THE DESIGN SPACE OF WIRELESS SENSOR NETWORKS

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In the recent past, wireless sensor networks have found their way into a wide variety of applications and systems with vastly varying requirements and characteristics. As a consequence, it is becoming increasingly difficult to discuss typical requirements regarding hardware issues and software support.

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ABSTRACT

In the recent past, wireless sensor networks have found their way into a wide variety of applications and systems with vastly varying requirements and characteristics. As a consequence, it is becoming increasingly difficult to discuss typical requirements regarding hardware issues and software support. This is particularly problematic in a multidisciplinary research area such as wireless sensor networks, where close collaboration between users, application domain experts, hardware designers, and software developers is needed to implement efficient systems. In this article we discuss the consequences of this fact with regard to the design space of wireless sensor networks by considering its various dimensions. We justify our view by demonstrating that specific existing applications occupy different points in the design space.

INTRODUCTION

In April 2004, the authors organized a workshop, funded by the European Science Foundation (ESF), with a view to carrying out coordinated research into wireless sensor networks in Europe [1]. Twenty-four experts from 11 European countries including academic researchers and representatives from industry were invited to discuss application areas with particular relevance for Europe as well as various aspects of the hardware and software architectures required to support these applications. Some of the more concrete questions discussed at the workshop were:

- Which prospective application domains and concrete applications are of particular value to Europe? What are the requirements and challenges involved in implementing these applications?
- What hardware requirements are needed to support these applications? Are existing systems sufficient, or is there a gap that needs additional research and development?
- What type of software is needed (e.g., operating systems, programming abstractions, tools) to support these applications and what requirements have to be met?
- How can we better coordinate the mostly isolated and disconnected research activities on sensor networks across Europe?

During the discussions it was observed that wireless sensor networks have found their way into a wide variety of applications and systems with vastly varying requirements and characteristics, and hence it was very difficult to discuss specific application requirements, research directions, and challenges. In the past, a number of early, mostly U.S.-based research projects established a de facto definition of a wireless sensor network as a large-scale, ad hoc, multihop, unpartitioned network of largely homogeneous, tiny, resource-constrained, mostly immobile sensor nodes that would be randomly deployed in the area of interest. While this characterization is certainly valid for a large class of applications (in particular from the military domain), an increasing number of sensor network applications cannot be adequately characterized in this way.

As a result of this observation, it was suggested that the *sensor network design space* and its various dimensions should be characterized. Such an explicit design space might not only prove helpful as a framework for discussing and structuring coordinated research (e.g., analyzing mutual dependencies between applications, software, and hardware; avoiding duplicate work), but might also provide a conceptual basis for the development of flexible software frameworks that can be adapted to meet different application needs.

This article is a partial answer to the questions raised during the above-mentioned workshop. We attempt to specify important dimensions of the sensor network design space and justify our findings by showing that existing sensor network applications occupy different points in the design space. We build on earlier work [2] that classified system models of sensor networks with respect to communication protocols but did not consider the diverse nature of concrete applications.

DESIGN SPACE

Initial research into wireless sensor networks was mainly motivated by military applications, with the Defense Advanced Research Projects Agency (DARPA) continuing to fund a number of prominent research projects (e.g., Smart Dust, NEST) commonly regarded as the cradle of sensor network research. The type of applications considered by these projects led to a de facto definition of a wireless sensor network as a large-scale (thousands of nodes, covering large geographical areas), wireless, ad hoc, multihop, unpartitioned network of homogeneous, tiny (hardly noticeable), mostly immobile (after deployment) sensor nodes that would be randomly deployed in the area of interest.

More recently, other civilian application domains of wireless sensor networks have been considered, such as environmental and species monitoring, agriculture, production and delivery, and healthcare. Concrete projects targeting these application areas indicate that the above definition of a wireless sensor network does not necessarily apply for these applications: networks may consist of heterogeneous and mobile sensor nodes; the network topology may be as simple as a star topology; networks may make use of existing communication infrastructures. To meet this general trend toward diversification, we discuss important dimensions of the sensor network design space in the following subsections. We informally characterize each of the dimensions and, where appropriate, identify (possibly orthogonal) property classes in order to support a coarse-grained classification of sensor network applications.

