PermaDAQ: A Scientific Instrument for Precision Sensing and Data Recovery in Environmental Extremes

Jan Beutel, Stephan Gruber[†], Andreas Hasler[†], Roman Lim, Andreas Meier, Christian Plessl[*], Igor Talzi[‡], Lothar Thiele, Christian Tschudin[‡], Matthias Woehrle, Mustafa Yuecel
Computer Engineering and Networks Lab, ETH Zurich, Zurich, Switzerland
[†]Physical Geography Division, Department of Geography, University of Zurich, Switzerland
[*]Paderborn Center for Parallel Computing, University of Paderborn, Germany
[‡]Computer Science Department, University of Basel, Switzerland
beutel@tik.ee.ethz.ch

ABSTRACT

The PermaSense project has set the ambitious goal of gathering real-time environmental data for high-mountain permafrost in unattended operation over multiple years. This paper discusses the specialized sensing and data recovery architecture tailored to meet the precision, reliability and durability requirements of scientists utilizing the data for model validation. We present a custom sensor interface board including specialized sensors and redundancy features for end-to-end data validation. Aspects of high-quality data acquisition, design for reliability by strict separation of operating phases and analysis of energy efficiency are discussed. The system integration using the Dozer protocol scheme achieves a best-in-class average power consumption of 148µA considerably exceeding the lifetime requirement.

Categories and Subject Descriptors

C.2.2 [**Network Architecture and Design**]: Distributed Networks; C.3 [**Special-Purpose and Application-Based Systems**]: Embedded Systems

General Terms

Design, Experimentation, Measurement, Reliability

Keywords

Architecture, Data Acquisition, Environmental Monitoring, Wireless Sensor Networks, Low-Power

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1. INTRODUCTION

The PermaSense project strives for collecting geophysical data in the high-altitude environment of the Swiss Alps with a wireless sensor network (WSN) running unattended for three years. The architecture aims to provide a long-term, high-quality wireless sensing and data recovery solution in extremely harsh environments with near complete recovery and near real-time delivery of the data. The observation periods targeted in conjunction with higher quality data than was previously feasible is expected to provide the relevant information for research and decision making, pioneering next generation early warning systems.

When using a sensor network as a scientific instrument for data gathering, the quality of data is of utmost importance. In PermaSense this is exacerbated by difficult access to the area under investigation and the labor intensive installation and maintenance of any sensing solution, wired or wireless. Current best practices require installation effort on the order of a man-day per sensor to achieve an accurate and well documented installation. Traditional WSN metaphors such as system-on-chip integration for cost reduction, smart clouds of redundant sensors or sensor placement scattered from a plane diminish in the light of such real world problems.

Based on a careful requirement analysis and close collaboration with the scientific partners, we have developed a specialized sensor interface board that integrates a TinyNode running Dozer [4] and is capable of acquiring data from a number of different sensors. The PermaDAQ system architecture is especially targeted at high precision measurements of slowly fluctuating quantities, reliable operation and an extremely tight energy budget. Powered from a single Li-$SOCL_2$ battery, an average power consumption of 148µA is achieved based on a 2min measurement interval. This exceeds the lifetime requirement by a factor 2x and is competitive when compared with other recent WSN developments, e.g. railway bridges ∼166µA at 1sample/day [5]. Data acquisition accuracy is achieved by a strict separation of functions, minimizing possible interference from both electric effects and concurrently operating software components. Data quality is achieved using precision sampling and continuous, uninterrupted operation is warranted by storing data duplicates on non-volatile memory. This additional mechanism allows for buffering of data for delayed transmission on network outages and also for end-to-end data validation accross the whole chain of system components.

The contributions made in this paper are (i) an autonomous and robust sensor node architecture allowing high-precision data acquisition from a multitude of sensors, (ii) an extremely energy efficient integration with the Dozer communication protocol and (iii) and analysis of the performance w.r.t to sensing precision, effects of the environment and energy consumption.

2. SENSING IN ENVIRONMENTAL EXTREMES

2.1 Project Background – Scientific Relevance

PermaSense is a joint geo-science and engineering project with the aim to pioneer engineering as well as scientific use of next-generation sensing systems in harsh environmental conditions. The measurement strategy and system are designed for and immediately motivated by high-mountain permafrost research, but with the underlying aim to serve as prototype for future systems of wider applicability in research and hazard surveillance. In this context, the difficult environmental conditions at high elevation serve as a difficult benchmark for system robustness. In cold and steep mountain terrain, permafrost thaw can reduce the stability of slopes (e.g., frequency/magnitude relationships for large rock fall) in response to climate change [8]. [9] presents a more comprehensive introduction. Measurements in support of process research or model validation, however, are difficult to realize. Here, WSNs can help to provide higher quality data more effectively, e.g. by helping to optimize the resources for fieldwork, because the battery level and functioning of each sensor is monitored continuously and because small devices are easier to deploy. Additionally, the use of low-power and small WSN devices opens new and very valuable possibilities: Because the length of wiring installed is minimal, the susceptibility to lightning damage – a major limitation to the lifetime of such installations – is drastically reduced. Signals measured at different locations can be correlated precisely because time is known with much greater accuracy than with independent logging systems. Finally, continuous transmission of data enables information retrieval from "sacrificial sensors" that may be lost during a campaign measuring a destructive event.

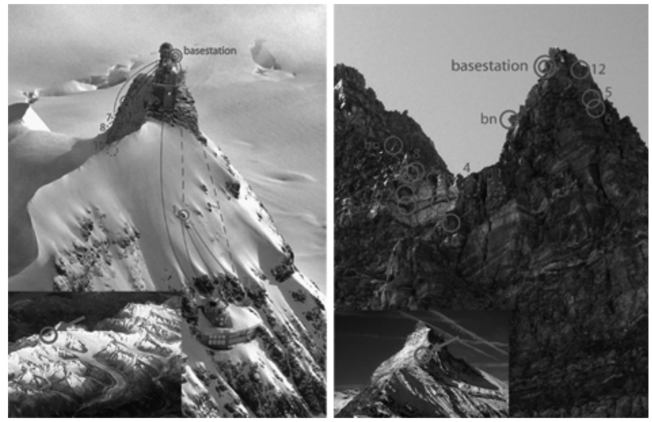

Figure 1: Deployment sites Jungfraujoch (left) and Matterhorn (right) in high-alpine ambiance

The project started with an early prototype deployment (Jungfraujoch, 3500 m a.s.l.) in 2006/07 [17]. Based on the experience gained with this prototype, a thorough analysis, identification of shortcomings and misconceptions of the initial system design, a second-generation system architecture was developed. The new system was installed on a second field site (Matterhorn, 3450 m a.s.l.) in 2007/08 and is currently operationally and delivering sensor data in real-time[1].

