PermaSense: Investigating Permafrost with a WSN in the Swiss Alps*

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ABSTRACT

Currently, there is a lack of stand-alone geo-monitoring systems for harsh environments that are easy to configure, deploy and manage, while at the same time adhering to science grade quality requirements. In a joint computer and geoscience project we have built and deployed a wireless sensor network for measuring permafrost related parameters. Using these high-precision data, geo-scientists will be able to calibrate their heat flux models in order to better predict the stability of steep rock slopes in the alps. In this paper we describe our system from a computer science and system point of view and report on some lessons learned, especially in the domain of sensor design, power-awareness and reliable data flow.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design; C.2.3 [**Computer-Communication Networks**]: Network Operations; J.2 [**Physical Sciences and Engineering**]: Earth and Atmospheric Sciences

General Terms

Design, Measurement

1. INTRODUCTION

The PermaSense project has two goals. The first objective is to build and customize a set of wireless measurement units for use in remote areas with very harsh environmental monitoring conditions. Ultimately, the wireless sensor network (WSN) should be fully self-organizing, should operate unattended for years, and the technology should be easily reusable in other environmental monitoring contexts.

The second goal consists in the gathering of environmental data that helps to understand the processes that connect climate change and rock fall in permafrost areas. Warming and thawing permafrost in steep alpine bedrock can affect slope stability and imperil the operation of man-made infrastructure (e.g. train tracks, roads and tourist resorts). In order to develop models for hazard assessment and the support of infrastructure maintenance, geo-scientists need continuous and reliable measurements of physical parameters of permafrost rock. At present, there exists limited measurement data for selected locations only, but large, specific, borehole based measurement series have not been collected yet which is in part due to the lack of inexpensive and suitable measurement systems.

To this end, we have built and deployed one sensor field in the Swiss Alps. In August 2006, a setup with 10 sensor nodes was installed on Jungfraujoch at 3'500 m above sea level ([18], Figure 1). Each node measures in near real-time four temperature and four conductivity values which are indicative for rock moisture content and its phase state in the near surface layer.

Figure 1: PermaSense deployment in the Jungfrau region, Aug 2006

During 7 to 8 months out of a full year, the WSN infrastructure is unreachable due to extreme weather conditions: Air temperature can be as low as −30 °C with strong winds, making it impossible to climb to the measurement points. Although the system must operate unattended most of the time, geo-scientists want to manage and configure it from their desk as well as having an advantage of context sensitivity allowing to take temperature measurements more effectively. The WSN contains therefore a GSM/GPRS node which connects the WSN to the Internet. Because a free line of sight to the GPRS equipped node can not be guaranteed for all WSN nodes, and also due to the large distances between them (250-300m), a multi-hop routing scheme must be used. At the same time, the amount of wireless transmis-

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*The work presented in this paper was supported (in part) by the National Competence Center in Research on Mobile Information and Communication Systems (NCCR-MICS), a center supported by the Swiss National Science Foundation under grant number 5005-67322. We also acknowledge substantial support from the Swiss Federal Office for the Environment (FOEN).

EmNets '07 June 25-26, Cork, Ireland

sions must be minimized because the long intervals between service make power budget a critical issue.

Although WSN platforms are now easily available on the market since many years, considerable soft- and hardware changes had to be made in order to cope with the above mentioned requirements. Similarly, the required high quality of the measured data led to many custom made solutions because the WSN community has not yet addressed environmental monitoring requirements with sufficient depth. We back this observation by discussing three major challenges that we met during the development and deployment stage of PermaSense. Section 2 describes the system architecture, hardware and algorithms. In Sections 3, 4 and 5 we discuss three of the most common and complex challenges of science grade environmental measurement and show how we solved them. After relating to similar research, we conclude this paper with the future plans for the PermaSense project.

2. SYSTEM ARCHITECTURE OVERVIEW

Our measurement system is structured as an Internet-attached wireless sensor network (Fig. 2). Data is collected in battery-operated sensor nodes. One (or more) of these nodes has a GPRS extension which permits to exchange data with the database side over the Internet. The database runs on a Linux server, which also hosts a web interface for data inspection and WSN steering. We used the TinyNode-584 hardware from Shockfish [5] [8], which was specifically designed for low-power operation and long distance range radio communications. When placed at soil level, we assessed reliable connectivity (with appropriate encoding, see Section 5) of up to 300 meters. It can be extended with a GPRS board [9] that runs Java for controlling the access to the Internet.

