Wireless Sensor Networks for Long Term Structural Health Monitoring

Jonas Meyer
Empa, Switzerland
jonas.meyer[at]empa.ch

Reinhard Bischoff
Empa, Switzerland

Glauco Feltrin
Empa, Switzerland

Masoud Motavalli
Empa, Switzerland

ABSTRACT

In the last years, wireless sensor networks have emerged as a promising technology that could induce an innovation wave in the field of structural monitoring. The main advantages of wireless sensor networks compared to conventional monitoring technologies are fast deployment, little interference with the surrounding, self-organization, flexibility and scalability. These features could enable a mass application of monitoring system, even on smaller structures. However, since wireless sensor network nodes are battery powered and data communication is the most energy consuming task, transferring all the acquired raw data through the network would dramatically limit the system life-time. Hence, a significant data reduction has to be achieved on the node level in order to meet the system life time requirements of real life applications.

The objective of this paper is to discuss some general aspects of data processing and management in wireless sensor network based monitoring systems, to present a prototype monitoring system for civil engineering structures and to illustrate long term field test results.

Keywords: wireless sensor networks, monitoring, cable stayed bridge, energy management, data reduction

1 INTRODUCTION

In the last decades, the progresses in electronics, computer science and sensor technology allowed to develop robust and reliable structural health monitoring systems which meet the requirements of autonomous long term applications. This intensified the research on structural health monitoring (SHM) with the goal to improve the effectiveness of condition and performance assessment methods. Nevertheless, in daily civil engineering practice, the application of structural health monitoring is still a rarity. Deployments are mainly limited to very large structures or are performed for demonstration and research purposes. Important factors, which prevent a broad adoption of SHM systems, are system costs and data management. Both aspects are closely related to the logical structure of conventional monitoring systems.

In conventional SHM systems each deployed sensor is connected via long cable runs to a central data logger. The installation of such SHM systems is time consuming and expensive, the sensors are located far away from the data logger (Figure 1). Furthermore, cabled systems show a limited flexibility in terms of rearrangement of sensors and scalability. The installation costs becomes uncritical with respect to operation and maintenance costs only for new structures or for monitoring tasks that last for many years. These cases however represent the minority of potential monitoring applications in civil engineering.

The adoption of wireless sensor networks (WSN) for structural health monitoring promises to drastically lower the installation costs. This is achieved by replacing the cables between the sensors and the data logger by wireless links. A WSN is basically a computer network consisting of many small, intercommunicating computers equipped with one or several sensors [1]. Each small computer represents a node of the network and is commonly called sensor node or mote. The hardware of a sensor node is built up of one or more sensors, a signal conditioning unit, an analog to digital conversion (ADC) module, a central processing unit (CPU) with memory, a radio transceiver and a power supply. The communication within the network is established using radio fre-
quency transmission. One or several sensor nodes act as root nodes and represent the data sink in the network. A root node is connected to a base station that aggregates all data that is originated by the sensor nodes.

WSN eliminate the cables connecting the sensors to the central logging unit and therefore solves the cable related problems of current conventional monitoring systems making rapid and flexible deployments feasible. However, new WSN related challenges arise. Particularly the resources to power the wireless sensing devices are highly affected by the absence of cables. In fact, the nodes of the network have to be powered by autonomous sources like batteries that are severely limited in capacity. These limited energy resources are the most restricting factor in designing and implementing WSN based monitoring systems for long term applications, since the advantages of WSN over wired sensing systems come into play only if an unattended operation of the WSN for a reasonably long period of time can be achieved.

So far, the validation with field tests of wireless sensor networks in structural health monitoring was performed with short term deployments [2, 3 and 4]. In these investigations, strategies for prolonging the life-time of WSN and their implications for the hard- and software design were discussed only marginally. This paper presents a monitoring system that is specifically designed for applications which target an overall system lifetime of several months to years and implements several methods for reducing energy consumption: ultra low power hardware components, multi-hop communication, low duty-cycle operation and significant data reduction. A long term real-life deployment is presented that exploits all these energy saving methods.

Figure 1: Traditional wired SHM installation.

2 ENERGY MANAGEMENT IN WIRELESS SENSOR NETWORKS

The energy consumption aspect in WSN is of outstanding importance when addressing long term monitoring applications. Because of the small capacity of batteries and the limited and unreliable recharging opportunities, the energy consumption must be controlled very tightly. The main energy consumers are the radio, the sensors with the associated signal conditioning and the microcontroller. Different approaches that engage on the hard- and software level of a sensor node have been investigated to reduce energy consumption in WSN. Here we briefly discuss the most relevant techniques and their implications for structural monitoring applications.

