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System design issues in advanced applications of wireless sensor networks

ABSTRACT

This paper tries to give an insight into the challenges into the design of wireless sensor networks for advanced application scenarios. It describes both technological and practical aspects and ways to mitigate them.

INTRODUCTION

Recent years have seen significant progresses in such areas as embedded systems, where controllers have become much more powerful, real-time operating systems have gained widespread adoption, platforms have been miniaturized, and power consumption has been reduced. Communications technology has seen a similar boost, with "wireless" becoming a hyped attribute. The fact that versatile sensors have become available and affordable has led to a growing demand in sensorics. As a result of these tendencies, a host of new application scenarios are becoming possible.

One typical rather recent technology which can be seen as a result of this convergence is that of *Wireless Sensor Networks* (WSNs) [1]. A WSN consists of any number of sensors, usually combined with a microcontroller, which form a network using RF links. Such sensor nodes are often referred to as "motes" [2], [3]. Depending on circumstances, wireless sensor networks can be realized using various topologies, ranging from simple point-to-point or point-to-multi-point through hierarchical to mesh topologies (see fig. 1).

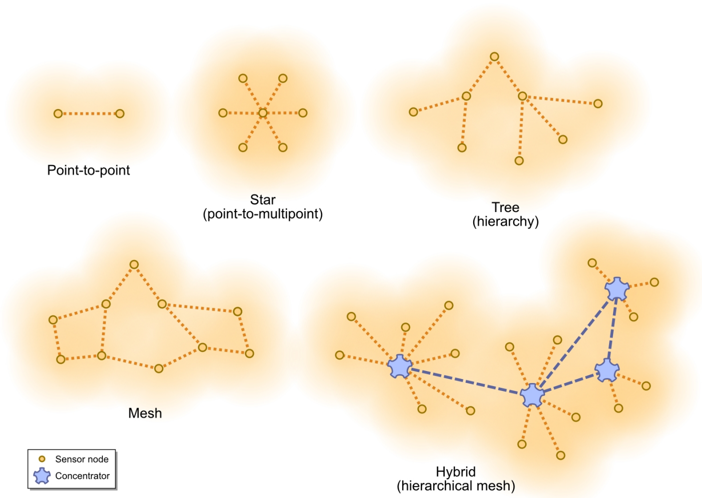

Figure 1: Possible topologies of wireless sensor networks.

There are efforts to standardize technologies — one example of this is the *ZigBee* standard for wirelessly-networked monitoring and control products [4].

The difficulties in designing WSN applications currently still lie mostly in a lack of experience. A wide range of available technologies and technical issues inherent to the subject matter often complicate both initial decisions and subsequent development. Despite the availability of individual components for WSN systems, the market has not yet seen the flood of actual installations one might expect. The simple truth is that there still is a significant need for research into various areas involved in the implementation and widespread deployment of WSNs.

ADVANCED APPLICATION SCENARIOS FOR WSNS

Successful installations of wireless sensor networks that have so far been publicly documented usually deal with rather simple scenarios, like monitoring agricultural cultivation areas [5], select buildings [6], or geological points of interest such as volcanoes [7]. The simplicity of these scenarios lies in favorable environmental conditions, such as open fields and line-of-sight connections, the use of mere point-to-point topologies, and small networks.

However, there is ample evidence of a demand for WSN solutions even in “tougher” environments, such as environmental monitoring or within industrial facilities. Environmental circumstances invariably involve such RF obstacles as hilly terrain or dense foliage as well as rough weather (EM interference). They also require long-term autonomous operation of sensors and the need to adapt to changing network topologies if sensors nodes are mobile (e.g., attached to an animal). Monitoring process quality or machines in industrial facilities may present a challenge with respect to EM interferences and shielded locations while imposing stricter requirements on reliability, latency, and the amount of data which to collect.

FUNDAMENTAL DESIGN CHALLENGES

The advanced application scenarios for WSNs described above result in various fundamental design challenges. Following below is a list of the most significant ones of these.

