Wireless Sensor Networks for Online Monitoring

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PermaSense – Aims and Vision

Geo-science and engineering collaboration aiming to:

- provide **long-term high-quality** sensing in **harsh environments**
- facilitate near-complete **data recovery** and **near real-time delivery**
- obtain **better quality** data, more effectively
- obtain measurements that have **previously been impossible**
- provide **relevant information** for research or decision making, **natural hazard early-warning systems**
Understanding Root Causes of Catastrophes

Eiger east-face rockfall, July 2006, images courtesy of Arte Television
Rockfall release mechanisms and their connection to time and climate (change) are not understood.
Our patient does not fit into a laboratory.
So the laboratory has to go on the mountain.
PermaSense

- Consortium of several projects, start in 2006
- Multiple disciplines (geo-science, engineering)
- Fundamental as well as applied research
- More than 20 people, 9 PhD students

Nano-tera.ch X-Sense is a PermaSense project

http://www.permasense.ch
PermaSense – Competence in Outdoor Sensing

- Wireless systems, low-latency data transmission
- Customized sensors
- Ruggedized equipment
- Data management
- Planning, installing, operating (years) large deployments
PermaSense Deployment Sites 3500 m a.s.l.

A scientific instrument for precision sensing and data recovery in environmental extremes
PermaSense – System Architecture

Processor
Low-power Radio
SD Card Storage

Different Sensor Options
Sensor Node

Sensor Node
Wireless Sensor Network

Access Node
CoreStation

Backup Database
Backup GSM

12V Solar Power
Base Station

WLAN

GSN

Server
Database

Backend

WLAN Router

Technische Informatik und Kommunikationsnetze
Computer Engineering and Networks
Simple Low-Power Wireless Sensors

- Static, low-rate sensing (120 sec)
- Simple scalar values: temperature, resistivity
- 3 years operation (~200 μA avg. power)
- < 0.1 Mbyte/node/day

3+ years experience, ~130’000’000 data points

In relation to other WSN projects
- Comparable to many environmental monitoring apps
  - GDI [Szewczyk], Glacswep [Martinez], Volcanoes [Welsh], SensorScope [Vetterli], Redwoods [Culler]
- Lower data rate
- Harsher environment, longer lifetime
- Higher yield requirement
- Focus on data quality/integrity
PermaSense – Sensor Types

- Sensor rods (profiles of temperature and electric conductivity)
- Thermistor chains
- Crack meters
- Water pressure
- Ice stress
- Self potential

Data: Simple sensors, constant rate sampling, scalar values
Established: Rock/ice Temperature

Aim: Understand temperatures in heterogeneous rock and ice

- Measurements at several depths
- Two-minute interval, autonomous for several years
- Survive, buffer and flush periods without connectivity

[Hasler 2011]
Established: Crack Dilatation

Aim: To understand temperature/ice-conditioned rock kinematics

- Temperature-compensated, commercial instrument
- Auxiliary measurements (temperature, additional axes, …)
- Two-minute interval, autonomous for several years
- Protection against snow-load and rock fall
Results: Rock Kinematics

Field Site Support

- Base station
  - On-site data aggregation
  - Embedded Linux
  - Solar power system
  - Redundant connectivity
  - Local data buffer
  - Database synchronization

- Cameras
  - PTZ webcam
  - High resolution imaging (D-SLR)

- Weather station

- Remote monitoring and control
WLAN Long-haul Communication

- Data access from weather radar on Klein Matterhorn (P. Burlando, ETHZ)
- Leased fiber/DSL from Zermatt Bergbahnen AG
- Commercial components (Mikrotik)
- Weatherproofed
Data Management – Online Semantic Data

Global Sensor Network (GSN)

- Data streaming framework from EPFL (K. Aberer)
- Organized in “virtual sensors”, i.e. data types/semantics
- Hierarchies and concatenation of virtual sensors enable on-line processing
- Dual architecture translates data from machine representation to SI values, adds metadata

![Diagram showing import from field and web export for GSN with metadata and data structures]
Multi-Site, Multi-Station, Multi-Revision Data...
Central Web-based Data Access

Welcome to the PermaSense Data Frontend.
PermaSense observes physical parameters related to permafrost in steep high-alpine terrain over a period of multiple years. Live sensor network data is transmitted from the Matterhorn and Jungfraujoch field sites at 3500 m a.s.l. every 2 minutes.
See the data live on the real-time tabs below or as plots in the data browser.