Ultra low power hardware enables designing sensor nodes which operate from a battery for a reasonably long time. Today, ultra low power microcontrollers, which consumes about a few mW, are commercially available. The power consumption of radio chips is mostly dictated by the transmission range and varies between 50 and 100 mW. A figure that is significantly greater than the energy consumption of the microcontroller. The most energy efficient commercial WSN platforms that are available today have a power consumption that is smaller than 80 mW [14]. However, this low power consumption is obtained at the price of a low processing power and small memory size, which significantly affects the complexity of the tasks that can be performed on the sensor node.

Another mean to reduce energy consumption is to operate the sensor nodes at low duty cycle. The duty cycle describes the fraction of time that a system is in an active state with high power consumption. Energy is saved by operating the network in switched-off state for a significant amount of time. In practice, only the radio, the sensors and the signal conditioning units are switched-off, the CPU remains turned on. In a low duty cycle operation mode, the lifetime of a system is predominately determined by the off state energy consumption of a node. The most energy efficient commercial WSN platforms have a power consumption at off-state that is smaller than 10 mW.

In terms of power consumption, wireless data transmission is much more expensive than data processing. In order to extend system lifetime, it is therefore inevitable to pre-process the raw sensor readings to reduce the
data items that need to be transmitted to the base station. Transmitting all the raw data to the base station is only feasible when monitoring slowly varying physical parameters like temperature, humidity, static strains etc., since only little raw data is acquired. When monitoring vibration based processes, which produce large amounts of raw data, this strategy is hardly applicable without introducing huge batteries if a system lifetime of several months is targeted. Furthermore, since a significant amount of data has to be transferred to the base station, the rate of packet collisions increases so that a certain amount of data does not reach the base station. This data has either to be retransmitted; further increasing traffic and collisions, processor load and energy consumption, or it will be lost. To overcome this problem, different data processing strategies have been investigated:

- The data is encoded with data compression algorithms in a new representation that uses fewer bits than the original not encoded data. This data reduction is either lossless or lossy. A lossless data compression, which was tested on WSN, is Huffman coding [7]. A compression algorithm with data loss was proposed by [8].

- The raw data is transformed into a new kind of information that requires less space in terms of bits. Examples of simple data transformation can be maxima, minima, mean values, rms of recorded time series etc. Computationally more demanding transformations are the computation of natural frequencies or mode shapes of a structure [4,9].

- Data evaluation on the sensor node level represents another mean to reduce the amount of data transferred to the base station. It differs from the methods described above because the raw data is subjected to an evaluation. The sensor node software analyzes the data according to given criteria and decides if the data is relevant or not. Irrelevant data can already be discarded at the sensor node level. Data evaluation can be used to detect the occurrence of an event that needs to be monitored (e.g. crossing of a train on a bridge).

The limited energy resources restrict the complexity of the computational hardware on the sensor node. These restrictions basically limit the processing power and the memory size and highly affect the achievable analysis complexity.

3 MONITORING SYSTEM

3.1 Overall structure

The monitoring system is composed of three subsystems, which are displayed schematically in Figure 1. The first subsystem is the wireless sensor network (WSN) installed on the structure, which is composed of the sensor nodes, which are the data sources, and the root node, which is the data sink and is linked to the base station. The WSN is operated as a multi-hop network (data is forwarded from node to node towards the base station). The routing tree is adapted periodically by assessing the link quality to adjacent nodes and choosing the most reliable one for transmission. Due to this flexibility, it is possible to transfer data to the base station, even if some sensor nodes fail or do not operate correctly.

The second subsystem is the remote control center that collects all the data originated by the WSN and is responsible for the long term storage of the data. Furthermore, it implements the data visualization and representation tools for the end users and provides an interface to the operator to observe, control and configure the WSN remotely.

The third subsystem forms the communication link between the WSN deployed on the structure and the remote control center. This link, which is secure in terms of authentication and encryption, is established by the base station using standard wired or wireless communication technologies like Wireless LAN (WLAN) or Universal Mobile Telecommunications System (UMTS).
Figure 2: Overview of the deployed health monitoring system showing the sensor network, the off site control and storage components and the link in between.

### 3.2 Hardware

The hardware components of a sensor node are the sensors, a signal conditioning unit, an analog to digital conversion (ADC) module, a central processing unit (CPU) with random access memory (RAM), a radio transceiver and the power supply (see Figure 3).