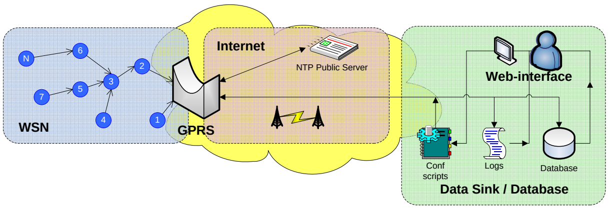

Figure 2: PermaSense system framework

Between sensors nodes, TinyOS messages of up to 42 bytes are exchanged using the the Semtech XE1205 RF chip [13]. The sensor node having a GPRS extension will forward data, also formatted as TinyOS messages, to the TC65 GPRS module from Siemens which contains the Java card. The Java card establishes TCP connections to the data sink server, where data is dumped into database and log files. Out of these files, the web interface generates reports and graphs for visualization of the measurements. Configuration scripts are used to send commands and runtime parameters to the WSN.

2.1 Hardware for Alpine Environments

Special care had to be applied for putting the sensor nodes into frozen rock faces. The node electronics is mounted in a waterproof aluminum housing. Additionally, a covering metal enclosure (stainless steel "shoe") was used to protect the housing, the connector cable and the antenna fixing part (Figure 1, left sub-figure). The external shoe is buffed to prevent heating by solar radiation. It provides a mechanical and electric shielding for the electronics (rock fall, lightning) and serves a ground plane for the radio and GSM antennas. All electronic parts are sprayed with coating gel in order to protect them from condensation.

A major concern was that our nodes do *not* have any switches or displays, as it is not feasible to fiddle around with sensor nodes when suspended on ropes. A first team drilled 1-meter holes, deployed the special sensor rods (see Section 3) and mounted the protective shoes to the rockface. In the lab, all nodes were pre-configured, enabled and sealed such that a second team could install them by simply slipping the node into the shoe and attaching the sensor cable.

2.2 Software for Permafrost Monitoring

PermaSense contains many different software pieces that we had to write from scratch in NesC, Java and Bash (CGI scripts).

The proper sensing software is written in NesC for TinyOS 1.x. Beside sensor specific drivers, the main code structure is the sleep/duty cycle which integrates a simple TDMA-like node synchronization protocol. Typically, measurements are taken half-hourly with a 0.003% duty cycle, which explains why we do not use existing schemes that rely on frequent flooding of time information (for instance, see [10]). Figure 3 shows the phases of the duty cycle.

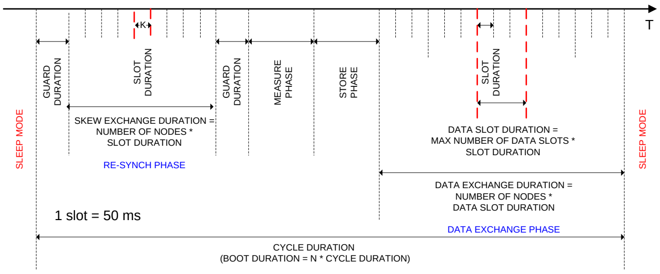

Figure 3: Sleep/wake cycle and the various activity phases

When waking up, all nodes exchange their local clock readings. They compute their relative skew and adjust ("balance") the time to wakeup again, in order to remain synced. Additionally, a nominal clock frequency correction table is used to compensate for the huge static deviations (max 70Hz eq 14ms per sec) of the on-board quartzes [2]. Local clocks are not adjusted, though. Instead, clock differences are recorded as events and used to reconstruct global time at the database side. In order to have measurements timestamped with universal time, connection with an external NTP server is periodically established by GPRS module and the pair of <local clock, UTC> information is transmitted to the database.

Measurements, as well as special events (clock skew, sensor replacement, etc) are numbered, recorded in flash memory and queued for transmission towards the GPRS node where they are cached. Some of the data message types are shown in Table 1. A simple spanning tree protocol establishes the routing paths. In Section 5 we provide more details on the transport and flow control protocols in place.

The Java- and CGI-scripts-based front-end software receives and stores all data packets, assigning valid time stamps to the measurements and visualizing them in a various ways. The collected data as well as the remote network are manageable online via Web-interface.