Design of large WSNs. During development, only small networks (both with respect to inter-node distances and the total number of nodes) can be tested practicably, i.e., with reasonable implementation and testing efforts. However, the scalability of the results of such limited tests is questionable as data rates,

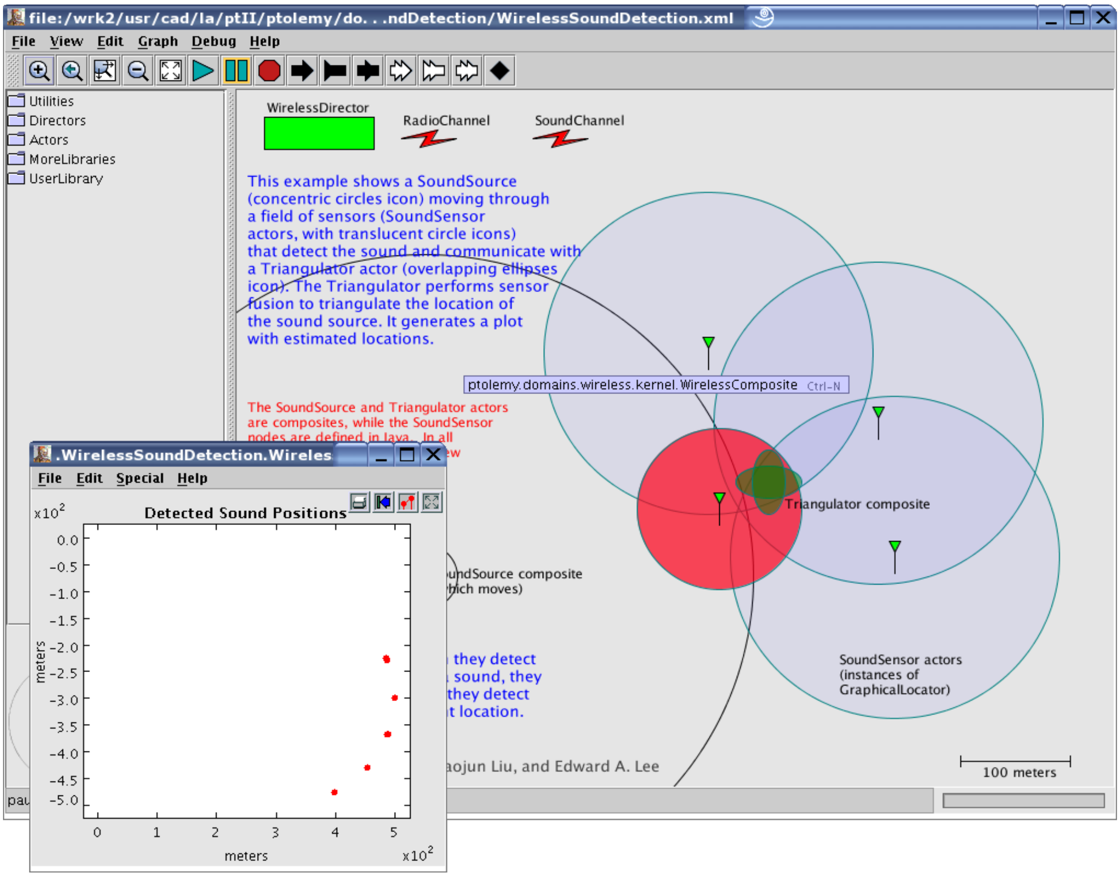

Figure 2: Ptolemy II simulating a sensor network.

communication links (in mesh networks) and the consequences of transmission errors are hard to predict.

It is therefore necessary to model and simulate a network prior to its implementation. Meanwhile, a wide variety of WSN modelling and simulation tools have become available. These modellers and simulators can roughly be categorized as network protocol simulators (e.g., *NS2* [8]), software/platform simulators (e.g., *TOSSIM* [9], *VIPTOS* [10]), and those employing domain-spanning approaches (e.g., *Ptolemy* [11], see fig. 2). In practice, the separate foci limit their usefulness because one has to switch among tools in order to model and simulate the various aspects of a WSN implementation. Moreover, there still is a significant demand for research regarding scalability, design flow integration, and reliability of simulation results.

Reliability and robustness. Different WSN topologies (see fig. 1) offer different levels of reliability. For example, self-adaptive mesh topologies are best suited in situations where individual nodes may fail or become disconnected, but the specific topology is defined by means of a distributed algorithm whose results are invariably hard to predict. On the other hand, a network made up of explicit point-to-point links in between pre-defined nodes will prove inflexible in the event of a failure.