2.2 PermaSense General Requirements

The refined requirements specification for the PermaSense system architecture is the following:

- About 25 nodes per site; node spacing ∼10-150m
- Minimum 3 years unattended lifetime
- Survival in harsh high-alpine environment (rock fall, avalanches, snow, ice, rime, lightning, storm)
- Ambient operating range -40 to +65°C, with max. 5°Cper minute change rate
- Capable of sensing basic environmental parameters (temperature, electric conductivity, crack motion, ice stress, water pressure)
- ADC resolution >12 bits with 50ppm/°C reference
- 1 to 60min adjustable sampling interval
- 99% data yield with max. 10 consec. samples lost
- Time synchronization to 1sec referenced to UTC
- 6 months autonomous storage capability
- No physical repairs or exchange of components
- No infrastructure support necessary

[1] See the data online at http://www.permasense.ch

2.3 PermaDAQ System Design Challenges

The two most prominent shortcomings of the first system developed [17] were limitations w.r.t the precision of the data acquisition and the ultra-low power design goal based on the TinyNode/TinyOS system design. These, and the high reliability requirement, both in terms of uninterrupted lifetime but also data integrity form the design challenges for the second generation architecture.

Precision Sensing – Emphasis is on the quality and accuracy of the sensing when used as a scientific instrument. Sensors, data acquisition, storage, data recovery and exact timing reconstruction have to be designed to increase accuracy and stability, even under severely adverse conditions. The altitude and fluctuations in environmental conditions, particularly in temperature, have a dramatic impact on the performance and reliability of the electrical components, e.g. oscillators or analog digital converters. Their characteristics deviate significantly at the limits of operating ranges. Radio communication interferes with precision measurements causing imprecise measurements. Since the effective quantitative changes observed are typically rather small, meticulous care is required to reduce measurement noise and to compensate for or identify dependencies, especially on temperature, in the system architecture.

Reliability in Harsh Environments – Long-term environmental monitoring relies on reliable and correct operation of all components that are linking the sensor to the data utilization or interpretation. Redundancy features that are reducing the risk of a single point of failure need to be incorporated in the system architecture as well as means for data replication and validation. Environmental conditions in high-alpine regions are very inhospitable. Sensors deployed there are subject to rock fall, avalanches humidity, deep snowcover, thunderstorm and lightening strokes in the immediate vicinity. Temperatures vary from -40℃ in wintertime to +60℃ if exposed to direct sunlight. Ice coating, rime and snow covering of the sensor nodes can interrupt wireless communication for longer periods of time. Some of the most interesting permafrost phenomena can be observed in exposed, steep rock walls in high-altitude mountains. Access to deployment sites is difficult; heavy equipment can only be brought in by airlifting with helicopters. This rough terrain demands that the deployment process for the sensor nodes is simple and does not require on-site programming, configuration or calibration. A robust mechanical design of nodes and sensors is important in order to protect from damage during deployment and operation.

Durability and Energy Constraints – A prime objective of PermaSense is to achieve multi-year continuous operation. This exceptionally long runtime is motivated by two factors: (i) Many geophysical phenomena in permafrost regions change at a rather slow rate but are superimposed with annual, daily and higher-frequency cycles, hence requiring long term measurements. (ii) The remote, high-alpine deployment area makes access to the sensor nodes difficult. Therefore a specialized power supply for the sensor nodes must be considered. The harshness of the environment, potentially prolonged coverage under a thick layer of snow, the size of the required panel, its resulting susceptibility to damage and especially the uncertain effectivity if nodes are deployed on a northerly exposition without the benefit of direct sunlight render a solar power supply impractical. A Li-$SOCl_2$ battery is optimized for slow discharge at low temperatures down to -40℃. The battery selected provides a capacity of approximately 8.2Ah under the expected operating conditions, resulting in an allowable current consumption of ~300µA to reach the anticipated system lifetime. This current is about 2 orders of magnitude lower than a node's consumption when all components are active. Hence, it is important to exploit sophisticated and rigorous power-saving techniques to achieve this ultra-low duty cycle.

In order to build a reliable environmental monitoring system that is able to cope with these challenges, careful orchestration and optimization of all system components, i.e., sensors, sensor nodes, wireless communication, base station, database backend at the soft- and hardware level is needed. In Section 4, methods are presented for highly accurate data acquisition, despite of the strong fluctuations in environmental conditions. In Section 5, we discuss the measures taken to build a highly reliable system in order to prevent the need for field maintenance. Section 6 shows how we customize hard- and software to meet the tight energy budget.

3. THE PERMASENSE ARCHITECTURE

The PermaSense architecture features the tiered architecture paradigm established since Great Duck Island [16]. Figure 2 displays an overview of the tiers: sensors, wireless sensor network, base station and backend and their respective individual components. Each of these tiers is able to operate self-supported in case one of the other tiers experiences failures or maintenance outages effectively minimizing data loss.

