A Survey on Power Management for Long-Term Measurements using Wireless Sensor Networks

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ABSTRACT: Wireless Sensor Networks (WSN) are often required to monitor structures over a long period of time. This specifies several requirements for the design of WSN hardware, such as the use of low-power chip components, the use of micro-electrical mechanical sensors (MEMS) instead of conventional sensors and the use of a hybrid power supply. On the software side it dictates the utilization of intelligent power saving mechanisms and adequate network algorithms. Only the combination of all these measures provides a practical solution to the desired long-term monitoring.

In this paper, a non-comprehensive survey on the measures that can be taken in each of the above-mentioned aspects is given. Different low-power chip components and MEMS are opposed and rated for several physical quantities. Then, some energy-harvesting methods (i.e. thermo-electric, photovoltaic and others) and the resulting hybrid power supplies with a supporting primary battery are presented. On the software side, duty-cycled and event-based measurements are opposed and several radio transmission regimes are presented.

The result is a combined low-power approach that prolongs uptime of WSNs. Measurement results of a WSN hardware platform incorporating the Material Testing Institute's data acquisition software are shown, where operating time was extended by using the presented measures.

1 INTRODUCTION

Many engineering buildings are inspected at regular intervals to ensure a maximum degree of safety and furthermore to make a smooth operation of the structure possible. Potentially suitable buildings for monitoring comprise those from underground and structural engineering, e.g. bridge structures. Misjudging the health condition of a structure can have fatal consequences as seen by the collapses of Bad Reichenhall, Germany in 2006 (Sennewald, 2008) or of Minneapolis, USA in 2007 (jdl/als/AFP/dpa, 2007). Structural health monitoring by means of wireless sensor networks, as shown in (Grosse, et al., 2007) and (Grosse, et al., 2006), represent a cost-effective possibility of monitoring the state of structures. The cost advantage results from the easy, wireless installation on site, as well as from the usage of state-of-the-art but, nevertheless, cheap components within the sensor nodes. To still make a reliable judgment of the (potential) damages or damage processes, the nodes communicate their data with their neighbors.

Most methods described in the literature to detect progressing damage rely on the observation of changes in material properties over a long period of time. This is why energy-aware operating methods are crucial, to get by with the limited energy resources.

The approach in this paper is to give a non-comprehensive overview on the general possibilities to erect a WSN system for long-term measurements, enriched with the realizations and experiences of the Material Testing Institute monitoring system, which is based on Moteiv Tmote Sky sensor nodes (Sentilla Corp., 2007) and the operating system TinyOS (UC Berkeley).

2 DOMINATING ASPECTS OF POWER CONSUMPTION

2.1 Data Acquisition

Unlike transient recorders, WSNs are not able to record data continuously at high sampling rates for long time periods. This results from the limited power and memory resources available in a single WSN node, together with other restrictions which originate in the highly integrated and miniaturized chip components that are made use of in the system design.

As a continuous operation is prohibitive, two options remain: duty-cycling with low periodicity and event-based measurements. The duty-cycling paradigm can be compared to a continuous recording with a very low sampling rate. The rate is usually in the range of less than 1 Hz, i.e. measurement values are recorded quite rarely. This paradigm is not feasible for all types of parameters. However, for temperature, humidity, quasi-static strain, quasi-static air flow and many others it is sufficient. If we assume small quiescent drain, the mean energy consumption of a measurement is linear to the reciprocal of the periodicity, i.e.

$$\bar{P} = \frac{T_M}{T_P} \cdot P_M + \frac{T_P - T_M}{T_P} \cdot P_q$$

where T_M is the measurement time, T_P the period between each measurement, P_M the power input while measuring and P_q the quiescent power. T_M varies with the type of sensor and the desired accuracy (some sensors need a certain stabilization phase) and cannot be influenced. The same is true for the power consumption, which depends on the sensor type. So, ultimately, the period T_P defines the energy balance.