Yet topology management is not a new problem: conventional, wire-bound networks such as the Internet have always had to deal with similar issues. Consequently, basic approaches and algorithms exhibit strong similarities. Still, specifics of wireless sensor networks have to be taken into account, most prominently, resource constraints (computation power, memory, battery life) of sensor nodes and intrinsic properties of wireless transmissions.

One particular issue with wireless transmissions lies in the fact that within the few frequency bands which are internationally license-free, a number of standardized and proprietary protocols have been put to use in recent years. In the case of the particularly-popular 2.4 GHz band, Bluetooth, WLAN, and the ZigBee standard "compete", among others. Beyond this concurrency, there also are side effects of other technologies, such as microwave ovens, which also cause interferences.

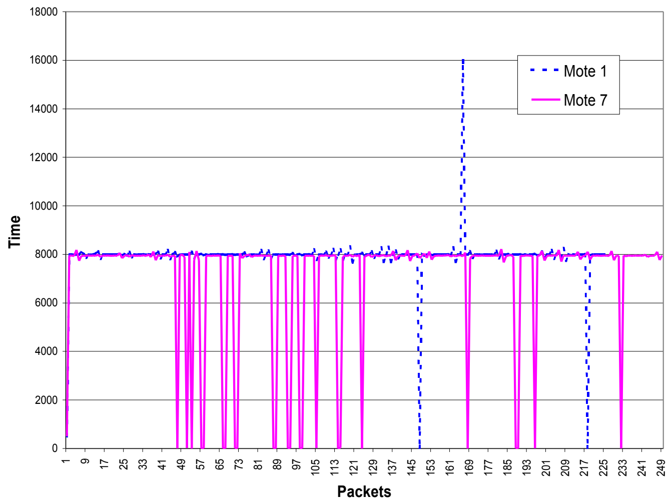

Figure 3: Influence of a microwave's EM emissions on packet transmissions.

The diagram of figure 3 shows measurements taken in order to determine the influence of a microwave oven's EM emissions on packet transmissions [12]. The diagram's x-axis enumerates individual packets, the y-axis indicates the reception interval to the respective preceding packet. In this experiment, a packet would normally reach the receiving mote every 8,000 ms. If another packet is received only a few milliseconds later, this is the result of either a multi-path reception or an interference of the microwave's EM emissions with the acknowledgement packet normally sent out by the receiving node. The bundles of negative spikes indicate periods during which the microwave oven was switched on, showing the severe disturbance of the WSN traffic caused by it.

Complementary requirements/goals and technological adaptation. The requirements of WSN designs tend to exceed what is technologically feasible.

Figure 4 shows a so-called Kiviat diagram comparing a selection of different application scenarios. In it, a number of axes show the scenarios' characteristics with respect to certain criteria. The different areas resulting from connecting these data points illustrate the respective scenario's feature-wise focus and their mutual differences. In the case of the two examples depicted, it is obvious that there is a significant difference regarding their requirements.

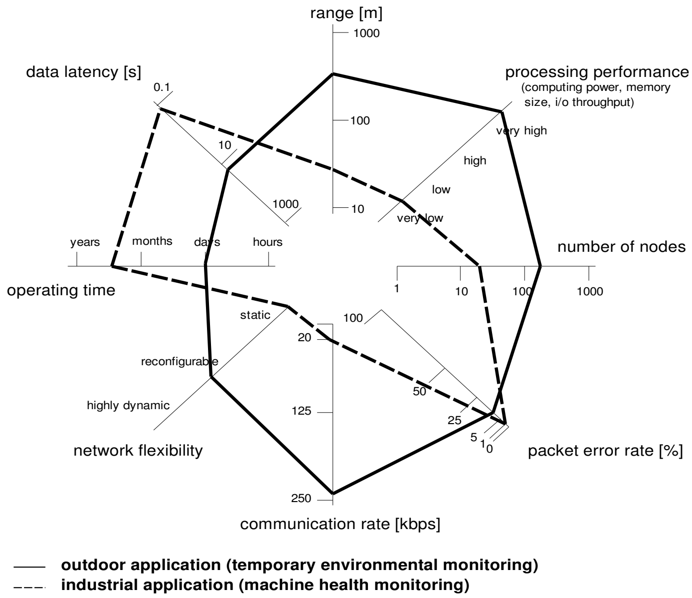

Figure 4: Requirements and properties of different WSN-based applications.

