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Wireless Sensor Networks and Their Application
A Survey

Abstract

This survey investigates the development of wireless sensor networks and their application to real world problems. It is analyzed how wireless sensor networks differ from existing, common ad-hoc network concepts. The driving forces behind the development of wireless sensor networks are investigated studying a couple of real world applications realized with wireless sensor network technology.

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Introduction

The Post-PC era of computing has seen the development of an array of small computing devices that perform a variety of specific functions. Common examples are: Cellular Phones and PDAs. As technology progresses those devices will become even smaller and more specialized. A class of such devices that emerged within the last couple of years is the embedded networked sensor: Those devices consist of a microprocessor capable of a couple of MIPS, limited storage in the order of a few kilobyte of RAM, a short-range radio transmitter, a small power source (often a battery) and a couple of sensors and/or actuators to interact with the environment.

Applications enabled by such networked sensor nodes range from environment monitoring to object detection and motion tracking. While the computing capacity of a single device is very limited, a collection of such devices working together to collectively solve problems can accomplish a range of high-level tasks: Systems of networked sensor nodes are touted as a revolution in Information Technology with "the potential to change radically the way people interact with their environment by linking together a range of devices and sensors that will allow information to be collected, shared, and processed in unprecedented ways." [1].

The hoped-for size for a single device would be a few cubic millimeters, the target price range less than one US$, including radio front end, microcontroller, power supply and the sensors / actuators. While these networks of sensor nodes share many commonalities with existing ad hoc network concepts, there are also a number of very differences and specific challenges. Some of the most important points that make wireless sensor networks (WSN) different are the following [6]:

1. *Application specific.* Due to the large number of conceivable combinations of sensing, computing and communication technology, many different application scenarios become possible. It is unlikely that there will be "one-size-fits-all" solutions for all these potentially very different possibilities. As one example, WSNs are conceivable with very different network densities, from very sparse to very dense deployments, which will require different or at least adaptive protocols.

2. *Environment interaction*. Since these networks have to interact with the environment, their traffic characteristics can be expected to be very different from other, human-driven forms of networks. A typical consequence is that WSNs are likely to exhibit very low data rates over a large time scale, but can have very bursty traffic when

something happens (a phenomenon known from real-time systems as event showers or alarm storms).

3. *Scale.* Potentially, such WSNs have to scale to much larger numbers (thousands, hundreds of thousands) of entities than current ad hoc networks, requiring different, more scalable solutions.

4. *Energy*. Akin to some forms of ad hoc networks, energy supply is scarce and hence energy consumption is a primary metric to be considered. Often the battery of a sensor node is not rechargeable and the need to prolong the lifetime of a sensor node has a deep impact on the system and networking architecture.

5. *Self-configurability*. Also similar to ad hoc networks, WSNs will most likely be required to self-configure into connected networks, but the difference in traffic, energy trade-offs etc. could require new design solutions. This includes the need for sensor nodes to learn about their geographical position.

6. *Dependability and Quality of Service*. Wireless sensor networks will exhibit very different concepts of dependability and quality of service - indeed, it is not entirely clear how to properly describe the service of a wireless sensor network. In some cases, only occasional delivery of a packet can be more than enough; in other cases, very high reliability requirements exist. The packet delivery ratio is an insufficient metric, what is relevant is the amount and quality of information that can be extracted at given sinks of information about the observed objects or area. Moreover, this information has to be put into perspective with the energy that is required to obtain it.

7. *Data centric*. Most importantly, the low cost and low energy supply will require, in many application scenarios, redundant deployment of wireless sensor nodes. As a consequence, the importance of any one particular node is considerably reduced as compared to traditional networks (where a user wants his laptop to communicate with that web server). More important is the data that these nodes can observe. This shift in importance both enables and requires a shift in networking paradigms, away from node-centric architectures towards data-centric architectures.

8. *Simplicity*. Since sensor nodes are small and energy is scarce, the operating and networking software must be kept orders of magnitude simpler as compared to state-of-the-art desktop computers. This simplicity may also require to break with conventional layering rules for networking software, since abstractions typically cost time and space.

WSN Application Overview

Wireless sensor networks have recently received significant attention in research literature. There have been multiple publications on the topic wireless sensor networks during the last decade – it seems that WSN is actually a highly attractive topic within the research community. What are the reasons for that development - what do people expect of WSN? To find an answer to this question we will investigate applications in the field of WSN, both future applications enabled by WSN technology, and applications already available.

