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Introduction to Wireless Sensor Networks

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Wireless Sensor Networks have gained a lot of attention lately. Due to technological advances, building small-sized, energy-efficient reliable devices, capable of communicating with each other and organizing themselves in ad hoc networks have become possible. These devices have brought a new perspective to the world of computers as we know it: they can be embedded into the environment in such a way that the user is unaware of them. There is no need for reconfiguration and maintenance as the network organizes itself to inform the users of the most relevant events detected or to assist them in their activity.

This chapter will give a brief overview of the whole area, by introducing the wireless sensor networks concepts to the reader. Then, a number of applications as well as possible typical scenarios will be presented in order to better understand the field of application of this new emerging technology. Up to this moment, several main areas of applications have been identified. New areas of applications are still to be discovered as the research and products grow more mature.

Wireless sensor networks bring lots of challenges and often contradictory demands from the design point of view. The last part of the chapter will be dedicated to highlighting the main directions of research involved in this field. It will serve as a brief introduction to the problems to be described in the following chapters of the book.

31.1 The Third Era of Computing

Things are changing continuously in the world of computers. Everything started with the mainframe era: some 30 years ago, these huge devices were widely deployed, for example, within universities.

Lots of users made use of a single mainframe computer which they had to share among themselves. The computation power came together with a high cost and a huge machine requiring a lot of maintenance.

Technology advanced as it was predicted by Moore's Law and we stepped into the second era of computers. It is a period that is still present today, but which is slowly approaching its final part. It is the era of the personal computers, cheaper and smaller, and increasingly affordable. Quite often, the average user has access to and makes use of more than one computer, these machines being present now in almost any home and work place.

But in this familiar environment, things are starting to change and the third era of computing gains more and more terrain each day. Let us take a look at the main trends today. The technology advancements cause the personal computers to become smaller and smaller. The desktop computers tend to be replaced by laptops and other portable devices.

The main factor that is influencing the new transition is the availability of wireless communication technology. People are getting rapidly used to wireless communicating devices due to their independence from fixed machines. The success and availability of the Internet brought even more independence to the user: the data could now be available regardless of the physical location of its owner.

The advancements in technology did not stop here: the processors became small and cheap enough to be found now in almost any familiar device around us, starting with an every-day watch and ending with (almost) any home appliance we own. The new efforts nowadays are to make these devices "talk" to each other and organize themselves into ad hoc networks to accomplish their design goal as fast and reliably as possible.

This is, in fact, the third computer age envisioned two decades ago by Mark Weiser [1]. Several names, such as ubiquitous computing, pervasive computing, ambient intelligence, invisible computing, disappearing computer, etc., were created to indicate different aspects of the new computing age (Mark Weiser himself defined it as "the calm technology, that recedes into the background of our lives").

The ubiquitous computing world brings a reversed view on the usage of computing power: instead of having lots of users gathered around the mainframe computer, now, each user will be using the services of several embedded networks. The user will be in the middle of the whole system, surrounded by an invisible intelligent infrastructure. The original functionality of the objects and application will be enhanced, and a continuous interaction will be present in a large variety of areas of daily life.

31.2 What Are Wireless Sensor Networks?

So what are wireless sensor networks and where is their place in this new environment that starts "growing" around us?

Wireless sensor networks is the generic name under which a broad range of devices hide. Basically, any collection of devices equipped with a processor, having sensing and communication capabilities and being able to organize themselves into a network created in an ad hoc manner falls into this category.

The addition of the wireless communication capabilities to sensors increased their functionality dramatically. Wireless sensor networks bring monitoring capabilities that will forever change the way in which data is collected from the ambient environment. Let us take, for example, the traditional monitoring approach of a remote location for a given phenomenon, such as recording the geological activity, monitoring the chemical or biological properties of a region, or even monitoring the weather at a certain place.

