (CCA) to transmit / wake-up
  - At high temperatures, the mechanisms breaks!

CCA is employed for:
- Collision avoidance
- Triggering the wake-up of nodes
Environment-Aware Protocols

- CCA threshold typically fixed at compile time
  - CC2420 uses CCA = -77 dBm

![Diagram showing RSSI (dBm) over time with CCA threshold and actions for TX and RX based on the RSSI level.]

- TX: defer transmission
- RX: wake-up (get packet)
- TX: start transmission
- RX: keep sleeping
Environment-Aware Protocols

- High temperatures may cause an intersection with CCA threshold
  - Receiver nodes will not wake-up at high temperature!

![Graph showing temperature and RSSI over time](image-url)
Environment-Aware Protocols

- Our solution: TempMAC
  - Exploits platform model and environmental model to dynamically adapt CCA threshold at runtime
  - Avoids adverse effects of temperature variations
Results

- Pilot deployment in Madrid
  - Performance requirements of application correctly met
Smart Parking

- Sense for car in the place and send occupancy to a central server
- Information about every parking spot in a city
- Information about movement of cars in a city (residential, commercial, etc.)
- Large scale (~1000 nodes)

<table>
<thead>
<tr>
<th></th>
<th>Must</th>
<th>Should</th>
<th>Could</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data loss</td>
<td>&lt; 10%</td>
<td>&lt; 5%</td>
<td>&lt; 1%</td>
</tr>
<tr>
<td>Latency</td>
<td>&lt; 30 seconds</td>
<td>&lt; 10 seconds</td>
<td></td>
</tr>
<tr>
<td>Battery lifetime</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(European)</td>
<td>&gt; 4 months</td>
<td>&gt; 8 months</td>
<td>&gt; 1.5 years</td>
</tr>
<tr>
<td>Battery lifetime</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Mediterranean)</td>
<td>&gt; 6 months</td>
<td>&gt; 1 year</td>
<td>&gt; 2 years</td>
</tr>
<tr>
<td>Battery lifetime</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Desert)</td>
<td>&gt; 3 months</td>
<td>&gt; 6 months</td>
<td>&gt; 1 year</td>
</tr>
</tbody>
</table>
Estimating Battery Lifetime

- Energy consumption estimation is important
  - Is a deployment (economically) viable?
  - This depends often on energy consumption patterns
  - Energy consumption patterns depend on radio interference

- Assumption: Idle energy consumption is the dominant cost
  - Most energy is consumed by the transceiver
  - Most transceiver energy is spent on listening

The lifetime of a node can vary by a factor of 10 depending on the present interference patterns!
Experimenting with Interference

- Low-cost (re)generation of interference
  - Using existing infrastructures (without adding expensive hardware)
  - Maximize flexibility and reduce setup time by avoiding manual relocation or activation of different devices

Carlo Boano et al: JamLab: Augmenting sensornet testbeds with realistic and controlled interference generation, IPSN 2011.
Impact of Interference on Idle Listening

- CSMA-based duty-cycled MAC protocols (such as ContikiMAC) are highly susceptible to interference!
  - They rely on clear channel assessment (CCA) to transmit / wake-up
  - Under interference, the mechanisms breaks!

- CCA is employed for:
  - Collision avoidance
  - Triggering the wake-up of nodes

![Diagram showing the impact of interference on idle listening between two nodes](example_image)
Meeting Lifetime Goals

- Target lifetime derived from use case:
  - 4 Months (must); 8 Months (should); 18 Months (could)
- Translates to
  - 1.38% radio-on time for 18 Month
- ContikiMAC options
  - Channel Check Rate (CCR) of 2, 4, 8, 16, 32 Hz
- Prior Deployment: Model Interference × CCR → Energy
- Operation: Monitor Interference → Select CCR
Interference intensity  

Energy consumption 

Model 

10 x reduced battery life
Results

- **Environmental model:**
  - Channel 12: average of 14%, significant bursts during days
  - Channel 14: average of 2%, less bursts ← selected channel

- **Parameter selection:**
  - Must achieve 1.38% duty cycle under interference
  - Based on model select a CCR of 16Hz

- **Results**
  - Some very short violations
  - Average of 1.32%
  - Below target of 1.38%
Environment-Aware IoT: General Architecture

- Dependability Requirements
- Protocol Selection & Parameterization
- IoT Application with Performance Guarantees
- Protocol Models
- Environment Models
- Environment Aware Protocols
- Platform Models

FIRE Experimental Infrastructures with Realistic Environmental Effects
Conclusions

- Critical IoT applications will be ubiquitous
  - People may be hurt
  - Business models may fail
- Harsh environments impact IoT performance
  - Temperature variations
  - Radio interference
- Need for guaranteed performance
  - Models of the environment and the system
  - Adaptive protocols
  - Configuration of parameters

Environment-Aware Networking
Acknowledgements

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- www.relyonit.eu