Table 1: Message Types

Msg Type	Contents
DA1/2/3	Data Block (type 1/2/3)
RBT	Reboot Event
UTC	Universal Time Clock
FRS	Flash Chip Reset
SKW	Skew Balance Message
NRD	New Sensor Rod
ST1/2/3	Common/Flash/MAC statistics

3. CHALLENGE 1: SENSOR DESIGN

The task we set ourselves was to produce a sensor system which would provide high-precision measurements and would be able to easily support new extensions. The main problem was the integration of all measuring technologies in one narrow (14mm in diameter) bore hole and the severe constraints on energy (see Section 4) still meeting the precision requirements.

The sensors measure the following parameters in the top meter of the lithosphere with high accuracy at four depths inside the borehole (for more details see [6]):

1. Temperature at depth between 10cm and max 1m from the rock surface with a calibrated accuracy/resolution of 1000ppm or $0.02\,^{\circ}$C at the melting point. The temperature range of the sensors is $-40\,^{\circ}$C to $+50\,^{\circ}$C.
2. Water content: volume content of liquid and frozen water in pore space and cracks. Conductivity is measured between brass rings. As an option, conductivity is also measured between pairs of electrodes.

All sensors are integrated into a carrier rod (a fiberglass tube) of low temperature conductance and high mechanical strength (Fig. 4). The mechanical setup has to guaranty a good thermal and electrical contact between the respective sensors and the rock. Interface electronics including references is integrated into the rod as well to make the logger/transmitter node independent from the sensor and to minimize the effect of temperature fluctuations. The sensors have an unique serial number identification chip that can be read by the node (see [3]). Cable length between sensor and node can be up to several ten meters but should be kept as short as possible to minimize EMV/lightning problems (Figure 1, right sub-figure). The sensor rod is recoverable and pluggable.

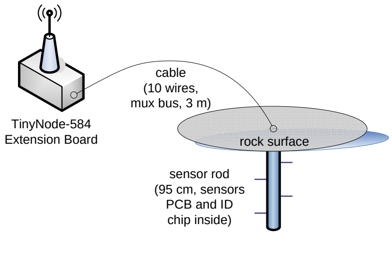

Figure 4: PermaSense node with a sensor rod attached

A set of protected I/O lines forms a multiplexing bus allowing to address up to 32 various sensors inside a rod. The measurements are based on the available 12-bit AD converter of the TinyNode's microcontroller (see [17]) and the external 2.5V voltage reference [16]. Sensor rod electronics is powered from the TinyNode allowing to regulate its supply voltage. In order to get rid of possible analog noise and reduce the total statistical error, each AD conversion is repeated 16 times and then is averaged. All radio transmissions are terminated during measuring cycle in order to avoid interference of HF signals upon measurements.

Before installation sensors were calibrated in a leak-proof ice-water bath. Calibration constants are used to compute coefficients of quasi-linear equations needed to convert raw AD values to absolute values of measured physical parameters. Because the reference resistors, drivers and switches are included in the sensor, calibration values do not depend on the connection to a given TinyNode.

Accurate measurements based on the pre-calibration provided by our system are the most valuable outcome for geoscience. Separating nodes from sensors by using pluggable and exchangeable sensor rods with an embedded ID chip makes the system more flexible and easy to deploy. Custom PCB design along with multiplexed bus architecture is an essential feature making our system extremely extensible for new sensor types in the future.

4. CHALLENGE 2: POWER-AWARE HARD- AND SOFTWARE

Data generated by the system must be available during the whole duration of the specified period (at least 1 year). The unreachability of the system for several months a year, low temperature conditions and the huge effort needed to replace power elements make a smart power management and the choice of power sources a significant challenge. Moreover, the powering solution turned out to be a critical point for the accuracy of the sensor data.

To power the TinyNode a battery of Li-SOCl2 type is used ([12]), because a photoelectric solution (i.e. a solar panel) is not reliable due to ice coating. We use lithium batteries as they perform better than alkaline at low temperatures. In order to stabilize voltage for the sensor rod electronics at low temperatures we introduced a second battery in parallel.

Two separated power sources are used on the GPRS node. To power the TinyNode part we use the same solution — one battery of Li-SOCI2 type ([12]). To power the GPRS part we use a set of batteries of Li-SO2 type ([11]) formed in an array (3 pairs in parallel of 2 units in series). This type of batteries provides maximum continuous current up to 2.5A. Such a high current level is required in GPRS-transmission mode where peak current can reach 2-3A!