The old approach was the following: rather big and robust devices needed to be built. They should have contained, besides the sensor pack itself, a big power supply and local data storage capabilities. A team of scientists would have to travel together to the destination to be monitored, place these expensive devices at predefined positions and calibrate all the sensors. Then, they would come back after a certain amount of time in order to collect the sensed data. If by misfortune some hardware would fail, then nothing could be done for it, as the information about the phenomenon itself would be lost.

The new approach is to construct inexpensive, small sized, energy-efficient sensing devices. As hundreds, thousands, or even more of these devices will be deployed, the reliability constraints for them will be diminished. No local data storage is needed anymore as they will process locally and then transmit by wireless means the observed characteristic of the phenomenon to one or more access points connected to a computer network. Individual calibration of each sensor node is no longer needed as it can be performed by localized algorithms [2]. The deployment will also be easier, by randomly placing the nodes (e.g., simply throwing them from a plane) onto the monitored region.

Having this example in mind, we can give a general description of a sensor node. The name *sensor node* will be used to describe a tiny device that has a short range wireless communication capability, a small processor and several sensors attached to it. It may be powered by batteries and its main function is to collect data from a phenomenon, collaborate with its neighbors, and forward its observations (preprocessed version of the data or even decisions) to the endpoint if requested. This is possible because its processor additionally contains the code that enables internode communication and setting up, maintenance, and reconfiguration of the wireless network. When referring to wireless communication, we have in mind mainly radio communication (other means such as ultrasound, visible or infrared light, etc., are also being used [3]). A *sensor network* is a network made up of large numbers of sensor nodes. By a large number we understand at this moment hundreds or thousands of nodes but there are no exact limits for the upper bound of the number of sensors deployed.

Wireless sensor networks are one of the most important tools of the third era of computing. They are the simplest intelligent devices around, their main purpose being monitoring the environment surrounding us and alerting us of the main events happening. Based on the observation reported by these instruments, humans and machines can make decisions and act on them.

31.3 Typical Scenarios and Applications

At this moment a large variety of sensors exist. Sensors have been developed to monitor almost every aspect of the ambient world: lighting conditions, temperature, humidity, pressure, the presence or absence of various chemical or biological products, detection of presence and movement, etc. By networking large number of sensors and deploying them inside the phenomenon to be studied we obtain a sensing tool way more powerful than a single sensor is able to do sensing at a superior level.

A first classification of wireless sensor networks can be made based on the complexity of the networks involved [4]:

"Intelligent" warehouse. Each item contained inside the warehouse will have a tag attached, that will be monitored by the sensor nodes embedded into the walls and shelves. Based on the read data, knowledge of the spatial positioning of the sensors, and time information, the sensor network will offer information about the traffic of goods inside the building, create automatic inventories, and even perform long-term correlations between the read data. The need of manual product scanning will thus disappear. In this category we can include the scenario of the modern supermarket, where the selected products of the customers will automatically be identified at the exit of the supermarket. This scenario also has the minimum complexity. The sensor nodes are placed at fixed positions, in a more or less random manner. The deployment area is easily accessible and some infrastructure (e.g., power supplies and computers) already exists. At the same time, the nodes are operating in a "safe" environment meaning that there are no major external factors that can influence or destroy them.

Environmental monitoring. This is the widest area of application envisioned up to now. A particular application in this category is disaster monitoring. The sensor nodes deployed in the affected areas will help humans estimate the effects of the disaster, build maps of the safe areas, and direct the human actions toward the affected regions. A large number of applications in this category address monitoring of the wild life. This scenario has an increased complexity. The area of deployment is no longer accessible in an easy manner and no longer safe for the sensor nodes. There is hardly any infrastructure present, nodes have to be scattered around in a random manner and the network might contain moving nodes. Also a larger number of nodes will have to be deployed.

Very-large-scale sensor networks applications. The scenario of a large city where all the cars have integrated sensors. These sensor nodes will communicate with each other collecting information about the traffic, routes, and special traffic conditions. On one hand, new information will be available to the driver of each car. On the other hand, a global view of the whole picture will also be available. The two main constraints that characterize this scenario are the large number of nodes and their high mobility. The algorithms employed will have to scale well and deal with a network with a continuously changing topology.