It is certainly debatable which issues are important enough to be explicitly considered as dimensions in the design space, and one could argue in favor of adding more dimensions or removing some from our suggestions detailed below. In fact, we expect that this might become reasonable in the future as the field and its applications evolve. However, we have tried to ensure that our initial suggestion consists of a sensible set of dimensions, by basing our choice on two principles. First, there should be notable variability between applications with respect to dimensions. Second, a dimension should have a significant impact on the design and implementation of technical solutions.

Deployment

The deployment of sensor nodes in the physical environment may take several forms. Nodes may be deployed at random (e.g., by dropping them from an aircraft) or installed at deliberately chosen spots. Deployment may be a one-time activity, where the installation and use of a sensor network are strictly separate activities. However, deployment may also be a continuous process, with more nodes being deployed at any time during the use of the network, for example, to replace failed nodes or improve coverage at certain interesting locations.

The actual type of deployment affects important properties such as the expected node density, node locations, regular patterns in node locations, and the expected degree of network dynamics.

Classes: random vs. manual; one-time vs. iterative.

Mobility

Sensor nodes may change their location after initial deployment. Mobility can result from environmental influences such as wind or water, sensor nodes may be attached to or carried by mobile entities, and sensor nodes may possess automotive capabilities. In other words, mobility may be either an incidental side effect or a desired property of the system (e.g., to move nodes to interesting physical locations), in which case mobility may be either active (i.e., automotive) or passive (e.g., attached to a moving object not under the control of the sensor node). Mobility may apply to all nodes within a network or only to subsets of nodes. The degree of mobility may also vary from occasional movement with long periods of immobility in between to constant travel.

Mobility has a large impact on the expected degree of network dynamics, and hence influences the design of networking protocols and distributed algorithms. The actual speed of movement may also have an impact, for example, on the amount of time during which nodes stay within communication range of each other.

Classes: immobile vs. partly vs. all; occasional vs. continuous; active vs. passive.

Cost, Size, Resources, and Energy

Depending on the actual needs of the application, the form factor of a single sensor node may vary from the size of a shoebox (e.g., a weather station) to a microscopically small particle (e.g., for military applications where sensor nodes should be almost invisible). Similarly, the cost of a single device may vary from hundreds of Euros (for networks of very few but powerful nodes) to a few cents (for large-scale networks made up of very simple nodes).

Since sensor nodes are untethered autonomous devices, their energy and other resources are limited by size and cost constraints. Varying size and cost constraints directly result in corresponding varying limits on the energy available (i.e., size, cost, and energy density of batteries or devices for energy scavenging), as well as on computing, storage and communication resources. Hence, the energy and other resources available on a sensor node may also vary greatly from system to system. Power may be either stored (e.g., in batteries) or scavenged from the environment (e.g., by solar cells).

These resource constraints limit the complexity of the software executed on sensor nodes. For our classification, we have partitioned sensor nodes roughly into four classes based on their physical size: *brick*, *matchbox*, *grain*, and *dust*.

Heterogeneity

Early sensor network visions anticipated that sensor networks would typically consist of homogeneous devices that were mostly identical from a hardware and software point of view. Some projects, such as Amorphous Computing [3], even assumed that sensor nodes were indistinguishable, that is, they did not even possess unique addresses or IDs within their hardware. This view was based on the observation that otherwise it would not be feasible to cheaply produce vast quantities of sensor nodes.

However, in many prototypical systems available today, sensor networks consist of a variety of different devices. Nodes may differ in the type and number of attached sensors; some computationally more powerful "compute" nodes may collect, process, and route sensory data from many more limited sensing nodes; some sensor nodes may be equipped with special hardware such as a Global Positioning System (GPS) receiver to act

These resource constraints limit the complexity of the software executed on sensor nodes. For our classification, we have partitioned sensor nodes roughly into four classes based on their physical size: brick, matchbox, grain, and dust.