The sensor network consists of Shockfish TinyNodes [6] running the ultra low-power Dozer protocol for multihop data gathering [4]. The TinyNodes are mounted on a sensor interface board (SIB) that contains all necessary circuitry for data acquisition, power management and system supervision. Additionally the nodes are equipped with external data storage using a 1GB flash memory SD card. The sensor nodes are powered from

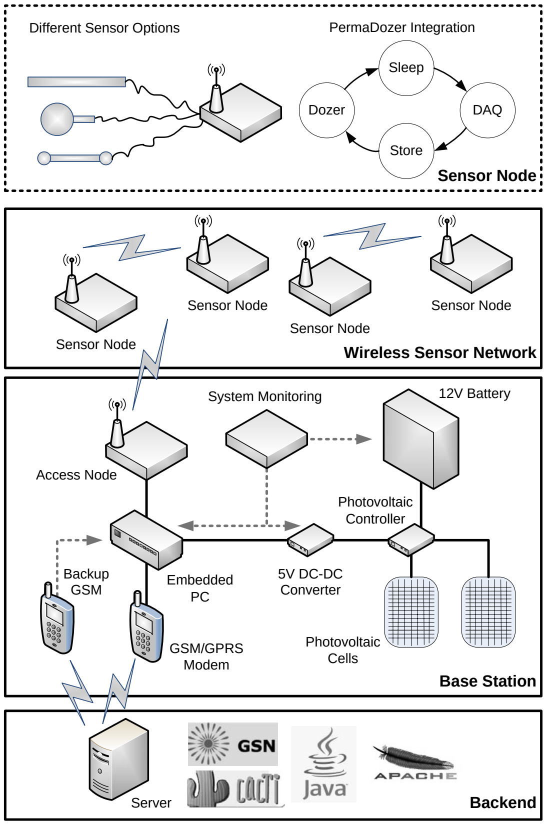

Figure 2: PermaSense System Architecture

a single non-rechargeable battery cell. The base station consists of an embedded PC platform connecting to a TinyNode used as access node to the sensor network and a data downlink (GPRS/EDGE) to the data backend.

Since it can be mounted in a shielded position, the base station is powered from a regenerative power supply using solar cells. The data backend consists of a server running GSN [1] as well as a number of control, supervision and management interfaces.

Constituting an obvious single point of failure and even worse, a component that is operated by an anonymous third party, the GSM/GPRS connection from the base station to the internet is an important reliability consideration for the whole system architecture. While multiple base stations and access nodes to the sensor network are an obvious way to circumvent any problems with reliable data transfers, they also add complexity and require to be installed and maintained. A backup using a second GSM/GPRS modem attached to the console of the base station is a simple yet effective method to remotely recover or reset a faulty base station or primary data link. This has been very successful and on several instances we have recovered and modified the base station software running at the deployment site.

In order to reduce the risk introduced by developing all necessary components from scratch, but also to lighten the workload and pressure on system development we made use of established solutions or adaptations of known and proven technologies wherever possible (cf. Table 1). In cases where no suitable solutions existed, a custom design specifically tailored to the given requirements of PermaSense was created.

Established Commodity Components
Base station embedded PC
Photovoltaic energy source
Online system monitoring and servicing
Adaptated/Partially Developed
Dozer multihop protocol
1 GB local storage extension
GSN data backend integration
Custom Developments Built from Scratch
Specialized sensors
Sensor interface board (SIB)
Data acquisition and storage integration
Mechanical component setup
Base station secondary communication

Table 1: Classification of technologies used according to the necessary development effort.

3.1 Dozer Operating Principles

To achieve reliable, high fidelity measurements the interference induced from other system components, e.g., radio communication or excessive processing demands needs to be observed with equal care as minimizing power and resource utilization. The Dozer protocol scheme [4] is optimally suited for this purpose as it leaves large windows for scheduling user tasks in between its periodic interaction with the radio for communication at a very low duty cycle of ~0.1% and consuming only 0.082mW. A likely scenario is that a sensor node can be disconnected from radio connectivity for prolonged periods of time, e.g., when snowed in in winter. In this aspect, the scheme is very adequate as it actively reduces its duty cycle when connectivity is lost.

Dozer uses a TDMA-based link scheduling along a tree based routing structure. The tree structure is controlled by beacon messages originating at one or more sink nodes serving synchronization and data flow control purposes. Data is transported from children to parent on dedicated upload slots that follow a link based schedule. All data transfers are acknowledged. Rather than investing in complex collision avoidance schemes Dozer uses a precisely timed retransmission reducing excessive idle listening to a minimum. The adaptation of Dozer with the integration of custom data acquisition and storage in the dedicated processing window is called PermaDozer and is implemented in TinyOS (cf. Figure 2).

3.2 Custom Developments for PermaDAQ

3.2.1 Modular Architecture for Specialized Sensors

The PermaSense system architecture supports a number of sensors, predominantly oriented towards the acquisition of long-term, slowly fluctuating quantities. Currently the sensors supported are: (i) a sensor rod for profiling of temperature and electrical conductivity in solid rock, (ii) thermistor chains for profiling of temperatures inside cracks, (iii) crack meters consisting of a linear potentiometer for measuring movements, (iv) digital water pressure sensors to assess water flow in cracks, (v) analog earth pressure cells for assessing ice stress inside larger cracks and (vi) self potential sensors using analog differential conductivity measurements with electrodes mounted on the rock surface. To be able to consistently relate data acquired, calibration values and in-field sensor placement, each sensor contains an individual sensor identification chip that contains a unique serial ID. With the exception of the sensor rod, all these sensors are commercial and commonly used in geo-sciences.

3.2.2 Sensor Interface Board

A key deficiency of the first generation PermaSense prototype hardware [17] was the accuracy of the acquired sensor data, primarily due to the use of the internal AD converter and reference voltage circuit on the TinyNode's TI MSP430 microcontroller. Based on the experience with the first field deployment a dedicated sensor interface board was designed featuring precision AD channels, controllable voltage references, signal filtering and conditioning circuitry, ESD protection as well as in- and external power supplies and power management functions (cf. Figure 3 and Section 4.1 for details). With respect to other designs [18, 7, 2], this solution allows to switch dedicated power groups for all subsystems when not in use limiting power losses to leakage only.

3.2.3 Multi-Sensor Data Acquisition

Rather than designing a custom sensor node per sensor type, the PermaSense data acquisition architecture (PermaDAQ) is designed around a modular interface able to accommodate different combinations of sensors (cf. Figure 2). The key benefit of a modular solution is the ease and flexibility in the application at the expense of a more complex hardware and data acquisition routine. Furthermore, a single, multifunctional hard- and software is easier to maintain than a whole family of devices with varying function. A central part of this architecture is the DAQ routine that initializes the necessary components, calibrates the AD converter using the internal reference voltages, reads health information and then samples analog and digital sensor channels. Subsequently it returns into low-power sleep mode.

