Sensing Temperature with Wireless Networks

Jan Beutel, ETH Zurich
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
Science Objective: Understanding Root Causes of Catastrophes

Eiger east-face rockfall, July 2006, images courtesy of Arte Television
Our patient does not fit into a laboratory.
So the laboratory has to go on the mountain
PermaSense Deployment Sites 3500 m a.s.l.

A scientific instrument for precision sensing and data recovery in environmental extremes
Competence in Outdoor Sensing

- Wireless systems, low-latency data transmission
- Customized sensors
- Ruggedized equipment
- Data management
- Planning, installing, operating (years) large deployments
Simple Low-Power Wireless Sensors

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

4+ years experience, ~530’000’000 data points

In relation to other well-known 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

[Beutel IPSN2009]
PermaSense System Architecture

- Processor
  - Low-power Radio
  - SD Card Storage
- Sensor Node
- Wireless Sensor Network
- CoreStation
  - Backlog Database
  - Backup GSM
  - Access Node
  - WLAN
  - Base Station
    - 12V Solar Power
- Backend
  - WLAN Router
  - Server
  - Database
Low-power WSN Technology

- **Dozer** - ultra low-power data gathering system
  - Protocol stack designed for mote-class devices
  - Multi-hop, beacon based, 1-hop synchronized TDMA
  - Per-hop acknowledgements
  - Multiple sinks possible

- **Optimized for ultra-low duty cycles**
  - 0.167% duty-cycle, 0.032mA

- **Separation of concerns**
  - Dedicated application processing window

[Page 1] [Burri IPSN2007]
Sensor Networks and Time Information

• Often global reference time (UTC) is not available
  – Implications on data usage

• Solution: Elapsed time on arrival
  – Sensor nodes measure/accumulate sojourn time
  – Base station annotates data with arrival time (e.g. UTC)
  – 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
Ruggedized for Alpine Extremes
Field Site Support

• Base station (Linux)
  – Local data buffer, aggregation
  – Redundant connectivity
  – Global time synchronization
  – Database synchronization

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

• Weather station

• Solar power system

• WLAN Backbone
WLAN Long-haul Communication

- WLAN (802.11a) backbone using directional links
- Leased fiber/DSL from Zermatt Bergbahnen AG to mountaintop
- Commercial components (Mikrotik)
- Weatherproofed, protected
Online Data Management

- 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 → Private

GSN

Public

Web export

Metadata

=============

Position

Sensor type

Validity period...

<table>
<thead>
<tr>
<th>Real-Time</th>
<th>Structure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>timestamp</td>
<td>1267047238207</td>
<td></td>
</tr>
<tr>
<td>generationtime</td>
<td>1267047167207</td>
<td></td>
</tr>
<tr>
<td>position</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>sensorid</td>
<td>snnull</td>
<td></td>
</tr>
<tr>
<td>sensor_serialid</td>
<td>204061154</td>
<td></td>
</tr>
<tr>
<td>header_seqnr</td>
<td>header_seqnr 22301</td>
<td></td>
</tr>
<tr>
<td>header_originator</td>
<td>2002</td>
<td></td>
</tr>
<tr>
<td>header_atime</td>
<td>132</td>
<td></td>
</tr>
<tr>
<td>payload_sample_valid</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>payload_sample_no</td>
<td>00397</td>
<td></td>
</tr>
<tr>
<td>sr_ref1</td>
<td>1.0695</td>
<td></td>
</tr>
<tr>
<td>sr_ref2</td>
<td>0.9820</td>
<td></td>
</tr>
<tr>
<td>sr_t1</td>
<td>0.98247</td>
<td></td>
</tr>
<tr>
<td>sr_t2</td>
<td>0.98771</td>
<td></td>
</tr>
<tr>
<td>sr_t3</td>
<td>1.91102</td>
<td></td>
</tr>
<tr>
<td>sr_t4</td>
<td>1.20795</td>
<td></td>
</tr>
<tr>
<td>sr_ref3</td>
<td>1.9923</td>
<td></td>
</tr>
<tr>
<td>sr_ref4</td>
<td>0.8147</td>
<td></td>
</tr>
<tr>
<td>sr_ref5</td>
<td>0.8990</td>
<td></td>
</tr>
<tr>
<td>sr_r1</td>
<td>743.168</td>
<td></td>
</tr>
</tbody>
</table>
Vizzly: Visualization of Large Data

- Fast access to millions of data samples
- Pan, zoom, channel selection
- Combination of historic and real-time data

[Keller SenSys2009, SenseApp 2012]
Selected Environmental Science Results
Jungfraujoch: 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]
Matterhorn: Crack Dilatation

Aim: To understand temperature/ice-conditioned rock kinematics
- Temperature-compensated, commercial instrument
- Measurement of multiple axes
- Reduction of cabling to a minimum
- Protection against snow-load and rock fall
Results: Rock Kinematics

Sensor Data Acquisition
Wireless Networked Embedded Systems

• Highly Resource Constrained

• Distributed State

• Unreliable Communication

• Interaction and Tight Embedding in Environment
Sensor Node System Design

- System design considerations
  - One platform vs. family of devices?
  - Make vs. buy?
  - Build on familiar components, existing subsystems?