In its simplest form, a sensor network forms a single-hop network, with every sensor node being able to directly communicate with every other node.

as beacons for other nodes to infer their location; some nodes may act as gateways to long-range data communication networks (e.g., GSM networks, satellite networks, or the Internet).

The degree of heterogeneity in a sensor network is an important factor since it affects the complexity of the software executed on the sensor nodes and the management of the whole system.

Classes: homogeneous vs. heterogeneous.

Communication Modality

For wireless communication among sensor nodes, a number of communication modalities can be used such as radio, diffuse light, laser, inductive and capacitive coupling, or even sound.

Perhaps the most common modality is radio waves, since these do not require a free line of sight, and communication over medium ranges can be implemented with relatively low power consumption and relatively small antennas (a few centimeters in the common sub-gigahertz frequency bands). Using light beams for communication requires a free line of sight and may interfere with ambient light and daylight, but allows for much smaller and more energy-efficient transceivers than does radio communication. Smart Dust [4], for example, uses laser beams for communication. Inductive and capacitive coupling only works over small distances, but may be used to power a sensor node. Most passive radio frequency identification (RFID) systems use inductive coupling, for example. Sound or ultrasound is typically used for communication under water or to measure distances based on time-of-flight measurements. Sometimes, multiple modalities are used by a single sensor network system.

The communication modality used obviously influences the design of medium access and communication protocols, but also affects other properties that are relevant to the application.

Classes: radio vs. light vs. inductive vs. capacitive vs. sound.

Infrastructure

The various communication modalities can be used in different ways to construct an actual communication network. Two common forms are so-called infrastructure-based networks on one hand and ad hoc networks on the other hand. In infrastructure-based networks, sensor nodes can only directly communicate with so-called base station devices. Communication between sensor nodes is relayed via the base station. If there are multiple base stations, these have to be able to communicate with each other. The number of base stations depends on the communication range and the area covered by the sensor nodes. Mobile phone networks and Smart Dust [4] are examples of this type of network.

In ad hoc networks, nodes can directly communicate with each other without an infrastructure. Nodes may act as routers, forwarding messages over multiple hops on behalf of other nodes.

Since the deployment of an infrastructure is a costly process, and the installation of an infrastructure may often not be feasible, ad hoc networks are preferred for many applications. However, if an infrastructure is already available anyway (e.g., the GSM network), it might also be used for certain sensor network applications.

Combinations of ad hoc and infrastructure-based networks are sometimes used, where clusters of sensor nodes are interconnected by an infrastructure-based wide area network.

Note that the above arguments not only apply to communication, but also to other infrastructures, such as localization or time synchronization (e.g., GPS satellites).

Classes: infrastructure vs. ad hoc.

Network Topology

One important property of a sensor network is its diameter, that is, the maximum number of hops between any two nodes in the network. In its simplest form, a sensor network forms a single-hop network, with every sensor node able to directly communicate with every other node. An infrastructure-based network with a single base station forms a star network with a diameter of two. A multihop network may form an arbitrary graph, but often an overlay network with a simpler structure is constructed such as a tree or a set of connected stars.

The topology affects many network characteristics such as latency, robustness, and capacity. The complexity of data routing and processing also depends on the topology.

Classes: single-hop vs. star vs. networked stars vs. tree vs. graph.

Coverage

The effective range of the sensors attached to a sensor node defines the coverage area of a sensor node. Network coverage measures the degree of coverage of the area of interest by sensor nodes. With sparse coverage, only parts of the area of interest are covered by the sensor nodes. With dense coverage, the area of interest is completely (or almost completely) covered by sensors. With redundant coverage, multiple sensors cover the same physical location. The actual degree of coverage is mainly determined by the observation accuracy and redundancy required. Coverage may vary across the network. For example, nodes may be deployed more densely at interesting physical locations.

The degree of coverage also influences information processing algorithms. High coverage is key to robust systems and may be exploited to extend the network lifetime by switching redundant nodes to power-saving sleep modes.