![Figure 3. Hardware structure of a sensor node.](image)

#### 3.2.1 Wireless sensor network platform

The sensor nodes are based on the commercial Tmote Sky WSN platform [11], which was chosen because it excels by very low power consumption (5.4 mW at radio-off state and 65 mW in full operational mode). The main components of the Tmote Sky sensor node platform are the ultra low power TI MSP430F1611 microcontroller, the FTDI FT232BM USB-interface, which allows for programming the microcontroller over USB (Universal Serial Bus), and the Chipcon CC2420 low power radio chip. The 16-bit microcontroller features 10kB of RAM and 48kB of program memory (flash). It has 8 external 12 bit ADC ports whereof 6 are accessible on a pin header. The ADC input ranges from 0 to 3.0V. The maximum total sampling rate for all ports is 200 kHz at 12 bit resolution. The Chipcon CC2420 low power radio chip enables IEEE802.15.4 standard compliant wireless communication that operates in the ISM (industrial, scientific and medical) 2.4GHz frequency bands. The radio chip is controlled by the microcontroller through the SPI port and a series of digital I/O lines and offers power management capabilities to ensure low power consumption. The theoretically achievable maximum data throughput of the transceiver system is 250 kbps without framing and packet headers. In practice, however, the achievable maximum bandwidth is about 50kbps.
3.2.2 Sensors and Signal Conditioning

The signal conditioning unit basically consists of amplification and filtering circuitry. It enables to interface various sensing elements like strain gages, capacitive and piezo-resistive accelerometers, LVDTs etc. However, considering power consumption, it is reasonable to implement dedicated signal conditioning for each type of sensor instead of a general purpose conditioning unit.

Vibrations are measured with a LIS2L06 MEMS accelerometer from ST Microelectronics. It has been selected because of its high sensitivity of 0.6 V/g, its good noise performance of 0.2mg at 50Hz bandwidth, its low power consumption and low costs. It has an amplitude range of 2g and a bandwidth of 0-2 kHz (capacitive accelerometer). The accelerometer is integrated into an electronic circuit containing a low pass filter with a cut-off frequency of 20 Hz and a low power signal amplifier. The power consumption of the accelerometer and signal conditioning is approximately 5 mW and hence of the same magnitude of the power consumption of the microcontroller.

Ambient temperature and humidity are measured with the single chip Sensirion SHT11 sensor. The sensor includes a capacitive polymer sensing element for measuring the relative humidity and a band gap temperature sensor. The maximum power consumption is achieved during measurements and amounts to 0.5 mW. The sensor is mounted into an opening of the housing and allows for temperature and humidity measurements outside of the enclosure.

3.2.3 Housing

Since the sensor nodes are deployed in harsh outdoor environments, the hardware components have to be protected against water, chemical and mechanical impacts. The mote components, i.e. the sensors, the signal conditioning unit, the Telos WSN platform and two 16500 mWh batteries are integrated into an aluminum enclosure Figure 1. Switches and status LEDs of the Tmote Sky hardware are externally accessible. Furthermore, an external USB connector permits to reprogram the nodes without opening the enclosure. The housing is greater in size than required to allow the installation of additional sensors or signal conditioning boards. An external connector allows for connecting of sensors which have to be mounted directly to the structure, i.e. strain gages, corrosion sensors etc.

![Figure 4: Rugged and waterproof ‘nomotidaBox’ for long-term outdoor deployments. Nomotida boxes mounted on the cable stays.](image)

3.3 Mote software

A WSN based monitoring system is a distributed sensing, computing and data storage system. A core component of the software system is the software running on the sensor nodes. Figure 3 displays the logical structure of the node software architecture. Each node of the WSN provides the following functionality:

- Scheduling and execution of measurement tasks
- Processing and temporary storage of the acquired data
- Management and configuration of the data acquisition and processing (e.g. changing the sampling rate, reprogramming of data processing algorithms)
- Self monitoring (e.g. supply voltage, communication link quality)
- Reception and forwarding of data packets
- Coordination and management of communication and networking.

![Software architecture of a sensor node](image)

Figure 5: Software architecture of a sensor node

The software running on each mote establishes the wireless network, organizes the communication between the motes, acquires measurements, performs data processing and analysis and generates alerts if particular conditions are met. Since every specific monitoring application differs from each other, flexible, open and scalable software architectures are desirable. The present monitoring application is implemented as TinyOS [13] components. TinyOS is a component-based software framework designed for sensor networks and tailored to fit the memory constraints of the motes. It provides a concurrency model and mechanisms for structuring, naming and linking software components to form a robust network embedded system.