Virtual sensors

- Group: jungfraujoch
  - matterhorn_backlogstatus_chart1
  - matterhorn_backlogstatus_mapped_1355
  - matterhorn_basestationstatus_chart1
  - matterhorn_basestationstatus_chart2
  - matterhorn_basestationstatus_chart3
  - matterhorn_basestationstatus_mapped_1355
  - matterhorn_crackmeter_nctc_1390
  - matterhorn_crackmeter_nctt_1396
  - matterhorn_crackmeter_pos1_chart1
  - matterhorn_crackmeter_pos1_chart2
  - matterhorn_crackmeter_pos2_chart1
  - matterhorn_crackmeter_pos2_chart2
  - matterhorn_crackmeter_pos3_chart1
  - matterhorn_crackmeter_pos3_chart2
  - matterhorn_crackmeter_pos4_chart1
  - matterhorn_crackmeter_pos4_chart2

Sensorrod temperatures (Position 10, 7d)
Visualization with Google Earth
In Real-Time: Combined Data Overlays
Central Web-based Data Access
Sensor Network Technology
Wireless Networked Embedded Systems

- Highly Resource Constrained
- Distributed State
- Unreliable Communication
- Interaction and Tight Embedding in Environment
PermaSense – Sensor Node Hardware

- **Shockfish TinyNode584**
  - MSP430, 16-bit, 8MHz, 10k SRAM, 48k Flash
  - LP Radio: XE1205 @ 868 MHz

- **Waterproof housing and connectors**

- **Protective shoe, easy install**

- **Sensor interface board**
  - Interfaces, power control
  - Temp/humidity monitor
  - 1 GB memory

- **3-year life-time**
  - Single Li-SOCl₂ battery, 13 Ah
  - ~300 µA power budget

measured avg. current consumption ~148 µA
TinyNode + Sensor Interface Board

- Extension: One Serial Bus
  - (Power) control using GPIO
  - Optimized for low-power duty cycling
External Storage Extension

- Data buffering
- End-to-end validation

<table>
<thead>
<tr>
<th>DAQ Interval</th>
<th>1min</th>
<th>2min</th>
<th>30min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Byte/day/node</td>
<td>233280</td>
<td>116640</td>
<td>7776</td>
</tr>
<tr>
<td>TinyOS packets&lt;sup&gt;a&lt;/sup&gt;/min</td>
<td>7.04</td>
<td>3.52</td>
<td>0.234</td>
</tr>
<tr>
<td>Mbyte/year/node</td>
<td>80.0</td>
<td>40.1</td>
<td>2.64</td>
</tr>
<tr>
<td>Mbyte/3years/20nodes</td>
<td>4805</td>
<td>2403</td>
<td>160</td>
</tr>
</tbody>
</table>

<sup>a</sup> 23 byte per TOS packet
Ultra Low-Power Multi-hop Networking

- Dozer ultra low-power data gathering system
  - Beacon based, 1-hop synchronized TDMA
  - Optimized for ultra-low duty cycles
  - 0.167% duty-cycle, **0.032mA** (@ 30sec beacons)

- But in reality: Connectivity can not be guaranteed…
  - Situation dependent transient links (scans/re-connects use energy)
  - Account for long-term loss of connectivity (snow!)

[Burri, IPSN2007]
Sensors Contribute to Power Consumption

The graph shows the current consumption over time for different components and sensors. The x-axis represents time in seconds, and the y-axis represents current consumption in milliamps (mA). The graph includes lines for:

- **Earthpressure cell**: 4.58 mA (avg)
- **Sensor rod**: 3.90 mA (avg)
- **Digital sensor**: 1.92 mA (avg)

The table on the graph lists the following categories and their associated sensors:

<table>
<thead>
<tr>
<th>Category</th>
<th>Sensor</th>
<th>Current Consumption (mA avg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC calibration</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sys Volt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp Humid</td>
<td></td>
<td></td>
</tr>
<tr>
<td>External ADC channels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Digital protocol</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The graph illustrates how the current consumption varies across different sensor types and how these sensors contribute to overall power consumption.
1-hop Power Trace Validation

(1) Receive parent beacon  (2) Send beacon to children  (3) Send data to parent  (4) Sampling sensor (DAQ)
## Total Power Performance Analysis