Off-the-shelf TinyNodes required further hardware changes in order to reach the lowest possible power consumption (for more details see [15]). Additionally, slight changes to the TinyOS source code were needed to correctly execute automatic power management. After all changes made and by switching off all peripheral components as soon as they are not needed anymore, we managed to reduce the total power consumption of a TinyNode mounted on the Standard Extension Board from 400μA down to 12μA in a sleep mode. During transmissions (see Figure 3), TinyNodes consume 14mA. The GPRS board power consumption (TinyNode-584 wireless module + GPRS board + Siemens TC65 GSM/GPRS module) was cut from 5.8mA down to 22μA for standby current. With these numbers our system can operate in an unmanned mode for a 4-5 years without exchange of power elements.

The significantly reduced power consumption increases the operational stability of our system, as well as ensures a longer life cycle. This results in much less effort in system maintenance and servicing, and saves geo-scientists from the possible data loss.

5. CHALLENGE 3: RELIABLE DATA FLOW

Wireless communications bring a few dangers to the data integrity such as mixing up data, lost and corrupted packets. Our system must continuously stream data needed to reconstitute a picture of progressing physical processes. Since measurements are taken rarely (see Section 2), gaps are not permissible. For the same reason, the system has to do its best to detect and as far as possible to restore corrupted data packets.

The need to work for a long time without servicing requires a mechanism to remotely control the WSN. For example, rock state is observed with different periodicity: at day- and night-time less frequent measurements may be taken since physical processes are stable. In contrast, during day-night changes (heating/cooling) it might be needed to measure minutely. The same is true for seasonal changes.

5.1 Node-to-Node Link Reinforced by FEC Scheme

In order to make radio communications more reliable and reduce high packet losses at distances more than 200 meters a Forward Error Correction (FEC) scheme was integrated in the radio stack. It goes under the link layer, so that full packet integrity can be asserted. Our experiments showed that most errors are 1 and 2 bit errors, therefore, a DECTED (Double Error Correction, Triple Error Detection) scheme ([7]) is used. Using FEC and by adjusting radio channel parameters (decreased base frequency, maximum output power (15dBm), disabled CCA and enabled MAC-layer ACKs) made it possible to significantly reduce (up to 50%) the number of lost and damaged packets.

5.2 Data Flow

In order to be able to recover any lost packet, a multi-level caching mechanism is applied. All packets (data logs, periodically registered sync and system events) are stored at the source in the on-board flash memory chip ([1]) which is organized as a circular buffer, plus a system configuration page at a constant position (Fig. 5). All messages have four major fields uniquely identifying them in the system: <message type, node ID, message ID (sequence number), local node's event timestamp>

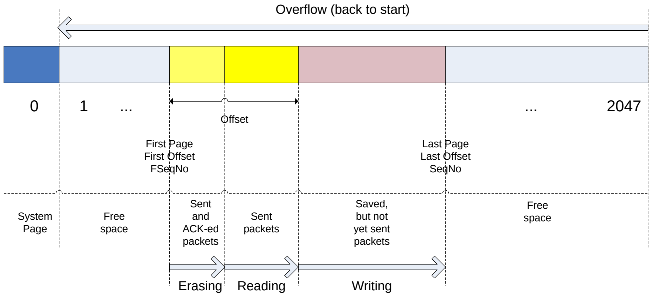

Figure 5: Usage of the on-board flash memory

While forwarding over the network, packets are cached in RAM on an intermediate nodes. Packets are transfered using directional transmissions based on link layer ACKs. In order to make it possible to request for retransmission if a packet has been lost, we use an end-to-end high-level acknowledgment mechanism (handshaking), where a packet can be erased at the source WSN node after receiving a notification about its successful reception at the DB side. The full data flow path is shown in Figure 6. The connection between the GPRS base station and the data sink server runs over TCP/IP protocol which is reliable by nature and does not need any additional measures.

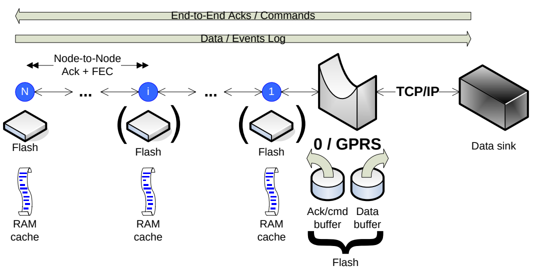

Figure 6: Data flow path

5.3 Multi-Hop Routing

As far as nodes are installed at large distances in order to cover broader area, a multi-hop routing scheme is used. The distinctive feature of our routing scheme is the integration of resource allocation and flow control. Network traffic is managed by using the concept of a "transmission corridor" where each node is assigned a number of packets which it is allowed to send. This improves network stability further and avoids that the network is flooded with data from some nodes which have been isolated for a long time (e.g. due to snow cover).