The basic network functionality is provided by low level network management components which operate independently from the actual monitoring application. They are responsible for:
- Establishing wireless links between adjacent nodes and building the routing tree.
- Network wide time synchronization to provide all nodes with a common time base.

From an application point of view it is not important how this is achieved. The application only has to have the possibility to send and receive data and to have access to global time information. The monitoring application is built on top of these modules. This allows for flexible exchange of the communication and time synchronization components.

A scheduler component forms the core of the actual monitoring application. It manages the measurement acquisitions performed by the mote. Its clock is synchronized to the global time. The scheduler configures the measurement and analysis parameters like sampling rates, filter coefficients, thresholds etc. and triggers the data acquisition at the scheduled time.

The present prototype allows collecting information about the structural condition based on temperature, humidity and acceleration measurements. Moreover, it is possible to receive information about the internal state of each sensor node (battery voltage) as well as communication parameters of the sensor network which describe the current condition of the monitoring system itself.

### 3.4 Uplink and Off Site Components
The data items from the sensor network are collected at the base station. In order to make this data accessible for further analysis, the base station is connected to the internet via an UMTS uplink. The data is transmitted to an off-site server and stored in a database (see Figure 2). A Web interface to the database has been implemented which allows for flexible access to the stored data. The Web interface additionally allows for configuration and management of the sensor network and the monitoring application. This functionality is not publicly accessible. The software architecture is discussed in more detail in [14].

4 LONG TERM FORCE MONITORING OF CABLE STAYS

A potential application of WSN is cable tension force monitoring of stay cable bridges. Since each cable can be monitored independently a completely distributed analysis algorithm can be adopted.

4.1 Background

Cable stay force can be monitored by means of vibration measurements and natural frequency estimation. An appropriate cable model describes the relation between the natural frequencies and the tensile cable force. The natural frequencies are usually determined by using frequency spectra or output only system identification algorithms. However, these methods are too expensive in terms of memory usage to be implemented on a mote. Parametric methods of spectral analysis allow estimating natural frequencies with much less data than averaged spectrogram methods. Furthermore, the natural frequencies can be estimated by computing the poles of the associated rational function model and are therefore not subjected to fixed frequency resolution issues.

In the present monitoring application, a simple autoregressive model has been used to estimate the natural frequencies of the cable stays. The natural frequencies are computed using a very simple 2 parameter discrete time AR-model. The use of such a simple model is only possible if the vibration components associated with a natural frequency can be isolated, which requires that the natural frequencies are well separated in the frequency spectrum. This is a requirement that cable stays usually fulfill quite well. The components can be isolated by first filtering the recorded data with a band pass filter. A detailed description of the implemented algorithm can be found in [9].

4.2 Laboratory Evaluation

Six cable stays of the laboratory bridge at Empa [10] have been instrumented with accelerometers. The bridge deck was excited with an electro-magnetic shaker driven by a broad band, stochastic signal ranging from 1 to 80 Hz. The cable accelerations have been simultaneously recorded with the motes and with a high precision data recorder. Subsequently the natural frequencies have been estimated during different deck loading states. The values computed on the motes fitted reasonably well with the results obtained using the data recorded with the high precision data acquisition device and reached an accuracy of approximately 1% (for more details see [9]).

4.3 Field Deployment at the Stork Bridge in Winterthur
After successful completion of the laboratory experiments, a real life field deployment has been started. The Stork Bridge (Figure 6) in Winterthur was chosen as investigation object. In a first phase, six of the 24 cable stays have been instrumented with accelerometers wired to a high precision data recorder and the cable vibration excited by ambient vibration as well as the impulse response of the cables was recorded. This data was used for system identification and as a reference for the data obtained with the WSN to. In a second phase, started in autumn 2006, the WSN has been deployed on the bridge. Figure 7 shows the setup.

Figure 6: Stork Bridge in Winterthur, Switzerland.

Figure 7: Drawing of the Stork Bridge indicating the six instrumented cables. C21 - C26 are the positions where the motes are mounted to the cables.