<table>
<thead>
<tr>
<th>Operating Mode Characterization</th>
<th>[mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleep</td>
<td>0.026</td>
</tr>
<tr>
<td>DAQ active(^a)</td>
<td>2.086</td>
</tr>
<tr>
<td>Dozer RX idle</td>
<td>13.64</td>
</tr>
<tr>
<td>Dozer RX</td>
<td>14.2</td>
</tr>
<tr>
<td>Dozer TX</td>
<td>54.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Measured Average Values</th>
<th>[mA]</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAQ only (2min)</td>
<td>0.110</td>
</tr>
<tr>
<td>Dozer only (30sec/2min)(^b)</td>
<td>0.072</td>
</tr>
<tr>
<td>PermaDozer total (30sec/2min)</td>
<td>0.148</td>
</tr>
</tbody>
</table>

\(^a\) Averages power consumption measured over a complete DAQ routine execution without attached sensor

\(^b\) Dozer only includes communication, not including network initialization and access to flash memory

148 uA average power
Timing Control = Energy Savings
Power Optimization – Squeeze with Implications

- Regulator uses 17\(\mu\)A quiescent current
- Bypass used to shutdown regulator -> \(\sim\)1\(\mu\)A in standby

- No Bypass increases ADC accuracy: stddev 0.8844 -> 0.0706
Power Quality Increases Data Accuracy

Before

Crack extension
Temperature

std dev = 24.0 μm

After

std dev = 1.0 μm

Temperature [°C]

15 Oct 07
20 Oct 07
25 Oct 07

Temperature

1.5
2.0
2.5

Crack extension [mm]

24 Feb 08
29 Feb 08
5 Mar 08

11.5
11.6
11.7
11.8
11.9
12.0

15 Oct 07
20 Oct 07
25 Oct 07
24 Feb 08
29 Feb 08
5 Mar 08

11.5
11.6
11.7
11.8
11.9
12.0

std dev = 1.0 μm
Reconstructing Global Time Stamps

- No network-wide time synchronization available
  - Implications on data usage

- Elapsed time on arrival
  - Sensor nodes measure/accumulate packet sojourn time
  - Base station annotates packets with UTC timestamps
  - Generation time is calculated as difference $\tilde{t}_g = t_b - \tilde{t}_s$

$$\begin{align*}
\text{a} & \quad 4 \text{ sec} \\
\text{b} & \quad 4 \text{ sec} \\
\text{c} & \quad 6 \text{ sec} \\
\text{a} & \quad 1 \text{ sec} \\
\text{c} & \quad 7 \text{ sec} \\
\end{align*}$$

$2011/04/14 \ 10:03:31 - 7 \text{ sec} = 2011/04/14 \ 10:03:24$
CoreStation – Embedded Linux & WLAN

- Gumstix Verdex
- TinyNode
- GSM
- WLAN Router
- EMP Protectors
- IP68 Enclosure and Connectors
Challenge: The Physical Environment

- Lightning, avalanches, rime, prolonged snow/ice cover, rockfall
- Strong daily variation of temperature
  - $-30$ to $+40^\circ\text{C}$
  - $\Delta T \leq 20^\circ\text{C}/\text{hour}$
Ruggedized for Alpine Extremes

- Coax Cable
- TinyNode
- Sensor-Interface Board
- External Antenna
- Sensor Connector
- SD Card
- Battery
- Metal Housing
- Protective Shoe
- Cover for Housing
Impact of Environmental Extremes

- Software testing in a climate chamber
  - Clock drift compensation yields ± 5ppm
- Validation of correct function
- Tighter guard times increase energy efficiency
WSN Testbed – DSN and FlockLab v2

Testbed Key Differentiators
- Distributed observers, local intelligence
- Mobility: Wireless, battery powered

Testbed Functionality
- Remote reprogramming
- Extraction of log data
- Stimuli, e.g. fault injection
- Synchronization of traces and actions

Target Sensor Network
- Centralized logging
- Detailed behavioral analysis

Physical Emulation Architecture

- Influence of power sources/quality
- Detailed physical characterization
  - Emulation of environment and resources
    - Temperature Cycle Testing (TCT)
    - Controlled RF attenuation
    - Sensor stimuli and references

[EmNets2007]
Installation Effort: \( \geq 1 \text{ man-day/sensor} \)
Key PermaSense Challenges

- System Integration
- Correct Test and Validation
- Actual Data
- Interdisciplinary Team
• ETH Zurich
  – Computer Engineering and Networks Lab
  – Geodesy and Geodynamics Lab
• University of Zurich
  – Department of Geography
• EPFL
  – Distributed Information Systems Laboratory
• University of Basel
  – Department Computer Science

Interested in more?
http://www.permasense.ch