Classes: sparse vs. dense vs. redundant.

Connectivity

The communication ranges and physical locations of individual sensor nodes define the connectivity of a network. If there is always a network connection (possibly over multiple hops) between any two nodes, the network is said to be connected. Connectivity is intermittent if the network may be occasionally partitioned. If nodes are isolated most of the time and enter the communication range of other nodes only occasionally, we say that communication is sporadic. Note that despite the existence of partitions, messages may be transported across partitions by mobile nodes.

Connectivity mainly influences the design of communication protocols and methods of data gathering.

Classes: connected vs. intermittent vs. sporadic.

Network Size

The number of nodes participating in a sensor network is mainly determined by requirements relating to network connectivity and coverage, and by the size of the area of interest. The network size may vary from a few nodes to thousands of sensor nodes or even more. The network size determines the scalability requirements with regard to protocols and algorithms.

Lifetime

Depending on the application, the required lifetime of a sensor network may range from some hours to several years. The necessary lifetime has a high impact on the required degree of energy efficiency and robustness of the nodes.

Other QoS Requirements

Depending on the application, a sensor network must support certain quality-of-service (QoS) aspects such as real-time constraints (e.g., a physical event must be reported within a certain period of time), robustness (i.e., the network should remain operational even if certain well defined failures occur), tamper-resistance (i.e., the network should remain operational even when subject to deliberate attacks), eavesdropping resistance (i.e., external entities cannot eavesdrop on data traffic), and unobtrusiveness or stealth (i.e., the presence of the network must be hard to detect). These requirements may impact other dimensions of the design space such as coverage and resources.

Applications

In this section we justify our design space model by locating a number of applications at different points in the design space. For this, we have selected concrete applications that are well documented and have advanced beyond a mere vision. Some of the applications listed are field experiments, some are commercial products, and some are advanced research projects that use sensor networks as a tool. For classification, we have used the reported parameters that were actually used in practical settings and have deliberately refrained from speculation as to what else could have been done.

Note that there are usually different technical solutions for a single application, which means that the concrete projects described below are only examples drawn from a whole set of possible solutions. However, these examples reflect what was technically possible and desirable at the time the projects were set up. Therefore, we have decided to base our discussion on these concrete examples rather than speculating about the inherent characteristics of a certain type of application. Table 1 classifies the sample applications according to the dimensions of the design space described in the previous section.

Bird Observation on Great Duck Island

A wireless sensor network (WSN) is being used to observe the breeding behavior of a small bird called Leach's Storm Petrel [5] on Great Duck Island, Maine, United States. These birds are easily disturbed by the presence of humans, so a WSN seems an appropriate way of better understanding their behavior. The breeding season lasts for seven months from April to October. Biologists are interested in the usage pattern of their nesting burrows, changes in environmental conditions outside and inside the burrows during the breeding season, variations among breeding sites, and the parameters of preferred breeding sites.

Sensor nodes are installed inside the burrows and on the surface. Nodes can measure humidity, pressure, temperature, and ambient light level. Burrow nodes are equipped with infrared sensors to detect the presence of the birds. The burrows occur in clusters, and the sensor nodes form a multihop ad hoc network. Each network cluster contains a sensor node with a long-range directional antenna that connects the cluster to a central base station computer. The base station computer is connected to a database backend system via a satellite link. Sensor nodes sample their sensors about once a minute and send their readings directly to the database backend system.

ZebraNet

A WSN is being used to observe the behavior of wild animals within a spacious habitat (e.g., wild horses, zebras, and lions) [6] at the Mpala Research Center in Kenya. Of particular interest is the behavior of individual animals (e.g., activity patterns of grazing, graze-walking, and fast moving), interactions within a species, interactions among different species (e.g., grouping behavior and group structure), and the impact of human development on the species. The observation period is scheduled to last a year or more. The observation area may be as large as hundreds or even thousands of square kilometers.