5 RESULTS

Figure 6 displays the natural frequencies of the cables C24, C25 and C26 of the Stork Bridge during a period of 10 days. The natural frequencies were estimated from ambient vibration data sampled at 100Hz using the algorithm described in [9]. The typical RMS magnitude of the ambient vibration data was 10 to 30 mg, which is a very small value for the accelerometer and the 12 bit AD converter integrated into the motes. The three bands displayed in Figure 8 demonstrate that the algorithm generates estimations with a significant scattering. The accuracy of the frequency estimations is within 5-10%, which is a direct consequence of low level of accelerations and the short data blocks used for estimating the natural frequency (blocks of 50 samples). Nevertheless, by using a moving average filter, relative small variations of natural frequencies are still detectable (black curves
inside the bands). This data processing step was done at the off-site control center with data retrieved from the database. For monitoring of cable tension, the accuracy is good enough, since only significant changes are of concern for ensuring structural safety of a bridge.

Figure 8 Natural frequencies of three cables of the Stork Bridge.

Figure 1 shows the battery voltage and the temperature on mote C26 over a 10 day period. It clearly depicts the dependency of battery capacity on temperature. The voltage graph seems to consist of two lines. This is due to the fact that the battery voltage drops about 100mV when the radio chip is turned on. Since the voltage measurement is not synchronized to this switching some measurements are taken when the radio is on and some when it is off. This results in the apparent double line voltage graph.

The graphs shown in Figure 8 and Figure 9 reveal data losses during some periods of time. The causes of these losses are on the one hand stability issues in the communication software on the motes which lead to communication link break down. On the other hand data from the motes is lost at the base station. Bugs in the software can render the base station irresponsive and block the reception of the data packets from the motes.

Figure 9 Battery voltage and temperature measured on cable C26.

5.1 Energy consumption
Figure 10 shows the battery voltage of the sensor node C26 over a period of 450 days starting from January 16th, 2007. New batteries were installed the day before. Three battery replacements were performed during this period: March 20th (day 63), August 6th (day 203) and December 14th (day 333). In the first period the network was operated with a duty cycle of 40% (40% of the time the radio is on) and the estimation of natural frequencies occurred every minute. Over this time period, the voltage dropped by approximately 0.5 V. Since a node operates correctly if the battery voltage is greater than 2.5 V, its lifetime was approximately 60 days.

After the first battery replacement on day 63 a new version of the sensor node software was installed that operated the network with a duty cycle of 10%. The estimation of natural frequencies occurred every 2 minutes. With this configuration the node lifetime reached approximately 180 days. After the second battery change, the duty cycle was reduced to 7%. The frequency of natural frequency estimations remained unchanged. This small reduction of duty-cycle did not influence the lifetime of the node, which was also approximately 180 days.

These measurements demonstrate that the node lifetime is not proportional to the duty-cycle. Although communication is the most energy consuming operation, the microcontroller, the sensors, the signal conditioning boards etc. are also consuming energy and these were always switched on. The smaller the duty cycle of the radio is chosen, the more important becomes this energy consumption and the stronger the node lifetime is affected by the power consumption of microcontroller and sensors.

The last sensor node software version, which was operating after the third battery replacement (day 200), switched the sensor off after completion of the data acquisition. The duty cycle was further reduced to 2% and the period of natural frequency estimations was set to 5 minutes. A lifetime estimation based on the voltage plots predicts a node lifetime of at least 450 days and therefore far beyond one year.

![Supply voltage of node C26. Battery replacements are marked with vertical dashed lines.](image)

**6 CONCLUSIONS AND FURTHER WORK**

The presented monitoring system has been successfully implemented and tested on the Stork Bridge in Winterthur. The deployment shows that cable stay force monitoring based on wireless sensor networks is feasible and that appropriate algorithms and strategies can be implemented which fit the limited memory and computation resources of the motes and provide reasonably accurate results. The feasibility is based on the integration of four methods for reducing energy consumption: ultra low power hardware components, multi-hop communication, low duty-cycle operation and data reduction. The latter method, which achieves a significant reduction of transmitted data by decentralized data processing, is a key aspect for enabling a long node lifetime. Various software tools have been developed which allow the monitoring system operator to access the aggregated data and configure the network and monitoring tasks in a suitable way.

In the next period the wireless sensor network prototype will be further improved and optimized. During the test some issues concerning the stability of the mote software arose which have to be addressed in order to provide reliable monitoring. Additionally the power consumption has to be further reduced to enable long term deployments.
7 ACKNOWLEDGEMENTS

Part of this work was performed within the Project “Sustainable Bridges: Assessment for Future Traffic Demands and Longer Lives” of the 6th Framework Program of the European Commission. The authors acknowledge the Swiss State Secretariat for Education and Research for its financial support.

8 REFERENCES