On the other hand, parameters where the dynamics of the value is of importance or for short events which will be missed otherwise, the sampling rate has to be high. This is where event-based measurements should be used. On the occurrence of a suitable indication, the measurement is triggered and sustained for as long as the memory is capable of handling, before needing an interrupt to save or transmit the recorded data packet. With this paradigm, high sampling rates (up to several hundred ksamples/s) can be realized with wireless sensor nodes, allowing the detection of high frequency components in a signal (Chatzichrisafis, et al., 2008), (Krüger, et al., 2008). This is useful for parameters like dynamic strain, vibration and sound and necessary for analysis methods like localization of acoustic emissions (AE) caused by fracture processes, modal analysis, fracture mechanical interpretation of AE data and others. In Figure 1, a voltage level is used as indicator for an event. After the occurrence of an event (voltage exceeds threshold), the main parameter is measured for a fixed time period Δt. Even if the indicator signal exceeds the threshold several times, an ongoing measurement is not restarted during Δt (see events #2 and #3).

For event-based measurements, the current draw is determined primarily by the periodicity of the events, the sampling-rate and the sensor type. For frequent events, the event-based case converges towards continuous sampling, with the restrictions mentioned. It should be taken care of, that events occur at a reasonable rate for the system to process. Otherwise, events should be discarded – e.g. by considering the most meaningful events only – to keep the system stable.

Sometimes, it is possible to reduce an event-based measurement to a duty-cycling problem by accepting a lower accuracy and/or response time. By doing so, it is possible to further decrease the demands regarding resource consumptions. E.g., if only the static load on a structure or structural part is of interest, the strain can be logged with a low cycle instead of recording dynamic strain graphs with a high sampling rate. Similarly, acoustic emission analysis usually relies on high sampling rates. However, with less sophisticated methods, valuable results can still be obtained for the assessment of structures (Bachmaier, 2008).

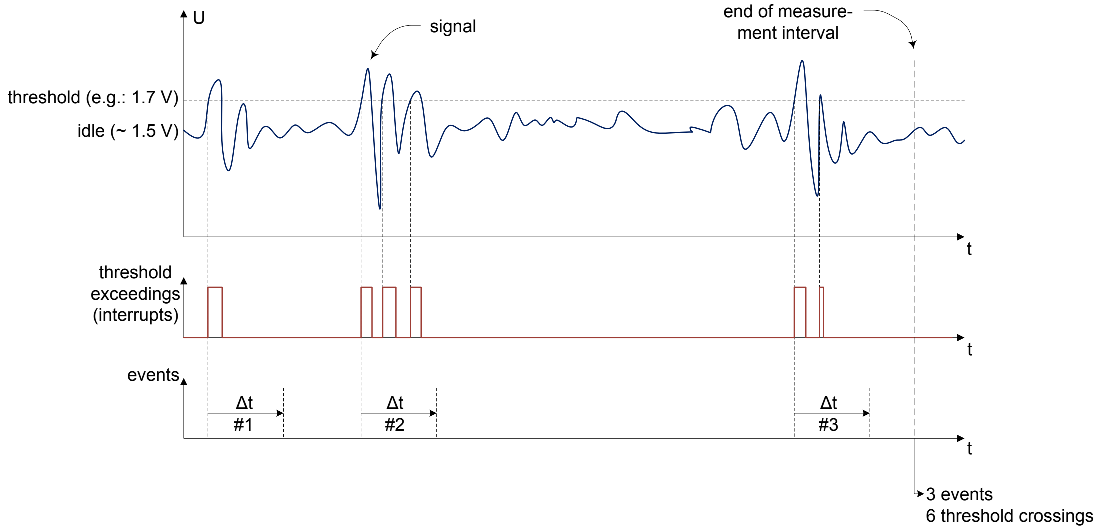

Figure 1: Sketch of event-triggering mechanism by threshold detection

With respect to the above mentioned aspects, adequate sensor choice is also essential. To achieve a long working time of the sensing unit, passive sensors seem to be the best choice. They do not require electric power, because they obtain their energy directly from the change of physical values (e.g. piezoelectric materials). However, also other sensors might be useful, such as micro electro mechanical sensors (MEMS) that support power saving and event detection modes. For detailed information on appropriate sensors for selected applications concerning this research field, please refer to (Krüger, et al., 2005).