Animals are equipped with sensor nodes. An integrated GPS receiver is used to obtain estimates of their position and speed of movement. Light sensors are used to give an indication of the current environment. Further sensors (head up or down, body temperature, ambient temperature) are planned for the future. Each node logs readings from its sensors every 3 min. Whenever a node enters the communication range of another node, the sensor readings and identities of the sensor nodes are exchanged (i.e., data is flooded across network partitions). At regular intervals a mobile base station (e.g., a car or plane) moves through the observation area and collects the recorded data from the animals it passes.

Glacier Monitoring

A sensor network is being used to monitor sub-glacier environments at Briksdalsbreen, Norway, with the overall goal of better understanding the Earth's climate [7]. Of particular interest are displacements and the dynamics inside the glacier. A lengthy observation period of months to years is required.

Sensor nodes are deployed in drill holes at different depths in the glacier ice and in the till beneath the glacier. Sensor nodes are equipped with pressure and temperature sensors and a tilt sensor for measuring the orientation of the node. Sensor nodes communicate with a base station deployed on top of the glacier. The base station measures supra-glacial displacements using differential GPS and transmits the data collected via GSM. Nodes are not recoverable after deployment. Radio communication through ice and water is a major problem.

Depending on the application, the required lifetime of a sensor network may range from some hours to several years. The necessary lifetime has a high impact on the required degree of energy efficiency and robustness of the nodes.

	Deployment	Mobility	Resources	Cost	Energy	Heterogeneity	Modality
Great Duck	Manual, one-time	Immobile	Matchbox	~200 USD	Battery, solar	Weather stations, burrow nodes, gateways	Radio
ZebraNet	Manual, one-time	All, continuous, passive	Matchbox	—	Battery	Nodes, gateway	Radio
Glacier	Manual, one-time	All, continuous, passive	Brick	—	Battery	Nodes, base station	Radio
Herding	Manual, one-time	All, continuous, passive	Brick	~1000 USD	Battery	Homogeneous	Radio
Bathymetry	Manual, one-time	All, occasional, passive	Brick	—	Battery	Homogeneous	Radio
Ocean	Random, iterative	All, continuous, passive	Brick	~15000 USD	Battery	Homogeneous	Radio
Grape	Manual, one-time	Immobile	Matchbox	~200 USD	Battery	Sensors, gateway, base station	Radio
Cold Chain	Manual, iterative	Partly (sensors), occasional, passive	Matchbox (sensors), brick (relays)	—	Battery	Sensors, relays, access boxes, warehouse	Radio
Avalanche	Manual, one-time	All, continuous, passive	Matchbox	—	Battery	Homogeneous	Radio
Vital Sign	Manual	All, continuous, passive	Matchbox	—	Battery	Medical sensors, patient identifier, display device, setup pen	Radio, IR light (for setup pen)
Power	Manual, iterative	Immobile	Matchbox	—	Power grid	Sensor nodes, transceivers, central unit	Radio (sensor unidirectional)
Assembly	Manual, one-time	All, occasional, passive	Matchbox	~100 Euro	Battery	Different sensors	Radio
Tracking	Random (thrown from aircraft)	All, occasional, passive	Matchbox	~ 200 USD	Battery	Homogeneous	Radio
Mines	Manual	All, occasional, active	Brick	—	Battery	Homogeneous	Radio, ultrasound (for localization)
Sniper	Manual	Immobile	Matchbox with FPGA	~200 USD	Battery	Homogeneous	Radio

Table 1. *Classification of the sample applications according to the design space (continued on next page).*

Cattle Herding

A WSN is being used to implement virtual fences, with an acoustic stimulus being given to animals that cross a virtual fence line [8]. Movement data from the cows controls the virtual fence algorithm that dynamically shifts fence lines. Such a system can reduce the overheads of installing and moving physical fences, and improve the usage of feedlots.

For the first experiment, each sensor node consists of a PDA with a GPS receiver, a wireless LAN (WLAN) card, and a loudspeaker for providing acoustic stimuli to the cattle as they approach a fence. These devices are attached to the neck of the cows. The nodes form a multihop ad hoc network, forwarding movement data to a base station (a laptop computer). The base station transmits fence coordinates to the nodes.