On the other hand, the authors of Reference 5 present a classification of sensor networks based on their area of application. It takes into consideration only the military, environment, health, home, and other commercial areas and can be extended with additional categories, such as space exploration, chemical processing, and disaster relief.

Military applications. Factors such as rapid deployment, self-organization, and increased fault tolerance make wireless sensor networks a very good candidate for usage in the military field. They are suited for deployment in battlefield scenarios due to the large size of the network and the automatic self-reconfiguration at the moment of destruction/unavailability of some sensor nodes [6]. Typical applications are: the monitoring of friendly forces, equipment, and ammunition; battlefield surveillance; reconnaissance of opposing forces and terrain, targeting, and battle damage assessment; and nuclear, biological, and chemical attack detection and reconnaissance. A large number of projects have already been sponsored by The Defense Advanced Research Projects Agency (DARPA) [7].

Environmental applications. Several aspects of the wildlife are being studied with the help of sensor networks. Existing applications include the following: monitoring the presence and the movement of birds, animals, and even insects; agricultural related projects observing the conditions of crops and livestock; environmental monitoring of soil, water, and atmosphere contexts and pollution studies; etc. Other particular examples include forest fire monitoring, biocomplexity mapping of the environment, and flood detection. Ongoing projects at this moment include the monitoring of birds on Great Duck Island [8], the zebras in Kenya [9], or the redwoods in California [10]. The number of these applications is continuously increasing as the first deployed sensor network show the benefits of easy remote monitoring.

Healthcare applications. An increasing interest is being shown to the elder population [11]. Sensor networks can help in several areas of the healthcare field. The monitoring can take place both at home and in hospitals. At home, patients can be under permanent monitoring and the sensor networks will trigger alerts whenever there is a change in the patient's state. Systems that can detect their movement behavior at home, detect any fall, or remind them to take their prescriptions are being studied. Also inside hospitals, sensor networks can be used in order to track the position of doctors and patients (their status or even errors in the medication), expensive hardware, etc. [12].

Home applications. The home is the perfect application domain for the pervasive computing field. Imagine all the electronic appliances forming a network and cooperating together to fulfill the needs of the inhabitants [13]. They will have to identify each user correctly, remember their preferences and their habits, and at the same time, monitor the entire house for unexpected events. The sensor networks also have an important role here, being the "eyes and the ears" that will trigger the actuator systems.

Other commercial applications. This category includes all the other commercial applications envisioned or already built that do not fit in the previous categories. Basically they range from simple systems as environmental monitoring within an office to more complex applications, such as managing inventory control and vehicle tracking and detection. Other examples include incorporating sensors into toys and thus detecting the position of the children in "smart" kindergartens [14]; monitoring the material fatigue and the tensions inside the walls of a building, etc.

The number of research projects dedicated to wireless sensor networks has increased dramatically over the last years. A lot of effort has been invested in studying all possible aspects of wireless sensor networks.

TABLE 31.1 List of Sensor Networks Related Research Projects

Project name	Research area
CoSense [15]	Collaborative sensemaking (target recognition, condition monitoring)
EYES [16]	Self-organizing, energy-efficient sensor networks
PicoRadio [17]	Develop low cost, energy-efficient transceivers
SensoNet [18]	Protocols for sensor networks
Smart Dust [19]	Cubic millimeter sensor nodes
TinyDB [20]	Query processing system
WINS [21]	Distributed network access to sensors, controls, and processors

TABLE 31.2 Current Sensor Networks Companies List

Company name	Headquarters location	HTTP address
Ambient systems	The Netherlands	http://www.ambient-systems.net
CrossBow	San Jose, CA	http://www.xbow.com
Dust networks	Berkeley, CA	http://dust-inc.com
Ember	Boston, MA	http://www.ember.com
Millennial net	Cambridge, MA	http://www.millennial.net
Sensoria corporation	San Diego, CA	http://www.sensoria.com
Xsilogy	San Diego, CA	http://www.xsilogy.com

Please refer to Table 31.1 for a few examples. Also, a number of companies were created, most of them start-ups from the universities that perform research in the field. Some of the names in the field, valid at the date of writing this document, are listed in Table 31.2.