2.2 Data Communication

Several modern radio transceiver chips support low-power modes implemented directly in hardware. They have a polling receiver feature (also called duty cycling or low power listening) which solves a common problem of WSNs. In ZigBee, e.g., there are three node types: end devices, routers and the coordinator. While the end devices can go into sleep mode and stop all data transmission for as long as they please, this is not allowed for routers and the coordinator. As there is no synchronization in beaconless mode, the routers always have to be in receive-mode, in case an end device wakes up and sends data. This data should not get lost only because an intermediate node is sleeping. In a typical ZigBee system, e.g. from home automation, the following two node types complement each other: end devices for battery-powered light switches and remote controls and router or coordinator for the mains-powered receivers that actually switch on and off devices. However, for structural health monitoring this semantics does not work. Here, because of the random topology in most deployments, each node has to be intermediary for its neighbors' packets and thus always has to be in receive mode.

With the polling receiver mode, for example like implemented in the wake-on-radio feature of the CC1100/CC2500 chips by Texas Instrument, the receiver only periodically wakes up from sleep mode and listens for incoming packets (Hellan, 2008). If the RF unit does not find a signal, it goes back to sleep mode immediately, which can have an average power consumption of less than 1 mW. If the RF unit does encounter a signal, it receives and preprocesses (validates) the packet. In order to not miss a packet, the transmitter has to send longer than the sleep period of the receiver (Figure 2 a). This is guaranteed by using a sufficiently long RF packet preamble (see packet layout of an IEEE 802.15.4 packet in Figure 2 b). This mechanism works without microcontroller (μC) interaction, which therefore can stay in sleep mode until a packet is received which is addressed to itself.

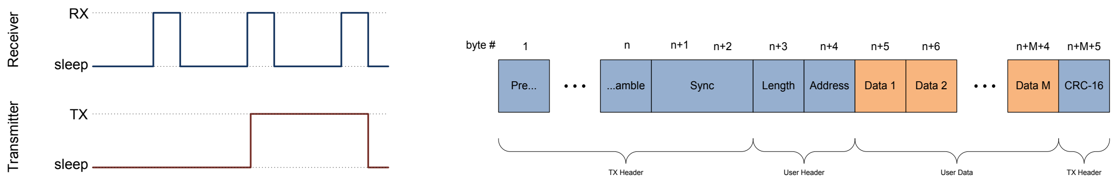

Figure 2: (a) Receiver and Transmitter activity for polling receiver; (b) packet layout for IEEE 802.15.4

Other features which are useful for energy saving are on-chip packet handling without µC interaction (validation of address and CRC in receive mode and formatting of packets and generation of CRC in transmit mode) and automatic acknowledgements. This prolongs the time the µC spends in sleep mode at low current draws.

The optimal sleep-to-listening-ratio is found by the (simplified) equations 1 and 2. As the minimum transmit time T_{TX} increases when increasing the sleep time $T_{sleep_{RX}}$ of the receiver, there is an optimum $T_{sleep_{RX}}$.

$$\bar{P}_{RX} = \frac{P_{sleep_{RX}} \cdot T_{sleep_{RX}} + P_{RX} \cdot T_{RX}}{T_{sleep_{RX}} + T_{RX}} \tag{1}$$

$$\bar{P}_{TX} = \frac{P_{sleep_{TX}} \cdot T_{sleep_{TX}} + P_{TX} \cdot T_{TX}}{T_{sleep_{TX}} + T_{TX}} \quad \text{with} \quad T_{TX} = T_{TX_{packet}} + T_{sleep_{RX}} \tag{2}$$

In general, the output power of the transmitter should be adaptive to maintain just the necessary signal-to-noise-ratio (SNR). This can be counterproductive in multi-hop networks as larger link budget can enable more direct links, hence avoiding relay transmissions by intermediate nodes.