Bathymetry

A sensor network is being used to monitor the impact on the surrounding environment of a wind farm off the coast of England [9]. Of particular interest here is the influence on the structure of the ocean bed (e.g., formation of sand banks) and on tidal activity.

Sensor nodes are deployed on the ocean bed by dropping them from a ship at selected positions, their location being fixed on the ocean bed by an anchor. Each sensor node is connected via a cable to a buoy on the ocean surface that contains the radio equipment and GPS, since radio communication under water is virtually impossible. The sensor nodes are able to measure pressure, temperature, conductivity, current, and turbidity, and form a self-organized ad hoc network.

	Infrastructure	Topology	Coverage	Connectivity	Size	Lifetime	QoS
Great Duck	Base station, gateways	Star of clusters	Dense (every burrow)	Connected	Tens–hundreds (~100 deployed)	7 months (breeding period)	—
ZebraNet	Base station, GPS	Graph	Dense (every animal)	Sporadic	Tens–hundreds	One year	—
Glacier	Base station, GPS, GSM	Star	Sparse	Connected	Tens–hundreds (9 deployed)	Several months	—
Herding	Base station, GPS	Graph	Dense (every cow)	Intermittent	Up to hundreds (10 deployed)	Days to weeks	—
Bathymetry	GPS	Graph	Sparse (0.5–1 km apart)	Connected	Up to hundreds (6 deployed, 50 planned)	Several months	—
Ocean	Satellite	Star	Sparse	Intermittent	1300 deployed, 3000 planned	4–5 years	—
Grape	Base station	Tree (two-tiered multihop)	Sparse (20 m apart)	Connected	Up to hundreds (65 deployed)	Several months (growth period)	—
Cold Chain	Relays, access boxes	Tree (three-tiered multi-hop)	Sparse	Intermittent	Up to hundreds (55 sensors, 4 relays deployed)	Years	—
Avalanche	Rescuer's PDA	Star	Dense (every person)	Connected	Tens–hundreds (number of victims)	Days (duration of a hike)	Dependability
Vital Sign	Ad hoc	Single-hop	Dense	Connected	Tens	Days to months (hospital stay)	Real-time, dependability, eavesdropping resistance
Power	Transceivers	Layered multihop	Sparse (selected outlets)	Connected	Tens–hundreds	Years (building lifecycle)	—
Assembly	Ad hoc	Star	Sparse	Connected	Tens	Hours (duration of assembly)	—
Tracking	UAV	Graph	Sparse	Intermittent (UAV)	Tens–thousands (5 deployed)	Weeks–years (conflict duration)	Stealth, tamper resistance, real-time
Mines	Ad hoc	Graph	Dense	Connected	Up to hundreds (20 deployed)	Months–years	Tamper resistance
Sniper	Ad hoc	Graph	Redundant (multiple nodes recognize shot)	Connected	Up to hundreds (60 deployed)	Months–years	Real-time

Table 1. *Classification of the sample applications according to the design space (continued from previous page).*

Ocean Water Monitoring

The ARGO project [10] is using a sensor network to observe the temperature, salinity, and current profile of the upper ocean. The goal is a quantitative description of the state of the upper ocean and the patterns of ocean climate variability, including heat and freshwater storage and transport. Intended coverage is global, and observation is planned to last for several years. Measurement data is available almost in real time.

The project uses free-drifting profiling sensor nodes equipped with temperature and salinity sensors. The nodes are dropped from ships or planes. The nodes cycle to a depth of 2000 m every 10 days. Data collected during these cycles is transmitted to a satellite while nodes are at the surface. The lifetime of the nodes is about four to five years.