- Requirements
  - Capabilities for multiple sensors
  - Extreme low-power
  - High quality data acquisition (ADC resolution on MSP430 not sufficient)
  - Reliability in extreme environment

- Decisions
  - Modular platform, accommodating different sensors on one platform
  - Single, switchable serial bus architecture
  - Strict separation of operating phases (TDMA)
  - Enough storage for disconnected operation over months
  - Temp/Humidity/System voltage supervision in every box
Sensor Node Hardware

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

- **Waterproof housing and connectors**

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

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

Extension: One Serial Bus

(Power) control using GPIO
Optimized for low-power duty cycling
External Storage

Data buffer for delay-tolerant networking
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(^a)/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>

\(^a\) 23 byte per TOS packet
Dedicated A/D Conversion System

Analog Devices high-resolution Σ-Δ ADC

16/24 bit resolution (65536/16’777’216 values)
3.84 mW operating, 30 µA power-down
Programmable gain
Single-cycle conversion
External reference voltage, 5 ppm/°C
Individual Control over Power Domains
Sensor Interface Board Hardware

- Analog Interface
- ESD Protection
- Power Supplies
- Power Control/Debug
- Digital Interface
Sensor Node Data Acquisition Cycle

- Accurate data acquisition takes time -> power
- Individual sensors contribute to power consumption
Total Power Performance Analysis

Operating Mode Characterization [mA]

<table>
<thead>
<tr>
<th>Mode</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>

Measured Average Values [mA]

<table>
<thead>
<tr>
<th>Mode</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
Tight Timing Control = Energy Savings
Challenge: The Physical Environment

• Strong daily variation of temperature
  – −30°C to +40°C
  – $\Delta T \leq 20°C$/hour

• Impact on
  – timing, energy availability, fatigue, SOFTWARE, ...
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
Power Squeeze with Implications

- Regulator uses 17uA quiescent current
- Bypass used to shutdown regulator -> ~1uA in standby
- No Bypass increases ADC accuracy: stddev 0.8844 -> 0.0706
Power Quality Increases Data Accuracy

- **Before**
  - Crack extension: std dev = 24.0 μm
  - Temperature

- **After**
  - Crack extension: std dev = 1.0 μm
  - Temperature
Internal Monitoring Sensors

- Internal Temp/Hum/Bat
Temperature Sensors
Sensirion SHT Humidity and Temperature Sensor ICs

- Internal system monitoring
  - Fully calibrated
  - Digital output
  - 14 bit ADC (16384 values)
  - Low power consumption
  - Excellent long term stability
MSP430 Built-in Temperature Sensor

• Silicon bandgap temperature sensor
  – Utilizes forward voltage of silicon diode
  – Simple and cost effective to integrate in CMOS

\[ \Delta V_{BE} = \frac{KT}{q} \cdot \ln \left( \frac{I_{C1}}{I_{C2}} \right) \]

• Internal 12-bit Successive Approximation ADC (SAR)
  – Converging on result via binary search
  – Fast
  – 12-bit (4096 values)
  – Uses built-in reference (±100 ppm/°C)