If the transceiver is capable of operating at different transmission rates, it is advisable to use the fastest transmission mode. Usually, the shorter transmission time (before entering sleep mode again) overcompensates the higher current draw at higher transmission rates. The net effect is a smaller mean current draw. This aspect should also be considered when comparing different types of RF chips by different vendors. In most cases, the energy per bit is a good measure. However, it depends on the activity periodicities of the sender which influence the necessity to compare the current draw in sleep mode. It is not good to use a transmission system with low energy per bit for transmission, if a sleep mode is not or not sufficiently supported while the WSN is in inactive state. To make short transmissions useful, fast RX-TX and TX-RX switching and fast PLL synchronization, as well as settling of channel filters should be implemented in the chip. Else, significant power can be lost during the synchronization and settling times.

For RF chips without hardware support for low-power operation, a similar mechanism has to be implemented in software. As an example, the TI CC2420 transceiver can be considered. This chip does not have a polling receiver mode implemented in its hardware. However, the behavior is reproduced in TinyOS by switching on and off the receiver by software and repeatedly sending the packet in the transmitter, instead of using a preamble. The result is similar, except that in contrast to the long-preamble method, the transmitter can stop as soon as it receives an ACK by the receiver, using even less power here. The disadvantages of this method are the larger complexity in the software, leading to more programming effort and to a larger binary size and the higher power consumption in the active µC. On the other hand, a software solution can be IEEE 802.15.4-compliant, whereas the long preambles are non-standard.

The above presented mechanisms do not need synchronized nodes. With beaconed or synchronized networks, efficiency can be elevated further. The sender does not have to send at random times, but as it knows the receivers' active times, it can send at the right time, thus minimizing the transmission time. For networks with little traffic, synchronization is not advisable, as further protocol overhead, i.e. complexity and transmission time, is introduced, perishing the benefits.

Concluding the above given considerations, the CC2420 transceiver in conjunction with a software implemented low-power mechanism was introduced in the Material Testing Institute's sensor network. This choice was mainly driven by practical reasons as hard- and software is ready to use and therefore implementation effort is minimized.

2.3 Power Supply

2.3.1 Design of a hybrid power supply

Using the technologies presented in the previous chapters for WSN node designs makes it feasible to operate a node from a standard state-of-the-art battery and still achieving long operation times in the range of several months to years. However, this is not true for all operation conditions. For more sophisticated analyses, higher sampling rates, and for higher accuracy measurement modules, the current draw can be orders of magnitude higher than for simple configurations. This depletes the battery faster and the operation time is significantly reduced. Hence, for autonomous systems, energy harvesting is an option to prolong the operation time.

Energy harvesting methods must not be too detached for real world applications. Some energy sources are solely accessible by experimental setups or usable in too few cases to be considered for a general purpose SHM system, e.g. raindrop generators (Guigon, et al., 2008). More common harvesting methods are based on solar power and thermoelectric generators. These technologies are robust, as they have no moving parts, unlike generators based on wind or hydro power. Vibration harvesting is an interesting option for small scale devices with a power draw of less than 100 µW. However, ready-to-use modules are still not widely available.

It would be desirable for energy harvesters to generate power constantly. This is not possible for most methods due to their functional principle. E.g. solar cells cannot generate power during night time, wind generators not during doldrums, etc. (Figure 3 b). Even in cases, where full-time energy generation is achievable, it is not advisable for economic reasons. The generator has to be oversized to a large degree to compensate periods of low generation due to fluctuating conditions (Figure 3 a). E.g. the wind can change and a short period generation gap can occur. Similarly, a cloud can temporarily diminish the generation of solar energy during daytime. An alternative is a hybrid system with either an energy backup or an energy buffer device. A backup device is an independent, non-renewable power source which takes over the supply of the node, when the harvesting main supply is not available. For WSNs this could be some kind of electro-chemical primary cell, usually Lithium-based for their high energy density.