Initially the development of WSNs was driven by military applications such as battlefield surveillance and enemy tracking. The vision is to deploy huge amounts of tiny sensor nodes in the field in order to detect and gain as much information as possible about enemy movements, explosions, and other phenomena of interest (see figure 1). Prerequisite is the availability of small and low-cost devices.

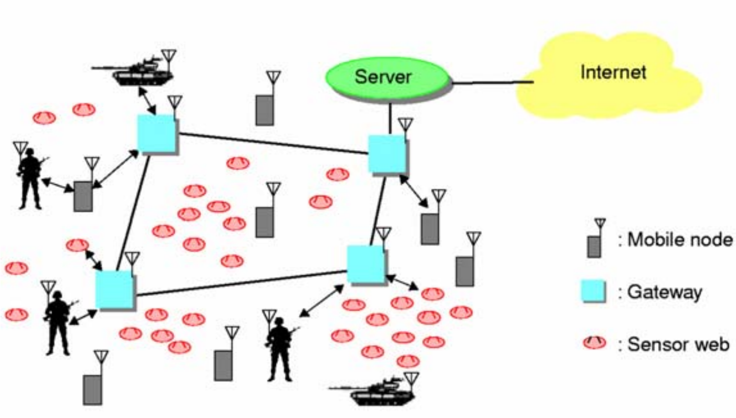

Figure 1: Battle field surveillance with WSN

MEMS and nanotechnolgy will yield tiny, low cost, low power sensor nodes. The ad-hoc nature of WSN networking and the smallness will enable a “deploy'em and leave'em” vision: the devices can be scattered in areas of interest to measure values such as temperature, light, vibration, sound, radiation, gas, the presence of toxic chemic and biological substances, etc. Deploying huge numbers of devices in the field will require the single device to be very inexpensive: During the past few years, great efforts have been directed to make this vision a reality. Research prototype sensor nodes (UCB motes [9, 10], uAMPS [11], PC104 [12], GNOMES [13] etc.) are designed and manufactured, operating systems [10], communication protocols [24], energy effecient MAC [14], topology control protocols [15, 16, 17] and routing schemes [18, 19, 20, 21, 22] are implemented and evaluated, and various enabling technologies such as time synchronizations [23], localization and tracking [24] are being studied and invented.

But still the state-of-the-art wireless sensor network node is too large and too expensive to be used for real-world applications depending on the deployment of huge numbers of nodes.

WSNs Enabling Homeland Defense

[7] gives an outlook on the planned development of a US nationwide early-warning system enabled by WSN technology: Once tiny, low power wireless sensor nodes are available and the measurements are communicated and coordinated through peer-to-peer wireless links, the technology moves to whole new software arenas: pattern-recognition, heuristic analysis, self-organizing systems, and complexity science.

The funding required to develop this significant new technology synthesis is rapidly becoming available: Against the backdrop of the war on terrorism in the US, work is progressing on a US nationwide sensor network that someday could provide a real-time early-warning system for a wide array of chemical, biological [8] and nuclear threats across the US [7].

With a $1 billion budget in 2004, the US Department of Homeland Security is doing a significant amount of new development, plus coordinating the efforts of key scientists at national laboratories. The core technology relates to materials, sensors, networks and chips. Field trials of prototype networks are already starting. MEMS and nanotechnology will be used to create several low-cost, highly accurate biological and chemical sensors. On the networking front, peer-to-peer networks with multilevel security and quality-of-service guarantees will span wireless, wired and satellite links.

Shooter Localisation

At the Institute for Software Integrated Systems of Vanderbilt University a WSN application was developed which detects the location of shooters in urban settings [34].

Although this application could also serve to detect civil shooters or terrorist activities, this project was initiated to support urban warfare (Developed within the Defense Advanced Research Projects Agency Network Embedded Systems Technology program)

An ad-hoc wireless network of cheap acoustic sensors detects phenomena of interest within the observed area and sends the sampled data to a base station via the wireless link. Individual nodes detect projectile shockwaves with latency in the tens of microseconds and muzzle blasts and use the time between the two observations to estimate the distance to the shooter. The actual shooter location is computed centrally at the base station. The prototype implementation uses the UC Berkeley Mica2 WSN node in conjunction with an acoustic sensor board developed by Vanderbilt University. The application requires fine grained time synchronization (less than 1ms accuracy) between the sensor nodes in the network.

