Wireless Sensor Networks in Extreme Environments

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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.
What is the Role of Ice Filled Clefts?
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

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

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

A **scientific instrument** for **precision sensing** and data recovery in environmental extremes.
Sensor Network Technology Challenges
PermaSense System Architecture
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, ~280’000’000 data points

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

- **Shockfish TinyNode184**
  - MSP430, 16-bit, 8MHz, 8k SRAM, 92k Flash
  - LP Radio: SX1211 @ 868 MHz

- **Sensor interface board**
  - 1 GB storage

- **3-year life-time**

- **Dozer - ultra low-power data gathering system**
  - Multi-hop, beacon based, 1-hop synchronized TDMA
  - Optimized for ultra-low duty cycles
  - **0.167% duty-cycle, 0.032mA**
Ruggedized for Alpine Extremes
Challenge: The Physical Environment

• Lightning, avalanches, rime, prolonged snow/ice cover, rockfall

• Strong daily variation of temperature
  – −30 to +40°C
  – \(\Delta T \leq 20^\circ\text{C}/\text{hour}\)
Impact of Environmental Extremes

- Tighter guard times increase energy efficiency
- Software testing in a climate chamber
  - Clock drift compensation yields ± 5ppm
- Validation of correct function

[Beutel, DATE 2011]
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
Redundant Access & Monitoring

• Dual WLAN & 3G access network
• Redundant base stations (DH/GG/RD)
• Distributed monitoring infrastructure
Installation/Maintenance Effort
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

Observation: Acceleration Behavior

![Graph showing temperature and acceleration behavior over time with three distinct phases labeled I, II, and III. Each phase is marked with vertical dashed lines highlighting specific events.]

1. Phase I
2. Phase II
3. Phase III
Data Reliability & Data Management
Local Data Storage on Every Layer

- Processor
  - Low-power Radio
  - SD Card Storage

- Sensor Node
  - Different Sensor Options

- Wireless Sensor Network

- CoreStation
  - Backup GSM
  - Access Node
  - Backlog Database

- Base Station
  - 12V Solar Power

- Backend
  - WLAN Router
  - Server
  - Database

- GSN
Hierarchical Online Data Processing

- 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

Import from field → GSN → Private
GSN
Public
Web export

Metadata

========
Position
Sensor type
Validity period
...
Multi-Site, Multi-Station, Multi-Revision Data...
Metadata Change Management

• Allows simple exchange of sensor hard-/software at runtime
• Post-deployment annotation
  – Stop GSN– deployment change – annotate metadata – restart GSN
• Automatic synchronization with 1 day change boundaries
Visualization with Google Earth
In Real-Time: Combined Data Overlays
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.

Live Demo
Reconstructing of Global Time Stamps

- WSN do not have network-wide time synchronization
  - 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 $\tilde{t}_g = t_b - \tilde{t}_s$

[2011/04/14 10:03:31 – 7 sec
  = 2011/04/14 10:03:24]

[Keller, IPSN 2011]
Resulting Challenge: Data Integrity

- Long term deployment
- Up to 19 sensor nodes
- TinyOS/Dozer [Burri, IPSN2007]
- Constant rate sampling
- < 0.1 MByte/node/day
Data is Not Correct-by-Design

- Artifacts observed
  - Packet duplicates
  - Packet loss
  - Wrong ordering
  - Variations in received vs. expected packet rates
- Necessitates further data cleaning/validation
Sources of Errors Included in Model

**Data Loss**
- Node reboot
- Queue reset
- Empty queue
- Waiting packets

**Clock Drift** $\rho \in [\hat{-}\rho; \hat{+}\rho]$
- Directly affects measurement of:
  - Sampling period $T$
  - Contribution to elapsed time $t_e$
- Indirectly leading to inconsistencies:
  - Time stamp order $t_p$ vs. order of packet generation $s$

**Packet Duplicates**
- Lost 1-hop ACK
- Retransmission

**Node Restarts**
- Cold restart: Power cycle
- Warm restart: Watchdog reset
- Shortens packet period
- Resets/rolls over certain counters

- Waiting packets
- Queue reset
- Empty queue
Model-based Data Validation Case Studies

- Validation of correct system function

<table>
<thead>
<tr>
<th>Counter</th>
<th>A) Jul 08-Nov 08</th>
<th>B) Nov 08-Aug 09</th>
<th>C) Sep 09-May 10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accepted packets</td>
<td>632,058 (59.4%)</td>
<td>2,110,855 (96.8%)</td>
<td>2,579,444 (95.4%)</td>
</tr>
<tr>
<td>Discarded packets</td>
<td>432,826 (40.6%)</td>
<td>69,829 (3.2%)</td>
<td>124,554 (4.6%)</td>
</tr>
<tr>
<td>Packet duplicates</td>
<td>4,020 (0.4%)</td>
<td>69,422 (3.2%)</td>
<td>44,601 (1.7%)</td>
</tr>
<tr>
<td>$t_n(i) &gt; t^\text{max}_n$</td>
<td>0 (0.0%)</td>
<td>0 (0.0%)</td>
<td>0 (0.0%)</td>
</tr>
<tr>
<td>Failed epoch assignment</td>
<td>235,927 (22.2%)</td>
<td>277 (0.0%)</td>
<td>2,466 (0.1%)</td>
</tr>
<tr>
<td>Invalid interval $t_n^\text{max}_n(i)$</td>
<td>192,879 (18.1%)</td>
<td>130 (0.0%)</td>
<td>77,487 (2.9%)</td>
</tr>
<tr>
<td>Total packets</td>
<td>1,064,884 (100.0%)</td>
<td>2,180,684 (100.0%)</td>
<td>2,703,998 (100.0%)</td>
</tr>
</tbody>
</table>

- Long-term comparison of three field sites

[Keller, SenseApp 2011, IPSN 2011]
New: acoustic emissions

Aim: To understand the importance that ice-segregation, volume expansion and thermal cycling have on rock damage in natural conditions – to infer instability zones.

- Continuous measurement, transmission of event statistics
- Storage of raw traces
- Auxiliary data (temperature, moisture, camera, ... )
Jungfraujoch Field Site

- ~3500m a.s.l.
- Facing South
- Granitic gneiss (2% porosity)
- MAAT (1961-1990) = -7°C
- Mean annual rock T° = -2°C (10cm depth)

(Hasler et al. 2011)
Installation of 2 sites:

- Strategy: same ‘settings’ for both sites (~60° slope, SE aspect)
- **But:** 1 site is ‘dry’ (spur-like feature), 1 site is ‘wet’ (gully-like)
First Acoustic Data

- Wet site
- Dry site

No activity!
(similar thresholds at both sites)
Essentials: Work Safety & Training
• 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
Jungfraujoch Tour Program
2nd Group Meets at Sphinx 14h