A buffer device, on the other hand, only buffers energy temporarily. The energy has to be generated by the harvester and is charged into the buffer. The buffer can be any device, which can convert the storage form of energy to electrical energy with a sufficient electrical current to operate the WSN node and at the same time support a vice-versa conversion during the charge phase at the maximum charge current, both with an acceptable efficiency. In most cases, electrical or electro-chemical devices are used. Like for the backup battery, lithium-based cells are favored, because of their high energy density and their convenient voltage range. Another option, which was examined during our work, is the use of electric double-layer capacitors. Though having a smaller energy density, both with respect to volume and weight, they have several advantages: easy chargeability with no limitations regarding the charge current, infinite charge cycles and small memory effects only. For small short term buffers, where the energy density is not of primary interest, these capacitors can be used. Two capacitors have been examined during this work: the WIMA SuperCap R 100 F (WIMA GmbH & CO.KG, 2008) and the AVX BestCap 1 F (AVX Corp.). While the 1 F capacitor is able to sustain power peaks in the range of seconds (at currents in the upper milliampere range, like they occur in WSN nodes), the 100 F capacitor can sustain much longer periods of time. With the larger type of capacitor, it is possible to maintain the supply during systematic non-generation times, enabling an unlimited operation time.

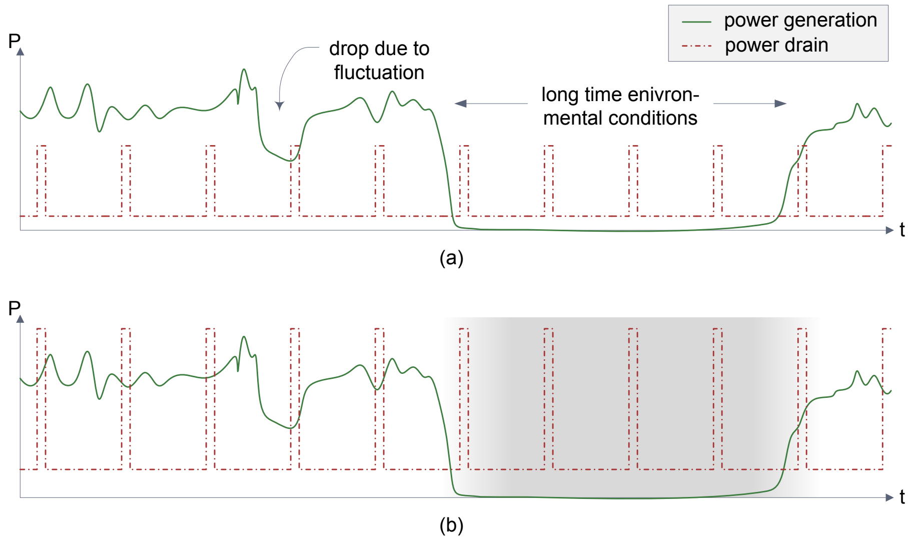

Figure 3: (a) Long-term buffer: can maintain the supply during times of systematic stagnation (b) Short-term buffer: only buffers for short periods of fluctuation and cannot hold up supply current for longer periods (grey area)

Figure 4 shows the proposed hybrid energy supply system. In the secondary supply branch, a voltage regulator is implemented, which is necessary to adapt the voltage of the harvesting system to the operating voltage of the WSN node circuit. This is unavoidable, as the voltage of any of these generators depends strongly on the prevailing environmental conditions and has to be converted into a useful voltage range.

For a paper with a similar scope like this, but focusing on novel electronics that can be used in relation to harvesting, please refer to (Maurath, et al., 2008). For a more complete overview on the generation and storage of electrical energy for small scaled systems see (Cook-Chennault, et al., 2008). Details on operation modes for power management and prediction algorithms are given in (Kansal, et al., 2007).