31.4 Design Challenges

When designing a wireless sensor network one faces, on one hand, the simplicity of the underlying hardware and, on the other hand, the requirements that have to be met. In order to satisfy them, new strategies and new sets of protocols have to be developed [22–24]. In the following paragraphs we will address the main challenges that are present in the wireless sensor network field. The research directions involved and the open questions that still need to be answered will be presented as well.

To begin with, a high-level description of the current goals for the sensor networks can be synthesized as:

Long life. The sensor node should be able to "live" as long as possible using its own batteries. This constraint can be translated to a power consumption $<100\ \mu$W. The condition arises from the assumption that the sensor nodes will be deployed in a harsh environment where maintenance is either impossible or has a prohibitively high price. It makes sense to maximize the battery lifetime (unless the sensor nodes use some form of energy scavenging). The targeted lifetime of a node powered by two AA batteries is a couple of years. This goal can be achieved only by applying a strict energy policy that will make use of power-saving modes and dynamic voltage scaling techniques.

Small size. The size of the device should be <1 mm^3. This constraint gave the sensor nodes the name of *smart dust*, a name that gives a very intuitive idea about the final design. Recently, the processor, the radio were integrated in a chip having a size of $\sim$1 mm^3. What is left is the antenna, the sensors themselves, and the battery. Advances are required in each of these three fields in order to be able to meet this design constraint.

Inexpensive. The third high-level design constraint is about the price of these devices. In order to encourage large-scale deployment, this technology must be really cheap, meaning that the targeted prices are in the range of a couple of cents.

31.4.1 Locally Available Resources

Wireless sensor networks consist of thousands of devices working together. Their small size comes also with the disadvantage of very limited resource availability (limited processing power, low-rate unreliable wireless communication, small memory footprint, and low energy). This raises the issue of designing a new set of protocols across the whole system.

Energy is of special importance and can by far be considered the most important design constraint. The sensor nodes will be mainly powered by batteries. In most of the scenarios, due to the environment where they will be deployed, it will be impossible to have a human change their batteries. In some designs, energy-scavenging techniques will also be employed. Still, the amount of energy available to the nodes can be considered limited and this is why the nodes will have to employ energy-efficient algorithms to maximize their lifetime.

By taking a look at the characteristics of the sensor nodes, we notice that the energy is spent for three main functions: environment sensing, wireless communication, and local processing. Each of these three components will have to be optimized in order to obtain minimum energy consumption. For sensing of the environment component, the most energy-efficient available sensors have to be used. From this point of view, we can regard this component as a function of a specific application and a given sensor technology.

The energy needed for transmitting data over the wireless channel dominates by far the energy consumption inside a sensor node. More than that, it was previously shown that it is more efficient to use a short-range multihop transmission scheme than sending data over large distances [5]. A new strategy characteristic to the sensor networks was developed based on a trade-off between the last two components and it is in fact, one of the main characteristics of the sensor networks (see e.g., techniques developed in References 25 and 26). Instead of blindly routing packets through the network, the sensor nodes will act based on the content of the packet [27].

Let us suppose that a certain event took place. All nodes that sensed it will characterize the event with some piece of data that needs to be sent to the interested nodes. There will be many similar data packets, or at least, some redundancy will exist in the packets to be forwarded. In order to reduce the traffic, each node on the communication path will examine the contents of the packet it has to forward. Then it will aggregate all the data related to a particular event into one single packet, eliminating the redundant information. The reduction of traffic by using this mechanism is substantial. Another consequence of this mechanism is that the user will not receive any raw data, but only high-level characterizations of the events. This makes us think of the sensor network as a self-contained tool, a distributed network that collects and processes information.