Besides military applications many industrial and commercial applications can be enabled with WSN as soon as the technology reaches industrial standard.
Wireless sensors are especially beneficial in industrial and commercial building settings where they can reduce the cost of wiring [5]. In addition to reducing energy consumption [5, 25], wireless sensors can reach places where wires will not go including areas that are filled with toxins or high temperatures. For example, opening a manhole can be very costly for the amount of effort that goes into ensuring it is safe. Wireless sensors can reduce these costs and ensure safety much more easily. Another application area is monitoring industrial processes and related equipment. Values measured by the wireless sensor nodes can be used to control the production process much more fine-grained than it is possible with the current wired automation solutions. In the case of imminent failures staff can be alerted, which can save millions in potentially lost productivity.

Structure Health Monitoring (SHM) is another promising domain for the application of wireless sensor networks. The state of the structure of buildings, bridges, etc. is monitored if damage has occurred due to e.g. vibrations or aging of the structure. The goals of SHM are detecting damage, localizing damage, estimating the extent of the damage, and predicting the residual life of the structure, as proposed in [35]. SHM has been an evolving technology since it was first proposed in the 1990's. The latest approach is to apply WSN technology [36, 37]. This is very promising because of the low deployment and maintenance cost, large physical coverage, and high spatial resolution a WSN approach offers. One of the limitations with the current approaches is that damage detection is very difficult even for sophisticated sensors.

Nowadays WSNs are still at the developmental state: the hardware has not yet reached the low-cost and diminutiveness as it would be necessary to be beneficial for applications which rely on deploying huge numbers of nodes. However, there are many applications which have already been enabled by WSN technology. Within the next section we will investigate a couple of real-world WSN applications out of different application domains.

Habitat and Environment Monitoring Applications

Environmental and habitat monitoring represent a class of WSN applications with enormous potential benefits for scientific communities. Natural spaces are instrumented with numerous networked microsensors which can enable long-term data collection at scales and resolutions that are difficult to obtain otherwise [2].

Habitat Monitoring was identified as one of the driving applications of WSN technology in [25]. In their approach for habitat monitoring they proposed a tiered architecture for such applications.

The Great Duck Island (GDI)

At Great Duck Island (Maine), the Colledge of Atlantic (COA) investigates the behavior of the storm petrels. COA has ongoing field research programs on several remote islands with well-established on-site infrastructure and logistical support. In July 2002 a WSN network using the UC Berkeley *Mica* sensor nodes was deployed at GDI.

The UC Berkeley Mica mote deployed in this application uses an Atmel Atmega 103 microcontroller running at 4MHz, a 916MHz radio to provide bidirectional communication at 40kbps, and a pair of AA batteries as its energy source.

The Mica Weather Board provides sensors that monitor changing environmental conditions with similar functionality as a traditional weather station. The Weather Board is stacked to the processor board via an extension connector and includes temperature, photoresistor, barometer, humidity and thermopile sensors. Some new designs to preserve energy on this version include an ADC and an I2C 8x8 power switch on the sensor board. To protect from the variable weather condition on GDI, the Mica mote is packaged in an acrylic enclosure, which will not obstruct the sensing functionality and radio communication of the motes (Figure 2).

Figure 2: The all-weather Mica Mote

The application topology (Figure 3) consists of several tiers: the lowest level consisting of the sensor nodes that are deployed at areas of interest in dense patches which may be widely separated, e.g. inside several burrows.

The patches of sensor nodes transmit sensor reading to a gateway, which is responsible for forwarding the data from the sensor patch to a remote base station through a local network. The base station provides WAN connectivity and data logging. The data is replicated every 15 minutes to a database in Berkeley over satellite link. Users can interact with the sensor network remotely via the replica database server in Berkeley, and local interactions such as adjusting the sampling rates, power management parameters etc. can be done via a small PDA-size device which can directly communicate with a sensor network patch.