3.2.4 Storage Integration

All sampled data is stored locally on the sensor node. A custom buffering routine in the PermaDozer application takes care of archiving all generated data on a flash memory SD card present on every node. Since the SD card access is energy consuming, the data is first gathered in RAM before multiple data samples are written collectively to the SD card. The locally archiving of data allows for a delayed transmission of the data due to network outages. When snowed in, data is backlogged and subsequently flushed to the network upon restoration of reliable connectivity to the base station. The second and equally important purpose of the data storage is post-deployment validation. The data archived locally is used for checking sensor data integrity.

3.2.5 Mechanical Component Setup

The extreme exposure to the environment requires a robust, weatherproof enclosure, sufficient for protection from the elements and to withstand rock fall, avalanches and electrostatic discharge in the vicinity, i.e. lightning. Especially due to the latter, an absolute minimum of cabling is a stringent requirement. Furthermore, it is desirable that the whole mechanical setup is operable and maintainable in cold and wet weather using gloves, possibly even one-handed while suspended from a rope. Each sensor node is housed in a Rose+Bopla die-cast aluminum enclosure, using Souriau UTS series connectors and an outdoor antenna, all with a protection rating of IP68 which allows to sustain submergion in water. A stainless steel protective shoe adds additional protection, especially from rock falling from above as shown in Figure 4. The hanging mounting position minimizes the ingress of water through the antenna and connector as drops of water are not forming on the rubber seals instantly slipping down the cable(cf. Figure 5). Additionally a large 10g pack of silica gel is added inside every enclosure to absorb excess moisture. Silicon lubing of the antennas prior to mounting in the field reduces the risk of rime building up in bad/wet weather conditions.

3.2.6 Sensors for Subsurface Measurements

Many key permafrost processes can only be observed inside the rock walls. Therefore it was necessary to design custom sensors that are able to make observations below the surface. The main sensor employed by the PermaSense project is a long sensor rod that allows to measure profiles of temperature and electrical resistivity to discriminate the changing composition, i.e., the relative amounts of rock, ice, water and air, inside vertical rock walls. Each rod contains 4 thermistors and 4 electrode pairs equidistantly spaced that are connected to a multiplexer inside the sensor rod. Each sensor rod is inserted into a 1m deep hole drilled into the rock and at-

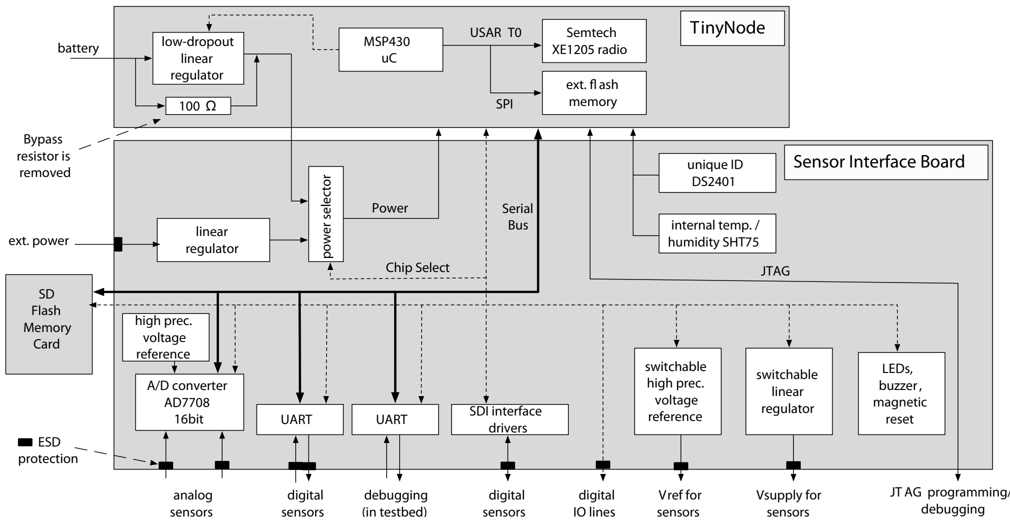

Figure 3: The SIB data acquisition architecture connects to a TinyNode over a single serial bus and uses GPIO pins to select dedicated power groups and address functional components.

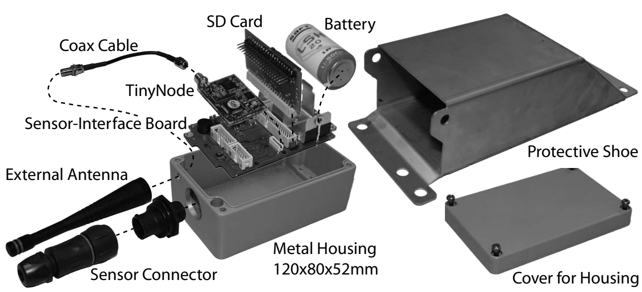

Figure 4: The sensor node is housed in an enclosure and mounted using a protective shoe.

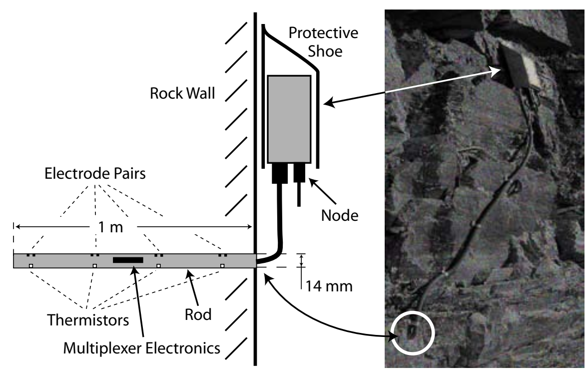

Figure 5: Sensor rod cross section diagram and a situation view from the mountain.

tached to a sensor node mounted nearby (cf. Figure 5). Calibration is done using a temperature controlled bath.