Grape Monitoring

A WSN is being used to monitor the conditions that influence plant growth (e.g., temperature, soil moisture, light, and humidity) across a large vineyard in Oregon, United States [11]. The goals include supporting precision harvesting (harvesting an area as soon as the grapes in it are ripe), precision plant care (adapting the water/fertilizer/pesticide supply to the needs of individual plants), frost protection, predicting insect/pest/fungi development, and developing new agricultural models.

In a first version of the system, sensor nodes are

The commercial Securifood system is a WSN for monitoring the temperature compliance of cold chains from production, via distribution centers and stores, to the consumer. Clients receive an early warning of possible breaks in the cold chain.

deployed across a vineyard in a regular grid about 20 m apart. A temperature sensor is connected to each sensor node via a cable in order to minimize false sensor readings due to heat disseminated by the sensor nodes. A laptop computer is connected to the sensor network via a gateway to display and log the temperature distribution across the vineyard. The sensor nodes form a two-tier multihop network, with nodes in the second tier sending data to a node in the first tier. Nodes in the first tier also collect sensor data, but additionally act as data routers.

Cold Chain Management

The commercial Securifood system [12] is a WSN for monitoring the temperature compliance of cold chains from production, via distribution centers and stores, to the consumer. Clients receive an early warning of possible breaks in the cold chain.

The system consists of four major components: sensor nodes, relay units, access boxes, and a warehouse. Sensor nodes are transported with the products and collect temperature data. Relay units collect and store temperature data from sensor nodes — they are more powerful devices with a permanent power supply. Multiple relay units form a multihop ad hoc network. An access box is an even more powerful embedded Linux device that acts as a gateway between the network of relay units and the Internet. There is one access box per production site. An Internet-hosted data warehouse acts as a central server, collecting data from all the access boxes. The data warehouse provides an online image of all the sensor data in the system and acts as a central data repository for applications.

Rescue of Avalanche Victims

A WSN is being used to assist rescue teams in saving people buried in avalanches [13]. The goal is to better locate buried people and to limit overall damage by giving the rescue team additional indications of the state of the victims and to automate the prioritization of victims (e.g., based on heart rate, respiration activity, and level of consciousness).

For this purpose, people at risk (e.g., skiers, snowboarders, and hikers) carry a sensor node equipped with an oximeter (a sensor that measures the oxygen level in blood) that permits heart rate and respiration activity to be measured. Additionally, an oxygen sensor is used to detect air pockets around the victim. Accelerometers are used to derive the orientation of the victim. The rescue team uses a PDA to receive sensory data from buried victims.

Vital Sign Monitoring

Wireless sensors are being used to monitor vital signs of patients in a hospital environment [14]. Compared to conventional approaches, solutions based on wireless sensors are intended to improve monitoring accuracy while also being more convenient for patients.

The system consists of four components: a patient identifier, medical sensors, a display device, and a setup pen. The patient identifier is a special sensor node containing patient data (e.g., name) that is attached to the patient when he or she enters the hospital. Various medical sensors (e.g., electrocardiogram) may be subsequently attached to the patient. Patient data and vital signs may be inspected using a display device. The setup pen is carried by medical personnel to establish and remove associations between the various devices. The pen emits a unique ID via infrared to limit the scope to a single patient. Devices that receive this ID form a body area network.

Power Monitoring

A WSN is being used to monitor power consumption in large and dispersed office buildings [15]. The goal is to detect locations or devices that are consuming a lot of power to provide indications for potential reductions in power consumption.

The system consists of three major components: sensor nodes, transceivers, and a central unit. Sensor nodes are connected to the power grid (at outlets or fuse boxes) to measure power consumption and for their own power supply. Sensor nodes directly transmit sensor readings to transceivers. The transceivers form a multihop network and forward messages to the central unit. The central unit acts as a gateway to the Internet and forwards sensor data to a database system.

Parts Assembly

A WSN is being used to assist people during the assembly of complex composite objects such as do-it-yourself furniture [16]. This saves users from having to study and understand complex instruction manuals, and prevents them from making mistakes.