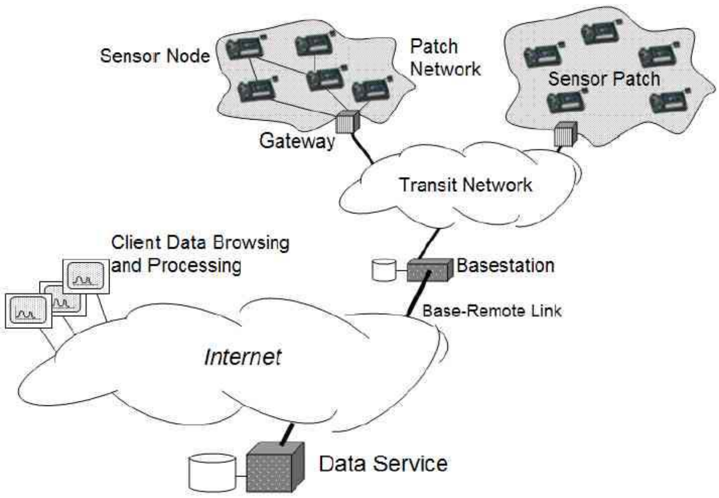

Figure 3: GDI Network Topology

A Remote Ecological Micro-Sensor Network - PODS

The University of Hawaii has built a wireless network of environmental sensors to investigate why endangered species of plants will grow in one area but not in neighboring areas. The research project is called PODS and was described in [2].

Camouflaged sensor nodes, called Pods, were deployed in Hawaii Volcano National Park. The Pods, consisting of a microcontroller, a radio transceiver and environmental sensors sometimes even including a high resolution digital camera, transmit sensor data via wireless link back to the Internet. Bluetooth and 802.11b were chosen as MAC, data is transmitted in IP packets. Energy efficiency was identified as one of the major design goals. This led to the development of an ad-hoc routing protocol called Multi-Path On-demand Routing (MOR). Two types of sensor data are collected: weather data, which is collected every ten minutes and image data, which is collected only once per hour. Users can use the Internet to access the data from a server at the University of Hawaii.

In [27] the placement strategy for those sensor nodes was further investigated. Sampling distance and communication radius were identified as key parameters, and topologies of 1-dimensional and 2-dimensional regions, such as triangle tile, square tile, hexagon tile, ring, star-m and linear are discussed.

The sensor placement strategy evaluation is based on 3 goals: resilience to single point of failure, area of interest to be covered by at lease one sensor, and minimum number of nodes to be deployed. The document concludes that the choice of placement depends on the sampling distance and the communication radius.

Environment Observation and Forecasting System (EOFS)

EOFS is a large distributed system that spans geographic areas and monitors, models and forecasts physical processes, such as environmental pollution, flooding etc. The topology consists of three components: sensor stations, a distribution network, and a centralized processing farm.

CORIE

CORIE [29] is a prototype implementation of the EOFS for the Columbia River. It integrates a real-time sensor network, a data management system and advanced numerical models. 13 stationary sensor nodes are deployed across the Columbia River estuary, while one mobile sensor station drifts offshore. The sensor stations are fixed on piers or buoys. The stationary stations are powered by a power-grid, the mobile station using solar panels to harness its energy. Sensor data is transmitted via wireless link to the onshore master stations which forward the collected data to a centralized server where data is fed into a complex physical environment model. The model is used to guide vessel transportation, to support hydropower management, and habitat restoration.

Several practical difficulties arose during the operation of the system: First, the power supply and antenna fixation for the offshore sensor nodes on buoys needed to be addressed. Second, the direct light-of-sight is frequently obscured, because the height of surface waves exceeds the height of the antenna and thus results in a highly dynamic connectivity. Third, since the topology of the network is known in this application, and the direction of data flow is from offshore towards the shore, a topology informed distribution algorithm is needed. Currently, a next generation of the system is being designed to address these problems.

ALERT

Automated Local Evaluation in Real-Time [28] is probably the first well-known wireless sensor network being deployed as real world application. It was developed by the US National Weather Service in the 1970's. ALERT provides real-time information on rainfall and water level information to evaluate the possibility of potential flooding. ALERT sensor sites are equipped with meteorological/hydrological sensors, such as water level sensors, temperature sensors, and wind sensors. Data is transmitted via light-of-sight radio communication from the sensor site to the base station, a Flood Forecast Model is adopted to process the data. Automatic warning is issued, web-based query of the results is available. Currently ALERT is deployed across most of the Western United States.

Health Applications

This class of WSN applications include telemonitoring of human physiological data, tracking and monitoring of doctors and patients inside a hospital, drug administration in hospitals [6] and even artificial organs.