From an algorithmic point of view, the local strategies employed by sensor nodes have as a global goal to extend the overall lifetime of the network. The notion of lifetime of the network usually hides one of the following interpretations: one can refer to it as the time passed since power on and a particular event, such as the energy depletion of the first node or of 30% of the nodes, or even the moment when the network is splitted in several subnetworks. No matter which of these concepts will be used, the nodes will choose to participate in the collaborative protocols following a strategy that will maximize the overall network lifetime.

To be able to meet the goal of prolonged lifetime, each sensor node should:

- Spend all the idle time in a deep power down mode, thus using an insignificant amount of energy.
- When active, employ scheduling schemes that take into consideration voltage and frequency scaling.

It is interesting to note at the same time, the contradictory wireless industry trends and the requirements for the wireless sensor nodes. The industry focuses at the moment in acquiring more bits/sec/Hz while the sensor nodes need more bits/euro/nJ. From the transmission range point of view, the sensor nodes need only limited transmission range to be able to use an optimal calculated energy consumption, while the industry is interested in delivering higher transmission ranges for the radios. Nevertheless, the radios designed nowadays tend to be as reliable as possible, while a wireless sensor network is based on the assumption that failures are regarded as a regular event.

Energy is not the only resource the sensor nodes have to worry about. The processing power and memory are also limited. Large local data storages cannot be employed, so strategies need to be developed in order to store the most important data in a distributed fashion and to report the important events to the outside world. A feature that helps dealing with these issues is the heterogeneity of the network. There might be several types of devices deployed. Resource poor nodes will be able to ask more powerful nodes to perform complicated computations. At the same time, several nodes could associate themselves in order to perform the computations in a distributed fashion.

Bandwidth is also a constraint when dealing with sensor networks. The low-power communication devices used (most of the time radio transceivers) can only work in simplex mode. They offer low data rates due also to the fact that they are functioning in the free unlicensed bands where traffic is strictly regulated.

31.4.2 Diversity and Dynamics

As we already suggested, there may be several kinds of sensor nodes present inside a single sensor network. We could talk of heterogeneous sensor nodes from the point of view of hardware and software. From the point of view of hardware, it seems reasonable to assume that the number of a certain kind of devices will be in an inversely proportional relationship to the capabilities offered. We can assist to a tiered architecture design, where the resource poor nodes will ask more powerful or specialized nodes to make more accurate measurements of a certain detected phenomenon, to perform resource intensive operations or even to help in transmitting data at a higher distance.

Diversity can also refer to sensing several parameters and then combining them in a single decision, or in other words to perform data-fusion. We are talking about assembling together information from different kinds of sensors, such as light, temperature, sound, smoke, etc., to detect, for example, if a fire has started.

Sensor nodes will be deployed in the real world, most probably in harsh environments. This puts them in contact with an environment that is dynamic in many senses and has a big influence on the algorithms that the sensor nodes should execute. First of all, the nodes will be deployed in a random fashion in the environment and in some cases, some of them will be mobile. Second, the nodes will be subject to failures at random times and they will also be allowed to change their transmission range to better suit their energy budget. This leads to the full picture of a network topology in a continuous change. The algorithms for the wireless sensor networks have as one of their characteristic the fact that they do not require a predefined well-known topology.

One more consequence of the real-world deployment is that there will be many factors influencing the sensors in contact with the phenomenon. Individual calibration of each sensor node will not be feasible and probably will not help much as the external conditions will be in a continuous change. The sensor network will calibrate itself as a reply to the changes in the environment conditions. More than this, the network will be capable of self-configuration and self-maintenance.

Another issue we need to talk about is the dynamic nature of the wireless communication medium. Wireless links between nodes can periodically appear or disappear due to the particular position of each node. Bidirectional links will coexist with unidirectional ones and this is a fact that the algorithms for wireless sensor networks need to consider.