Yet as the diagrams in figure 5 show, seemingly separate parameters are in fact often correlated in that changing one such aspect affects one or more of the others. The diagrams illustrate the correlation in between transmission range, communication rate, and power consumption: Increasing one of these three aspects results in a reduction of the other two if the same technology is used in each case.

Consequently, there is no silver bullet design; instead, it is necessary to adapt available technologies in order to achieve a compromise between desired and feasible parameters fulfilling the requirements of advanced application scenarios (as detailed in the above section).

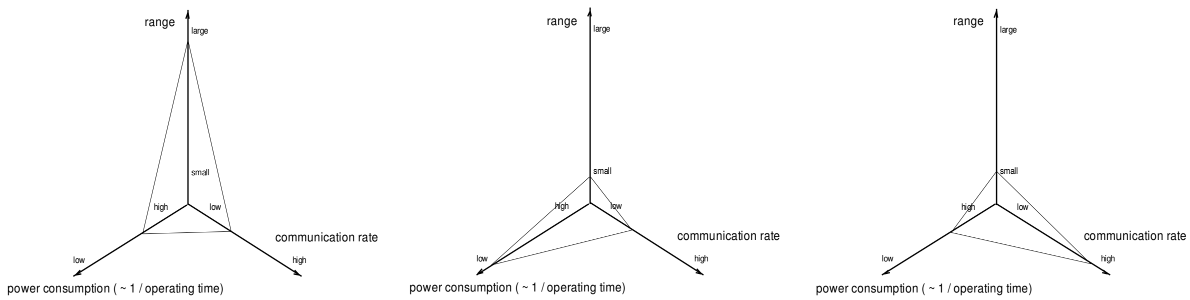

Figure 5: Interdependence of some key WSN properties.

PARTICULAR IMPLEMENTATION ASPECTS

Besides technology-implied issues, there usually are various pragmatic, application-specific ones when implementing WSNs. These issues have to be handled in the context of the application at hand and often incur specific R&D efforts.

Expectations vs. reality. Theoretical attributes of a given RF technology are one thing, but experience has it that practical properties often differ by a large margin. The environment in which a WSN is finally installed often brings about particular RF characteristics influencing signal propagation and reception. This fact makes it necessary to perform practical measurements of these characteristics.

In the course of WSN projects of our own, we have conducted experiments regarding the RF range of various sensor mote platforms and their susceptibility to EM interference. Figure 6 shows RSSI (Received Signal Strength Indication) measurements taken indoors at different distances among two *Crossbow MICAz*-type motes [13] running TinyOS [14], an operating system developed for sensor motes with minimal resources. As can be seen in that diagram, there are strong deviations from the expected exponential gradient. Analogous experiments conducted outdoors yielded smoother but still not perfect curves. Determining the reason for this requires further examinations.

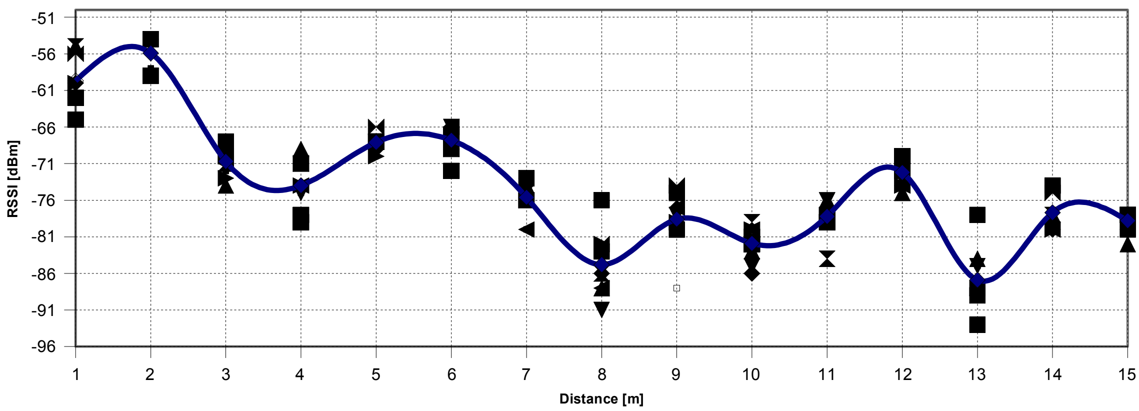

Figure 6: Received signal strength (RSSI) measurements within a building.