4. HIGH-QUALITY DATA ACQUISITION

4.1 Power Efficient Serial DAQ Architecture

The multitude of different sensors to be used in conjunction with the TinyNode and their precision requirements necessitate custom data acquisition hardware. The sensor interface board (SIB) is designed to allow flexible use of different sensors, both analog and digital; its supply can either be an internal battery or external 12V supply power source. Power consumption is minimized while components are not in use, which in the case of PermaSense is the predominant part of the time.

For this purpose all components are wired to a single serial bus using individual chip-select lines for selectively enabling these components (cf. Figure 3). The required 2.8V operating voltage is generated using the linear regulator on the TinyNode and distributed to the consumers on the SIB. Similarly to the multiplexing of the data bus, the power distribution to individual groups of consumers can be controlled in software.

The analog channels are sampled using an 8-channel Σ-Δ analog digital converter with 16-bit resolution (Analog Devices AD7708) and an external, temperature compensated precision voltage reference. An upgrade to a 24-bit ADC is possible if required. A number of features to aid testing, maintenance and deployment are integrated in the SIB: A unique serial ID allows to identify the individual hardware entity used, an additional UART allows synchronous debugging in a testbed setting, JTAG supports interactive debugging, LEDs can be enabled by individual jumpers to assure they are not accidentally powered on in a field deployment, a buzzer and magnetic reset (reed contact) allow to reset and check the booting sequence in the field and a temperature and humidity sensor is used to assess node health.

4.2 Increasing the Data Acquisition Accuracy

An initial implementation of the DAQ routines was designed in distinct phases of initialization, calibration, analog common ground and differential modes and digital measurements to ease future customization when optimizing for a single sensor type only, e.g., when only analog multiplexed is required. Each sensor measurement routine is furthermore preceded by a measurement of local node health parameters internal voltage, temperature and humidity inside the enclosure.

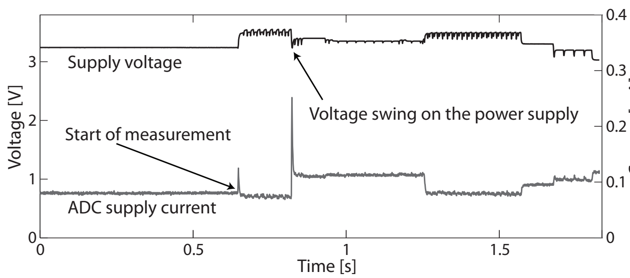

Figure 6: Detail measurement of the voltage supply swing in relation to the current consumed by the ADC causing imprecise measurements.

This DAQ routine functionally worked but showed considerable noise, especially on sensor types, such as the crack meter, that do not contain any higher frequency noise components (cf. the left on Figure 8). A more detailed analysis revealed some deficiencies in the actual drivers and routines, but more severely a direct connection to the stability and quality of the power supply. A detailed measurement was performed (cf. Figure 6) and the source of the considerable voltage swing on the supply voltage of the AD converter and reference voltage circuit on the SIB could be identified. Due to the bypass resistor present on the linear regulator on the TinyNode (100Ω as shown in Figure 3) the voltage generated is not fix but depends on the input voltage, i.e. the battery level and the actual current drawn. The TinyNode uses this feature to be able to shut down the regulator when entering sleep modes saving the quiescent current of 17µA versus 1µA in standby. The magnitude of this effect is especially prominent when the load is low and the battery level is high, i.e., when the regulator is not actually working, but the main current is drawn through the 100Ω bypass resistor. Only when the current exceeds the amount the bypass resistor is designed to handle, the regulator kicks in and actually supplies a regulated system voltage. Spontaneous peaks on the current being drawn, e.g., when turning on the radio transmitter add to the instability of this voltage, driving the critical data acquisition.

In order to resolve this issue, the bypass resistor was removed and the linear regulator forced on by an extra pull-up resistor. While at a first glance not deemed extremely severe, an increase in the sleep current consumption by 16µA is a considerable price to pay for the required data accuracy.

4.3 Strict Separation of Operating Phases

The reduction of all possible interference is of concern in the overall system integration of the PermaDozer application. If not accounted for properly a number of issues can lead to degraded performance: (i) Any consumer has influence on power quality and supply stability. (ii) Any switching of circuits causes noise on other circuits. This is especially prominent with RF interference from the radio on analog measurements, e.g. when coupled over a common ground plane. (iii) Exact timing is critical for many low-level software routines controlling critical hardware in real-time. Accurate and timely servicing of all interfaces in the order specified at design time and actively reducing any unnecessary interruption at run-time are the key requirements to achieve precision and reliability. Figure 6 shows an example of the ADC operation impacting voltage stability. If not separated clearly by the design, different components are bound to interfere which each other, degrading performance or even breaking the functionality.

The system model behind Dozer lends itself to an integration with a strict separation of the coarse grained operating phases responsible for different subsystems that would otherwise not be enforced in the event driven TinyOS operating model. Dozer supports a processing window in between its periodic interactions with the radio. All processing designed to be performed inside this window must be guaranteed to finish before the next communication phase commences. Therefore the DAQ routine runs (nearly) uninterrupted inside this window.

The separation and interleaving of the operating phases DAQ and Dozer is shown in Figure 7 for a network of three nodes (and one access node not displayed here). The DAQ routine is triggered every two minutes and is not synchronized across the network. The current peaks resembling Dozer beacons and data transfers depict the synchronization of the Dozer protocol scheme. With the improvement in power quality and strict separation of functions the data acquisition precision was improved by ∼24x (cf. Figure 8). This accuracy now leads to first results in the geo-science domain [10].