5.4 Runtime Parameters

The need for adjustable duty cycle is reached by using four so-called "scale factors":

1. transmission scale factor (T-scale)
2. storing scale factor of sync messages (S-scale)
3. measuring/storing scale factor of data packets (M-scale)
4. NTP synchronization scale factor (U-scale)

The scaling mechanism is based on the 16 seconds quantum which respects the overall TDMA sync scheme. That is, a scale factor is a multiplication coefficient that can be set for each aspect and node individually. This fine-grained reconfiguration is the main mechanism in our system to smoothly manage and control network traffic.

5.5 Commands

Per-node reconfiguration is performed at run time using commands sent by an end user to the WSN. The main task of commands is to maintain continuity of the data stream in the database. Commands can be classified into three major groups which are i) control commands, ii) status requests and iii) acknowledgment related commands. In order to give an impression of what our system is up to, a number of selected commands are listed in Table 2.

All mechanisms described above result in a system that provides highly reliable data delivery which is a major criteria for a high quality science data monitoring system. The achieved robustness is a prerequisite for running measurements for long time scales without repairing and physical reconfiguration.

Table 2: Commands

	Command	Operation
i	SSA	Set sampling on/off
	SLX	Set transmission on/off
	FRS	Flash chip reset
	SCO	Set clock offset
ii	GSL	Generate Status Log request
	MRS	MAC stat reset
	SRD	Sensor Rod ID request
iii	ACK	Acknowledgment
	PCP	Retransmission request

6. RELATED WORK

Probably the project that is closest to PermaSense is SensorScope [14] which has gone through 3 generations so far and in the last stage has been deployed on the Glacier de la Plaine Morte. Its main objective is to gather environmental data for modeling of energy fluxes at the earth-atmosphere boundary. Similarly to our project, SensorScope's network is based on the TinyNode platform, but the network size is much greater – the second generation used 110 nodes and 700+ sensors. Communication concept is also different: Aiming at a single-hop, multi-sink topology, it uses existing time synchronization and MAC-layer protocols. For power supply a solar panel is used as a secondary source.

Very similar to SensorScope is WaterSense [20] intended to support agriculture and water management in India with the use of wireless sensor networks. Most of ideas used in WaterSense are rather like those found in SensorScope. A noteworthy feature is the use of a 802.11 bridge to a local server and dial-up connection to a central server.

A very interesting project which gave us many ideas is the Volcano Monitoring System which is described in [19]. Data fidelity, timing accuracy and high-resolution signal collection were main stumbling blocks for the Volcano project too.

7. FUTURE WORK

Based on our first experience, a number of modifications to our system are upcoming. These modifications mainly concern communication and time synchronization stability, as well as further reduction of power consumption which requires both software and hardware improvements. The upgrade of the system with 15 nodes will be deployed in spring 2007 on the Jungfrau east ridge and Sphinx. Moreover, we plan to build a second generation of sensors and deploy two additional sites for summer 2007 that can also measure crack dilatation, moisture/ice content and possibly acoustic (micro-seismic) events. The second generation will be based on a fully customized extension board and a TinyNode wireless module, keeping all other form-factor features the same. Additionally, we plan to use the DSN solution [4] for more comprehensive debugging of all algorithmic aspects.

8. CONCLUSIONS

Off-the-shelf WSN solutions currently available in the market are not ready for real deployments for environmental monitoring. They need considerable modifications and improvements in order to meet the requirements of the natural sciences. Three challenges discussed in this paper are common problems encountered by many start-up projects for environmental sciences: extensible sensor attachment interfaces, extremely power-aware hard- and software, adaptive end-to-end data collection and WSN steering. As a research field, WSNs need to incorporate solutions to these challenges such that they become a standard level of service for high quality scientific monitoring tasks.

Acknowledgment

We would like to thank the members of the TIK group at the ETHZ for all of their software testing efforts, and especially Jan Beutel for making the second generation of PermaSense feasible. We would like to specifically thank Roger Meier and Maxime Müller from Shockfish SA for all of their software and hardware testing efforts, comprehensive support and sensible advice.

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