The furniture parts and tools are equipped with sensor nodes. These nodes are equipped with a variety of different sensors: force sensors (for joints), gyroscope (for screwdrivers), and accelerometers (for hammers). The sensor nodes form an ad hoc network for detecting certain actions and sequences thereof, and give visual feedback to the user via LEDs integrated into the furniture parts.

Tracking Military Vehicles

A WSN is being used to track the path of military vehicles (e.g., tanks) [17]. The sensor network should be unnoticeable and difficult to destroy. Tracking results should be reported within given deadlines.

Sensor nodes are deployed from an unmanned aerial vehicle (UAV). Magnetometer sensors are attached to the nodes in order to detect the proximity of tanks. Nodes collaborate in estimating the path and velocity of a tracked vehicle. Tracking results are transmitted to the UAV.

Self-Healing Mine Field

Anti-tank landmines are being equipped with sensing and communication capabilities to ensure that a particular area remains covered even if the enemy tampers with a mine to create a potential breach lane [18]. If tampering is detected by the mine network, an intact mine hops into the breach using a rocket thruster.

The mines form a multihop ad hoc network and monitor radio link quality to detect failed mines. Nodes also estimate their location and orientation using ultrasonic ranging. When a node failure is detected, one of the mines is selected to relocate itself using one of eight rocket thrusters.

Sniper Localization

A WSN is being used to locate snipers and the trajectory of bullets [19], providing valuable clues for law enforcement. The system consists of sensor nodes that measure the muzzle blast and shockwave using acoustic sensors. The sensor nodes form a multihop ad hoc network. By comparing the time of arrival at distributed sensor nodes, the sniper can be localized with an accuracy of about 1 m, and with a latency of under 2 s. The sensor nodes use a field programmable gate array (FPGA) chip to carry out the complex signal processing functions.

Conclusions

There are several important consequences of the design space as discussed above. Clearly, a single hardware platform will most likely not be sufficient to support the wide range of possible applications. In order to avoid the development of application-specific hardware, it would be desirable, however, to have available a (small) set of platforms with different capabilities that cover the design space. A modular approach, where the individual components of a sensor node can be easily exchanged, might help to partially overcome this difficulty. Principles and tools for selecting suitable hardware components for particular applications would also be desirable.

As far as software is concerned, the situation becomes even more complex. As with hardware, one could try to cover the design space with a (larger) set of different protocols, algorithms, and basic services. However, a system developer would then still be faced with the complexity of the design space, since each application would potentially require the use of software with different interfaces and properties.

In conventional distributed systems, middleware has been introduced to hide such complexity from the software developer by providing programming abstractions that are applicable for a large class of applications. This raises the question of whether appropriate abstractions and middleware concepts can be devised that are applicable for a large portion of the sensor network design space. This is not an easy task, since some of the design space dimensions (e.g., network connectivity) are very hard to hide from the system developer. Moreover, exposing certain application characteristics to the system and vice versa is a key approach for achieving energy and resource efficiency in sensor networks. Even if the provision of abstraction layers is conceptually possible, it would often introduce significant resource overheads, which is problematic in highly resource-constrained sensor networks.

At the workshop mentioned above, some possible directions were discussed for providing general abstractions despite these difficulties. One approach is the definition of common service interfaces independent of their actual implementation. The interfaces would, however, contain methods for exposing application characteristics to the system and vice versa. Different points in the design space would then require different implementations of these interfaces. A modular software architecture would then be needed, together with tools that would semi-automatically select the implementations that best fit the application and hardware requirements. One possible approach here is the provision of a minimal fixed core functionality that would be dynamically extended with appropriate software modules. We acknowledge that all this is somewhat speculative. However, research into software support for WSNs is still at an early stage, and significant advances will be required to approach the goal of easy and consistent programmability, testing, and deployment of applications across the design space.

In addition to these more technical issues, the design space we advocate can hopefully bring more clarity to the often somewhat diffuse discussions about the typical or right characteristics and requirements of wireless sensor networks.

Research into software support for WSNs is still at an early stage, and significant advances will be required to approach the goal of easy and consistent programmability, testing, and deployment of applications across the design space.

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