4.4 Exemplary Sensor Rod Data from the Field

An intermediate deployment using a logging only version of the software was used to gather first sensor data in the field and prove the SIB hardware design. This step was necessary both from a geophysical standpoint preliminary data analysis as well as from an engineering standpoint to see the performance of the system design

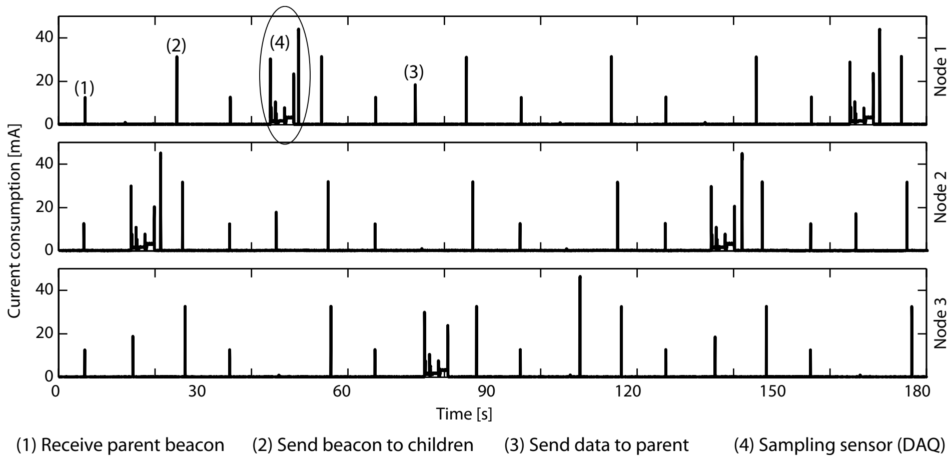

Figure 7: Power traces measured show periodic but asynchronous invocation of the DAQ routine (4) with subsequent data transfers (3) every 2min. Dozer beacon transfers (1) and (2), responsible for network synchronization are executed every 30sec.

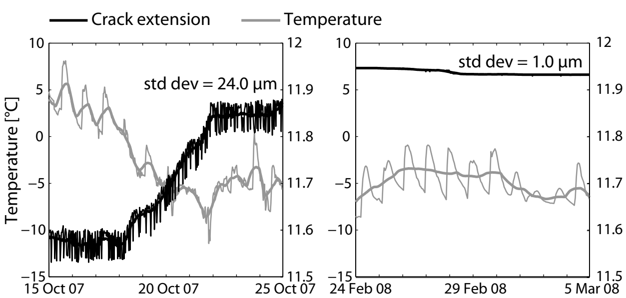

Figure 8: Improved accuracy and signal stability as a result of software refinement and stabilized power supplies. The difference in the two data sets shown is attributed to the measures described in Section 4.

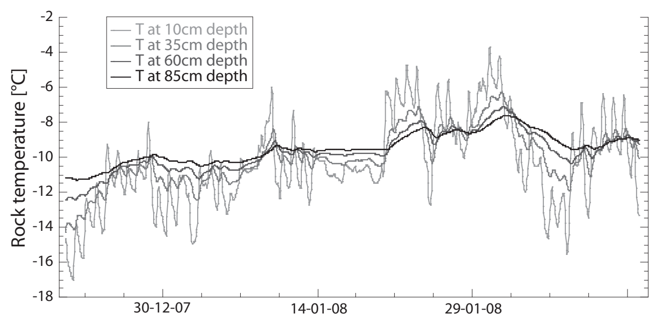

Figure 9: Example field data: As daily temperature cycles progress into the rock the signal is attenuated and phase shifted.

in a real operating case. Figure 9 shows example data generated using a sensor rod and SIB/TinyNode during the winter of 2006/2007 on Matterhorn. The strong peaks seen near the surface are attenuated and shifted as they protrude through the rock which is one of the phenomena that PermaSense is trying to observe in detail. This exemplary data is presented here as a proof of the validity and applicability of the system designed.

5. RELIABILITY – A LOOK UNDER THE HOOD

5.1 Energy Supply for Subzero Temperatures

Standard batteries, especially widely used NiMH and Li-Ion rechargeable cells have very bad characteristics in low temperatures. Their ability to deliver current close to the rated cell voltage diminishes quickly with the temperature dropping as well as the total capacity contained over a longer period of time. In contrast, specialized cell chemistries such as Li-$SOCl_2$ batteries exhibit good performance across a much wider temperature range at the cost of reduced peak discharge capability. Based on the expected peak current consumption of the SIB/TinyNode combination, a maximum form factor of a D-cell and the extremely high lifetime requirement under the given temperature constraint, a suitable Li-$SOCl_2$ cell (Saft LSH-20) was selected.

Nominal battery capacity [mAh]	13000
Nominal voltage [V]	3.6
Self discharge rate per year [%]	3%
Capacity at -40°C, 20mA discharge [mAh]	8200
Capacity at -40°C, 20mA, 3 years [mAh]	7462
Mean current available [mA]	**0.284**

Table 2: Power budget based on Saft LSH-20

The key characteristics can be seen in Table 2. Based on a self discharge rate of 3% per year and a nominal worst case capacity of 7462mAh the mean current available for the whole application was estimated to be 0.284mA. Of course there are a number of unknowns: (i) the peak discharge current (Table 4) is considerably higher than 20mA but again the average is much lower; (ii) temperature is expected to not always remain at -40℃; (iii) different sensors require different amounts of energy that can only be accounted for in average here and (iv) the actual discharge characteristics over such a long period of time are not available. This energy supply was selected from several competitors and deemed suitable for the formulated design goal of an average current consumption of ∼300 µA. As a safeguard against further adverse effects, e.g., peak currents, an optional super capacitor is integrated. So far the energy resources have been sufficient without this additional super capacitor.

5.2 Increasing the Storage Capabilities

The reliability constraint for PermaSense is a data yield of 99% with max. 10 consecutive samples being lost. While this primarily translates into an uptime requirement of the nodes and the network, it also requires correct dimensioning of the network and most importantly local storage when the communication system experiences failures. In general, such communication failures are attributed to poor connectivity, interference or system component failures. In the special case of high-alpine environmental monitoring the seasonal snow cover and the weather induced build-up of rime, e.g., on nodes and antennas, can mean that parts of the network are inaccessible for longer periods of time. During this time data sampling naturally must continue with local buffering and data delivery happening delayed when connectivity is restored. The specification lists 6 months of autonomous storage as a requirement.

Table 3 shows an approximate calculation of the data amounts generated by the data acquisition routine for a relaxed 30min DAQ interval, and also for 2, respectively 1min worst case calculations. Given that a single node only generates about 240MB and a network of 20 nodes only generates about 4.8GB of sensor data over a period of three years it seems feasible to equip both sensor nodes and the base station with sufficient storage resources using conventional flash memory technology. The cost on the bill of material is negligible and energy requirements can be kept low if bulk access methods are used and integration is performed with some care [15].