Smart Sensor Gateways. Despite the distributed, localized measurement (and, possibly, pre-processing) of sensor data, these values often have to finally be processed centrally. Also, during the set-up and operation of WSNs, a supporting entity is desirable. The logical consequence consists in incorporating a “smart sensor gateway” into the network which gathers data in a central location, makes them available for examination and external access, and acts as a coordinator within the network (fig. 7).

There is no general-purpose solution for this type of entity. However, smart wireless communication devices (SWCDs), such as introduced in [15], represent an adequate basis. An SWCD is a compact, embeddable module with one or more wide-range communications interface and, in this case, an interface to the sensor network. Its platform-oriented architecture allows for complex applications to be realized. Running a web server on an SWCD would be just one possibility of interfacing a WSN with other infrastructure.

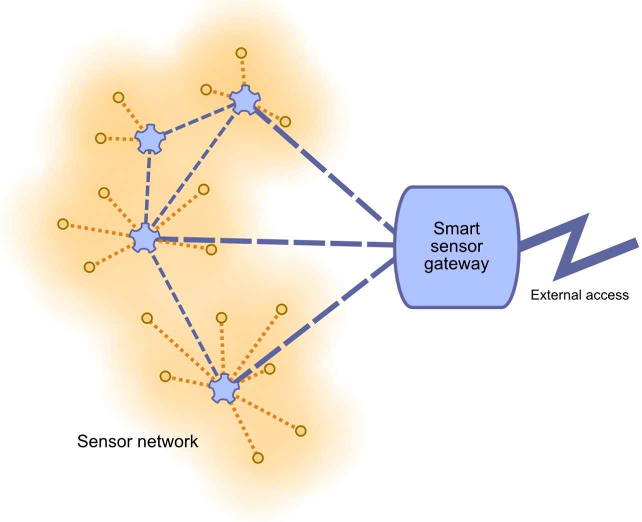

Figure 7: Smart sensor gateway.

Most of a smart sensor gateway's functionality is implemented as software. By decoupling generic from application-specific functionality, significant portions of a smart sensor gateway design can be reused among different WSN projects. Software design approaches supportive of this idea include platform-based design (operating systems, middlewares), component-based design for configurability and extensibility, and a design flow for automated (and thus fast and cost-effective) implementation (again suggesting a component-based design).

CONCLUSIONS & SUMMARY

This paper has given an insight into the challenges in the design of wireless sensor networks, particularly such for advanced application scenarios resulting in difficult environmental characteristics for RF infrastructures. Both technology-related and practical aspects have been described and approaches to mitigate them outlined.

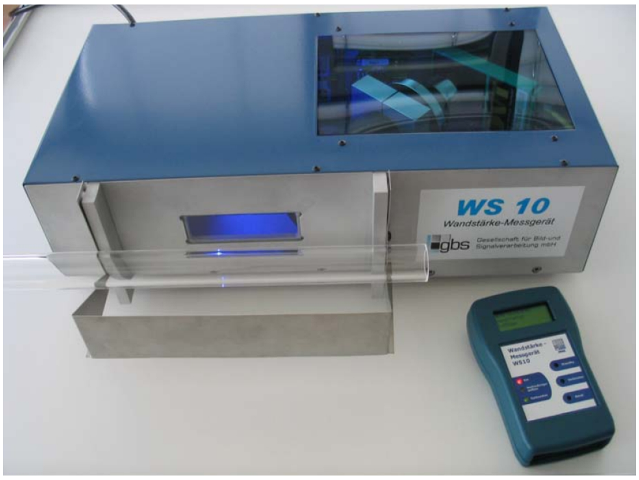

Figure 8: Example of industrial application of WSNs (glass wall thickness meter).

If appropriate attention is paid to the aspects described, it is still possible to design wireless sensor systems which can be operated in rough environments. One example of this is a prototypical wall thickness metering system to be used in glass manufacturing developed in a joint effort with one of our industrial partners. In this system, data acquired by sensors within the manufacturing machinery is transmitted wirelessly to a handheld device displaying it, facilitating quality assurance and process control.

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