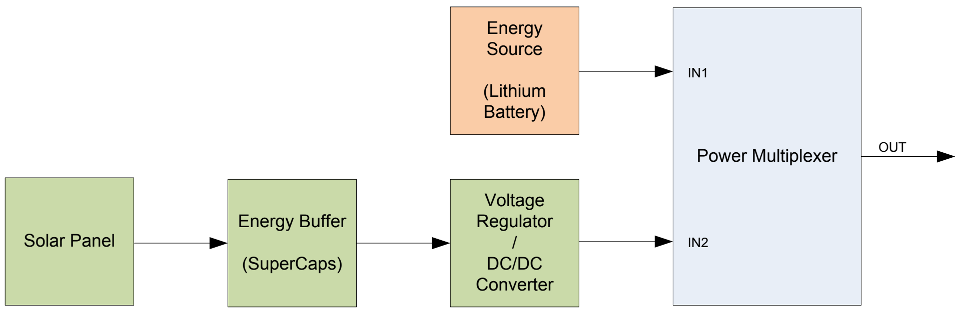

Figure 4: Hybrid energy supply with primary cell and solar generator

2.3.2 Measurement results for hybrid energy supply

To validate our hybrid power supply, several tests have been conducted. First, the self-discharge curve of several types of electric double-layer capacitors have been recorded, after having charged them for 24 hours. Figure 5 depicts the self-discharge curve of a 100 F capacitor by WIMA, which had been charged to 2.5 V. It can be seen, that the self-discharge is high in comparison to standard batteries. The equivalent parallel insulation resistance is approximately $R_{is} \approx 100$ kΩ in the long run. This results in an equivalent load in the range of a sleeping sensor node and hence cannot be neglected. Nevertheless, by proper dimensioning of the generator, this is acceptable.

As described in the previous chapter, a voltage regulator is necessary. Two basic choices exist: linear regulators and switched converters. Figure 6 shows the discharging of two series-connected 1 F capacitors (Panasonic Co., 2008) with a constant current, provided by both a DC/DC converter (Texas Instruments TPS63001) and linear regulator (Texas Instruments TPS73633). The capacitors had been charged to about 4.8 V and the output voltage of the regulator was set to 3.3 V. From Figure 6, the time until the output voltage could no longer be provided by the regulator can be deduced. Switched DC/DC converters have a higher efficiency when high currents are required from the source. However, for small load currents, switched converters are less efficient than linear regulators, which should hence be favored in WSN application, where nodes drain little power most of the time.

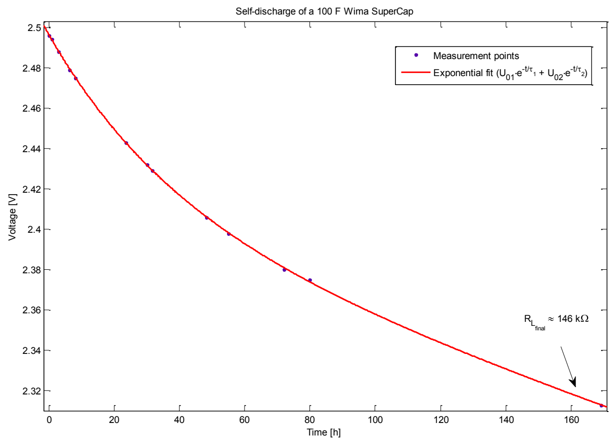

Figure 5: Self-discharge curve of super capacitors with approximation as exponential function

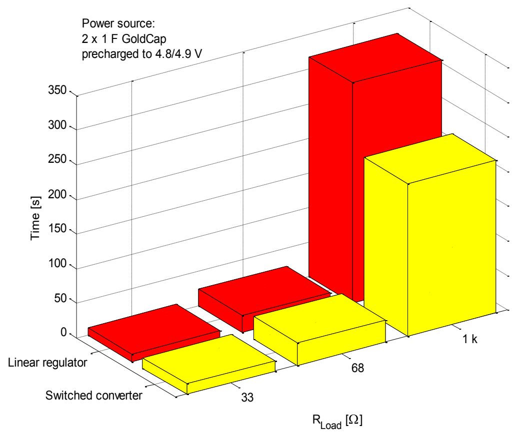

Figure 6: Discharge with constant current using a voltage regulator as depicted

3 CONCLUSIONS

It is the balanced combination of suitable hard- and software, which allows applicable SHM measurement systems. Only a holistic approach leads to functionally adequate results. The difference in the technology is often subtle; however, the net effect is considerable. Also, it is not only the implemented hardware that defines the power consumption. The embedded software has to support the chosen paradigm.

The proposed mechanisms will be implemented in our next generation WSN, which is supposed to be fully operable around the end of 2009. It will be used for applications assessing the conditions of historic structures in a project funded by the Seventh Framework Programme of the European Union: "Smart Monitoring of Historic Structures" (University of Stuttgart, 2008).

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