The Division of Engineering and Applied Sciences of the University of Harvard together with the Boston Medical Center explore applications of wireless sensor network technology to pre-hospital and in-hospital emergency care. Vital sign data, such as pulse oximetry, are yet poorly integrated with pre-hospital and hospital-based patient care records. A wireless pulse oximeter and 2-lead EKG based on the UC Berkeley Mica2 sensor node platform was developed [32]. The device collects the heart rate, the oxygen saturation, and EKG data and relay it over a short-range wireless network to a PDA or ambulance-based terminal, where it is displayed and integrated into the developing pre-hospital patient care record. Continuous sampling of vital sign data allows these parameters to be carefully monitored and any adverse change in patient status to be signalled to a nearby doctor or paramedic.

In addition to this medical sensor node platform a scalable, ad hoc wireless infrastructure for medical care settings, called CodeBlue [33], is currently developed. Primary design goals of the network infrastructure are provision of routing, naming, discovery, and security for wireless medical sensors (like the Mica based device mentioned above), PDAs, PCs, and other devices that may be used to monitor and treat patients in a range of medical settings.

Loren et al. [30] describe a biomedical application they were working on: the artificial retina. In the Smart Sensors and Integrated Microsystems (SSIM) project, retina prosthesis chips [31] that consist of 100 microsensors are built and implanted within a human eye. This allows patients with no vision or limited vision to see at an acceptable level. The wireless communication is required to suit the need for feedback control, image identification and validation. The communication pattern is deterministic and periodic, so TDMA fits best in this application to serve the purpose of energy conservation. Two group communication schemes are investigated: a LEACH-like clusterhead based approach and tree-based approach. Some other similar applications include Glucose level monitors, Organ monitors, Cancer detectors and General health monitors. The idea of embedding wireless biomedical sensors inside the human body is promising, although many additional challenges exist: the system must be safe and highly dependent; require minimal maintenance; energy-harnessing from body heat.

Funding

During the last couple of years there was and there still is a lot of funding in the area of wireless sensor networks. Besides the financing of military and homeland defense projects mentioned above there is also funding for scientific and commercial projects:
The National Science Foundation (NSF) announced a funding program in 2003 supporting research on WSN with a first-year funding of $47 million [3].
But also companies and private organisations provide funding in the area of WSN:
Millennial Net, Inc., developer of ultra low-power, self-organizing, wireless mesh networking systems, in May 2004 announced that it has closed $15 million in funding.

WSN Mass Market Opportunities

As a matter of fact, a lot of effort has been put into research and development of WSN so far and also a lot of funding has already been provided in this field. What do people expect of applications enabled by WSN? Is it possible to make enough money with this technology so funding pays off?
ON World [5] prognosticates a nearly unlimited future potential in the area of WSN:

By 2010, ON World projects that wireless sensors will also be widespread for consumer markets such as monitoring and controlling heating, lighting, venting and appliances. In the future, consumers will also likely use wireless sensors to track their belongings, pets and children, monitor their cars and even their own vital signals. Within the next ten years, wireless sensors will be used in a wide range of applications: More than half a billion nodes will ship for wireless sensor applications in 2010 for an end user market worth at least $7 billion.

The Current State of WSN Applications - Conclusion

As pointed out by Deborah Estrin [1], there is no real WSN application yet, if short-lived demo does not count. The situation of the whole field is comparable to the situation of internet 30 years ago. The field is highly application-specific, the constraints and requirements of the most applications are yet not fully understood and as a consequence, most of the current applications are yet not ready for the real world.

Current WSN applications expose some common characteristics such as: read sensor data, transmit the raw sensor data via the network and process data centralized, deploy simple routing schemes and best effort data transport design to route data through the network. It is obvious that those applications still serve as test bed, to identify research goals and to verify proposed methods. With the progress on sensor fabrication, further miniaturization of the sensor nodes and ongoing research in the application domain of sensor networks we can expect that there will be real-world applications in the near future.

Nevertheless the applications investigated within this report showed that WSN technology has already been successfully applied across a wide range of domains. One can imagine that the application of WSN technology is possible for nearly every aspect of daily life: By establishing ubiquitous wireless sensor networks for example, that will pervade society redefining the way in which we live and work. Application scenarios we can right now not even imagine will be possible.

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