Using the worst case calculation with a 1min interval, single nodes are equipped with a 1GB storage resource leaving enough room for auxiliary timestamping and data structures. Since enough storage space for copies of all data acquired at every node is available, we store duplicates of all data, to be used for validation of the sensor data across the whole system. Remember that accurate and valid data is of primary importance when using a sensor network as a scientific instrument.

DAQ Interval	**1min**	**2min**	**30min**
Byte/day/node	233280	116640	7776
TinyOS packets[a]/min	7.04	3.52	0.234
Mbyte/year/node	80.0	40.1	2.64
Mbyte/3years/20nodes	4805	2403	160

[a] 23 byte per TOS packet

Table 3: Estimation of the DAQ data volume

The sensor nodes use a stripped down FAT file system that allows for reading out the buffered data on every PC. The base station writes an additional copy to its flash disk, including an NTP synchronized time stamp, which allows backup and direct validation with the data contained in the final database.

5.3 Dimensioning the Networking Component

Dozer is based on a quasi-periodic, extremely low duty cycle that can be parameterized. Data gathering is initiated and controlled by beacon packets that contain synchronization as well as routing and flow control information. In agreement with the original Dozer publication [4] and further counseling with its authors a ratio of a maximum of 1:4 between the packet generation rate and the beacon rate has been used in the parameterization of the PermaDozer application. With the calculated load on the network, the Dozer protocol is parameterized to sample and generate data packets every 2min and Dozer beacons every 30sec. This beacon interval has been optimized and carefully tested by its original authors to account for temperature drift that would eventually lead to de-synchronization and loss of connectivity. Each beacon period is capable of transmitting 20 data packets. In the case of flushing data backlogged on a node, a maximum of 10 packets is submitted to the network queue per beacon period as not to excessively overload the network. This has been found to be robust and offer sufficient performance for this application. The discussion in this paper is based on this 2min and 30sec case. Effects of varying network traffic, topology etc. have been neglected.

5.4 Internal Node Health Indicators

The protection from the elements and sufficient energy are key to a durable and lasting outdoor sensor network deployment [16]. In order to continuously assess node health and to be able to schedule repair or replacement of faulty node hardware well in advance every enclosure contains an individual node health indicator that measures ambient temperature, humidity and the battery voltage. Figure 10 shows such health data over a period of one month for a node mounted on a vertical rock wall, facing south, exposed to considerable temperature variability on clear weather conditions. Especially notable is the stress induced by the large daily temperature variation. The system voltage is extremely stable and the low humidity values around 10% suggest that the enclosure and connector are in good condition. This indicator is invaluable should any moisture protrude inside the enclosure causing permanent damage.

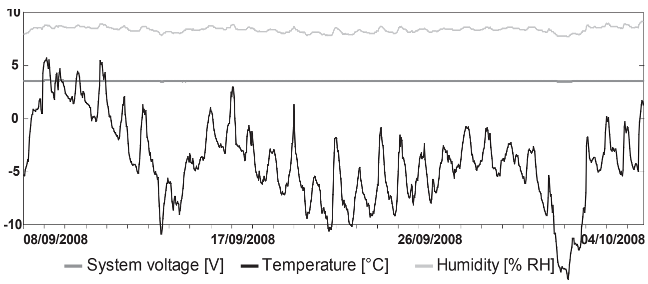

Figure 10: The system voltage shows exceptional stability over strong variation in temperature.

6. ENERGY EFFICIENT DESIGN

The PermaDAQ data acquisition architecture is a complex system composed of a number of individual consumers (e.g., radio, microcontroller, memory, data acquisition, sensors, debugging) each with their own characteristics and operating modes. Due to the complexity and interaction of system components, it is not possible to calculate the power consumption of the complete system in detail in advance, but only simple estimations based on individual values derived from datasheets. However in order to be able to assess the lifetime of a sensor node a detailed analysis of the power consumption and the contribution of the different subsystems is required. Measurements characterizing the operating modes sleep, data acquisition (DAQ) and communication (Dozer), are shown in Table 4. Additionally, average power consumption over a 10min period is shown for partial implementations (DAQ only, Dozer only) as well as the complete PermaDozer application. Measurements have been performed using a fixed 3.6V power supply and a 12 node tabletop network. A detailed power trace of several nodes in operation is shown in Figure 7.

The important fact to note is that with a total power consumption of 148µA the required goal of ∼300µA has been achieved if not surpassed. An analysis of the individual components contributing to this power consumption is calculated as follows: Both partial implementation values contain the same system overhead for running the system core but differ in contribution in their respective function. This overhead is calculated as the

Operating Mode Characterization	**[mA]**
Sleep	0.026
DAQ active[a]	2.086
Dozer RX idle	13.64
Dozer RX	14.2
Dozer TX	54.6
Measured Average Values	**[mA]**
DAQ only (2min)	0.110
Dozer only (30sec/2min)[b]	0.072
PermaDozer total (30sec/2min)	**0.148**

[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

Table 4: Power consumption for individual modes as well as the aggregate duty cycle for PermaDozer, measured at 3.6V

difference between the two partial values and the total: $P_{SYS} = P_{DAQ} + P_{DOZER} - P_{TOTAL}$. In an approximation this system overhead can be split into a contribution of the lowest achievable power state (sleep) and a functional overhead. The individual contributions in mA for the contributions of P_{SYS} (sleep + overhead) 23.0%, P_{DAQ} 51.4% and and P_{DOZER} 25.7% leading to the total of 0.148mA are presented in Figure 11.

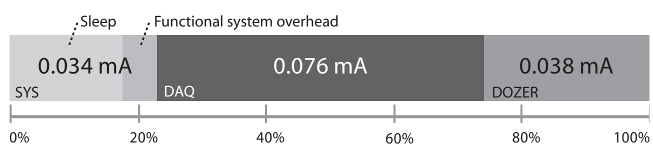

Figure 11: 0.148mA total power consumption is split into contributions for SYS (with sleep and overhead), DAQ and DOZER at a ratio 1:2:1.