• Co-located with CPU (thermal energy!)
The Hasler Sensor Rod

Thermistors vs. Thermocouples

The internal construction of a YSI thermistor

<table>
<thead>
<tr>
<th>Thermistors</th>
<th>Thermocouples</th>
<th>Platinum</th>
<th>Integrated Circuit</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 ohms to 1 megoohms at 25°C</td>
<td>7 to 62 μV/°C</td>
<td>0.00385 and 0.00392 ohms/°C</td>
<td>1 μA/°C</td>
</tr>
<tr>
<td>3.3 to 53K ohms/°C at 25°C</td>
<td>±0.8 to ±4.4°C</td>
<td>±0.3°C</td>
<td>±0.6 to ±5.0°C</td>
</tr>
<tr>
<td>±0.05 to ±0.2°C</td>
<td>Depends on environment</td>
<td>0.05°C/year (film)</td>
<td>0.1°C/month</td>
</tr>
<tr>
<td>0.02°C/month (epoxy)</td>
<td>0.02°C/year (glass)</td>
<td>0.002°C/year (wire)</td>
<td></td>
</tr>
<tr>
<td>Power Required</td>
<td>Stable voltage or current</td>
<td>Self-powered</td>
<td>Stable voltage or current</td>
</tr>
<tr>
<td>Minimum Practical Span</td>
<td>1°C</td>
<td>100°C</td>
<td>100°C</td>
</tr>
<tr>
<td>Temperature Range</td>
<td>-100 to +250°C</td>
<td>-100 to +1750°C</td>
<td>-200 to +750°C</td>
</tr>
<tr>
<td>Reference</td>
<td>None</td>
<td>Cold junction</td>
<td>None</td>
</tr>
<tr>
<td>Ruggedness</td>
<td>Very rugged</td>
<td>Large wire diameter very rugged</td>
<td>Very Rugged</td>
</tr>
<tr>
<td>Maximum Power (self-heat) for Stated Accuracy</td>
<td>50 μW</td>
<td>NA (susceptible to amplifier bias current error)</td>
<td>500 μW</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>&lt;0.01°C</td>
<td>&gt;1°C</td>
<td>0.01°C</td>
</tr>
<tr>
<td>Hysteresis over Range</td>
<td>&lt;0.01°C</td>
<td>±0.5°C</td>
<td>Not available</td>
</tr>
<tr>
<td>Repeatability over Range</td>
<td>&lt;0.01°C</td>
<td>&lt;0.01°C</td>
<td>±0.1°C</td>
</tr>
<tr>
<td>Lead Wire Configuration</td>
<td>2-wire</td>
<td>Thermocouple or extension wire</td>
<td>2-, 3-, 4-wire</td>
</tr>
</tbody>
</table>
YSI 4xxxx Thermistors

Super-Stable Thermistors

**YSI 46000 Series**

YSI 46000 Series components represent the state of the art in long-term stability performance. By coupling glass hermetic encapsulation with 100% resistance shift screening, we offer stability never before realized with thermistor components.

We offer YSI 46000 Series thermistors with interchangeability tolerances as tight as ±0.05°C, as well as ±0.1°C and ±0.2°C.

Many leading aerospace companies have recognized the advantages of these parts, developing their own specifications for qualifying, screening and using these thermistors in high-reliability applications. We welcome your inquiry on special measurement points and special test services.

**Tests Show Thermistor Stability**

YSI 45000 and 46000 Series Thermistors offer unparalleled stability and moisture resistance in thermistor components. The data from the three tests performed demonstrate that YSI glass thermistors are the device of choice in extreme environments.

**High-Temperature Testing**

The first was static high-temperature testing. All thermistors show some increase in resistance over time: the higher the temperature, the greater the shift. We placed YSI glass thermistors in an isothermal 150°C environment for extended time testing. On average, they shifted less than 0.04°C in 5,000 hours.

**Differential Dew Point Cycling**

The second test was cycling from ambient to below the dew point. Moisture is a major cause of failure in standard non-hermetic thermistors. This test exposed the thermistors to multiple cycles with 11 minutes below the dew point and 11 minutes at ambient. After over 3,500 cycles, we saw no appreciable shifts.

**High-Temperature Cycling**

The last, and most rigorous test, was thermal cycling. This cycle consisted of 11 minutes at ambient and 11 minutes at 200°C. We ran several hundred cycles. Shifts after 700 cycles averaged less than 0.2°C.

<table>
<thead>
<tr>
<th>Ordering Part Numbers</th>
<th>Zero Power Resistance</th>
<th>Delta 0 to 50°C</th>
<th>Beta</th>
<th>Delta 0 to 50°C</th>
<th>Beta</th>
<th>Delta 0 to 50°C</th>
<th>Beta</th>
<th>Maximum Working Temperature</th>
<th>Mix</th>
</tr>
</thead>
<tbody>
<tr>
<td>46004</td>
<td>225Ω</td>
<td>385Ω</td>
<td>29.26</td>
<td>25°C</td>
<td>200°C</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46005</td>
<td>3000Ω</td>
<td>385Ω</td>
<td>29.26</td>
<td>25°C</td>
<td>200°C</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46006</td>
<td>5000Ω</td>
<td>385Ω</td>
<td>29.26</td>
<td>25°C</td>
<td>200°C</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46007</td>
<td>6Ω</td>
<td>385Ω</td>
<td>29.26</td>
<td>25°C</td>
<td>200°C</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46008</td>
<td>10K</td>
<td>385Ω</td>
<td>29.26</td>
<td>25°C</td>
<td>200°C</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>46009</td>
<td>30K</td>
<td>385Ω</td>
<td>29.26</td>
<td>25°C</td>
<td>200°C</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

How to Order

Please order from your YSI representative or YSI Customer Service.
YSI 4xxxx Thermistors

±0.2°C Interchangeability Tolerance Data

The table shows nominal resistance values, ohms per degree (sensitivity), and tolerances in °C and percent for the YSI Thermistor Series.

<table>
<thead>
<tr>
<th>YSI Series</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>440_</td>
<td>Epoxy-Encapsulated Thermistors</td>
</tr>
<tr>
<td>450_</td>
<td>High-Temperature Hermetic Thermistors</td>
</tr>
<tr>
<td>460_</td>
<td>Super-Stable Thermistors</td>
</tr>
<tr>
<td>550_</td>
<td>GEM Glass-Encapsulated Thermistors</td>
</tr>
</tbody>
</table>

1

±0.05°C Interchangeability Tolerance Data

The table shows nominal resistance values, ohms per degree (sensitivity), and tolerances in °C and percent, for the YSI Thermistor Series.

<table>
<thead>
<tr>
<th>YSI Series</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>460_</td>
<td>Super-Stable Thermistors</td>
</tr>
</tbody>
</table>

1

For more information, contact us at 800 747-5367 or 937 427-1231 • Fax 937 427-1649
Info@YSI.com • www.YSI.com
Sensor Rod Multiplexing
## Vaisala Weather Transmitter WXT520

### Access to Real Time Weather Data

#### Technical Specifications

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Units</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind speed</td>
<td>0 - 60 m/s</td>
<td>±3% at 10 m/s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direction</td>
<td>0 - 360°</td>
<td>±3°</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall</td>
<td>0.001 mm, 0.001 inches</td>
<td>0.25%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rainfall duration</td>
<td>one-minute running average in ten-second steps</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barometric pressure</td>
<td>0 - 1100 hPa</td>
<td>±0.5 hPa at 0 - 30 °C (+32 - +86 °F)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air temperature</td>
<td>0 - 50 °C (-40 - +150 °F)</td>
<td>±0.3 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative humidity</td>
<td>0 - 100 %RH</td>
<td>±3 %RH within 0 - 90 %RH, ±5 %RH within 90 - 100 %RH</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### General

- Operating temperature: -50...+70 °C (-58...+158 °F)
- Storage temperature: -50...+170 °C (-58...+338 °F)
- Input voltage: 5...32 VDC (with defaults)
- Typical power consumption: 3 mA at 12 VDC
- Heating voltage: 5...32 VDC (or AC, max. 30 VAC)
**UMS TH3 Soil Profiling Probe**

<table>
<thead>
<tr>
<th>Material und Abmessungen</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Gehäuse</td>
<td>PA66GF30-Hohlstab Kunststoffspitze.</td>
</tr>
<tr>
<td>Länge</td>
<td>1020mm</td>
</tr>
<tr>
<td>Durchmesser</td>
<td>20mm</td>
</tr>
<tr>
<td>Schutzklasse</td>
<td>IP68</td>
</tr>
</tbody>
</table>

**Kabel (Standard)**

<table>
<thead>
<tr>
<th>Material</th>
<th>PUR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stecker</td>
<td>4 polig, Schraubgewinde M12, wasserdicht bei zeitweiligem Untertauchen (IP67)</td>
</tr>
<tr>
<td>Länge</td>
<td>4,5 m (Standard SC-Kabel 5m, andere auf Anfrage)</td>
</tr>
<tr>
<td>Kabelschutz</td>
<td>Geschlitzter Wellrippenschlauch empfohlen, andere auf Anfrage</td>
</tr>
</tbody>
</table>

**Sensorspezifikationen**

| Genauigkeit       | ± 0,1°C              |
| Messbereich       | -20°C - +50°C         |
| Auflösung         | 0,034°C              |
| Stromversorgung   | 6-18VDC              |
Campbell Scientific CR1000

- Master-Slave setup with standard datalogger
- Augmentation of existing boreholes
- Data continuity
- Test implementation
  - Aiguille du Midi (3x 15 m)
Lessons From Practice
A (not so) Good Idea? Squid Cables
A Source of Water Ingress
Better: Single Cable per Gland/Connector
Some Practical Advice

• Don’t squid connect cables
• Use correct cables (low-temp flexible, UV)
• Don’t compromise on connectors (assembly)
• Watch length/radius on installation
• Use tubing whenever possible
Take Home Messages

• Know your power source (under load)
• Know your analog to digital conversion
• Cross check everything: timing, system health
• Nothing is really linear
• Observe correct operating conditions
• Understand the datasheets
• Have good, consistent documentation
- 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