Surprising is the high contribution of the sensing routine. This is in strong contrast to the common belief that the dominant cost of low-power wireless sensing systems is in the communication [13, 12]. Not the general assumptions on the relation of the energy cost for communication and computation are wrong or have changed, but past discussion has been focusing mainly on the power consumption of the individual subsystems in isolation, and not in an integrated context. In the given system context, especially with a complex and time consuming DAQ routine (cf. Figure 12), the overall picture changes which can be seen in the ratio of 1:2:1 for P_{SYS}, P_{DAQ} and P_{DOZER} respectively. It is neither the modular design nor poor engineering of the DAQ routine that causes such a high contribution: The cause is in the fundamentals of sensing itself. The dominant time of the DAQ routine is spent waiting for power hungry components to initialize, reference voltages and frequencies to stabilize and on refining precision on elaborate interleaved measurements of analog channels and references in order to achieve the precision required. Related sensor network projects [18], although operating at a different performance point, have also noted this dominant contribution of the ADC power consumption.

It is worth to note, that although meticulous care has been taken to reduce sleep consumption to an absolute minimum, the influence on overall power performance is significant and further reduction should be pursued. The contribution of sleep, including the 16 µA introduced by the stability enhancement described in Section 4.2 are visible in the leftmost grey bar in Figure 11.

Figure 12 shows the complete DAQ routine measured for different types of sensors. Depending on the sensor type used and especially the duration of the SIB-sensor interaction the average power consumption of the DAQ part alone can vary by as much as 250%. In the case of some sensors, e.g., electrodes used for conductivity measurements on the rock surface (not shown here), the power consumption is additionally dependent on the actual material and environmental conditions encountered at the specific location. As a result, the type of sensor and its respective energy requirement must also be considered in the discussion of the total power budget.

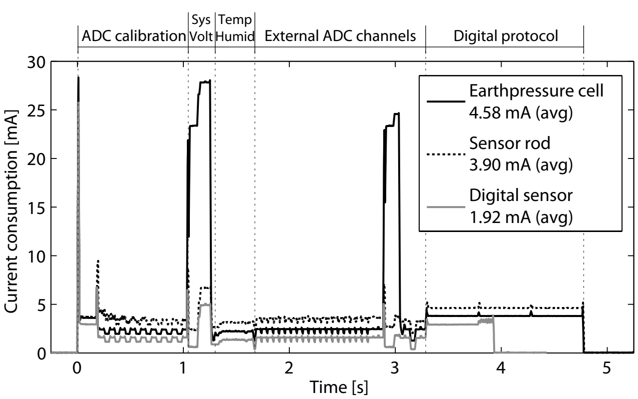

Figure 12: Detailed operating mode characterization of the multifunctional DAQ routine for different sensors shows significant difference depending on the sensor type used.

7. RELATED WORK

There is an extensive body of work on environmental monitoring deployments [14]. We concentrate our discussion on representative deployments targeting the three criteria for the PermaSense project.

Great Duck Island (GDI) [16] is one of the earliest long-term sensor network deployments monitoring a wildlife habitat for a period of 123 days. While the tiered architecture proposed then is a standard followed by most other systems and much of the initial experience gained remains a valuable contribution, both the sensing requirements and the environmental constraints of GDI are rather relaxed compared to PermaSense. Custom, high-quality sensing, the extreme environmental conditions and required longevity require additional measures to be taken both for node and system reliability.

Similar in terms of extreme environmental conditions and longevity is the Glacsweb project [11] monitoring subsurface phenomena in the Briksdalsbreen glacier. Sensor nodes are submerged inside the glacier, flowing along within the ice at different depths. Sensor data is gathered over multiple years, with intermediate data storage accommodating for periods of communication loss. Ranging between sensor nodes determines node positions. The main difference is the quality of sensor data and the non-retrievable nodes. Glacsweb probes merely pressure and resistivity using a simple microcontroller, while PermaSense supports a number of novel high quality sensors with precision data acquisition hardware providing data of diverse permafrost related phenomena.

Sensorscope [3] is a prominent environmental monitoring project in the Swiss Alpes. It differs in its goals, as the deployments are targeted for shorter term measurement campaigns. Instead of accuracy of individual sensors, the system design strives for generating models by high spatial density of inexpensive sensors in parts following the original Smart Dust paradigm. All nodes are powered by solar cells and hence do not require the strict conservation of energy like PermaSense.

From a data acquisition quality perspective, the closest project to PermaSense is volcano monitoring [18], which requires high fidelity data sampled at a very high rate (100Hz). As a result of the combination of energy required to transmit the high data rate, the choice of the Telos platform and the use of a standard, small form factor battery, the deployments are not designed for a long lifetime, i.e., requiring several battery changes over a project lifetime of 19 days.

8. CONCLUDING REMARKS

PermaSense is an ambitious project opening new horizons in the otherwise well-travelled domain of WSNs for environmental monitoring. Particulars are the high reliability, accuracy requirements, the extremes of the environment targeted as well as the longevity. Contrary to many first generation efforts PermaSense builds on the refinement of proven technology in practice, rather than dominantly building from scratch. In this sense the PermaDAQ architecture with the sensor interface board (SIB) and PermaDozer integration presented in this paper evolved based on the large body of related work and own prototypical experience and of course also failures.

This practical and requirement driven approach has lead to a number of successes that are described here. The mechanical setup designed has shown to work extremely well, significantly simplifying deployment and maintenance. So far no mechanical damage to nodes has been observed and servicing of a 15 node deployment with the exchange of nodes is performed in under two hours.

A strict design for testability and many redundancy features are key to success with respect to accurate, timely and complete data recovery from the field. The field site on Matterhorn has been operating continuously since being equipped in mid July 2008. An analysis of the network performance and especially the sensor data is not the focus of this paper. Temporary servicing of individual components during the initial deployment phase has resulted in no significant data losses. The preliminary analysis presented suggests that the accuracy improvements made will lead to substantial scientific results in the near future. The storage component introduced further enhances reliability by allowing delayed transmission and precision by support of post-deployment data validation – a necessity should WSNs be more widely adopted as a scientific instrument. The power consumption goal set or the operable PermaDAQ architecture has been more than achieved leaving enough slack to guarantee the required lifetime.

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