31.4.3 Needed Algorithms

For a sensor network to work as a whole, some building blocks need to be developed and deployed in the vast majority of applications. Basically, they are: a localization mechanism, a time synchronization mechanism, and some sort of distributed signal processing. A simple justification can be that data hardly has any meaning if some position and time values are not available with it. Full, complex signal processing done separately at each node will not be feasible due to the resource constraints.

The self-localization of sensor nodes gained a lot of attention lately [28–31]. It came as a response to the fact that global positioning systems are not a solution due to high cost (in terms of money and resources) and it is not available or provides imprecise positioning information in special environments, such as indoors, etc. Informations, such as connectivity, distance estimation based on radio signal strength, sound intensity, time of flight, angle of arrival, etc., were used with success in determining the position of each node within degrees of accuracy using only localized computation.

The position information once obtained was not only used for characterizing the data, but also in designing the networking protocols, for example, leading to more efficient routing schemes based on the estimated position of the nodes [32].

The second important building block is the timing and synchronization block. Nodes will be allowed to function in a sleep mode for long periods of time, so periodic waking up intervals need to be computed within a certain precision. However, the notion of local time and synchronization with the neighbors is needed for the communication protocols to perform well. Light-weight algorithms have been developed that allow fast synchronization between neighboring nodes using a limited number of messages. Loose synchronization will be used, meaning that each pair of neighbor nodes are synchronized within a certain bound, while nodes situated multiple hops away might not be synchronized at all.

Global timing notion might not be needed at all in most of the applications. Due to the fact that many applications measure natural phenomenon, such as temperature, where delays up to the order of seconds can be tolerated, the trade-off between latency and energy is preferred.

The last important block is the signal processing unit. A new class of algorithms has to be developed due to the distributed nature of wireless sensor networks. In their vast majority the signal processing algorithms are centralized algorithms that require a large computation power and the availability of all the data at the same time. Transmitting all the recorded data to all nodes is impossible in a dense network even from theoretical point of view, not to mention the needed energy for such an operation. The new distributed signal processing algorithms have to take into account the distributed nature of the network, the possible unavailability of data from certain regions due to failures, and the time delays that might be involved.

31.4.4 Dependability

More than any other sort of computer network, the wireless sensor networks are subject to failures. Unavailability of services will be considered "a feature" of these networks or "regular events" rather than some sporadic and highly improbable events. The probability for something going wrong is at least several orders of magnitude higher than in all the other computer networks.

All the algorithms have to employ some form of robustness in front of the failures that might affect them. On the other hand, this comes at the cost of energy, memory, and computation power, so it has to be kept at a minimum. An interesting issue is the one on the system architecture from the protocols point of view. In traditional computer networks, each protocol stack is designed for the worst-case scenario. This scenario hardly ever happens simultaneously for all the layers, and a combination of lower layer protocols could eliminate such a scenario. This leads to lot of redundancy in the sensor node, redundancy that costs important resources. The preferred approach is that of crosslayer designing and studying of the sensor node as a whole object rather than separate building blocks. This opens for a discussion on the topic of what is a right architecture for all the sensor networks and if a solution that fits all the scenarios makes sense at all.

Let us summarize the sources of errors the designer will be facing: nodes will stop functioning starting with even the (rough) deployment phase. The harsh environment will continuously degrade the performances of the nodes making them unavailable as the time passes. Then, the wireless communication medium will be an important factor to disturb the message communication and to affect the links and implicitly the network topology. Even with a perfect environment, collisions will occur due to the imprecise local time estimates and lack of synchronization. Nevertheless, the probabilistic scheduling policies and protocol implementations can be considered as sources of errors.

Another issue that can be addressed as a dependability attribute is the security. The communication channel is opened and cannot be protected. This means that others are able to intercept and to disrupt the transmissions or even to transmit their own data. In addition to accessing private information, a third party could also act as an attacker that wants to disrupt the correct functionality of the network. The security in a sensor network is a hard problem that still needs to be solved. Like almost any other protocol in this sort of network, it has contradictory requirements: the schemes employed should be as light as possible while achieving the best results. The usual protection schemes require too much memory and computation power to be employed (the keys themselves are sometimes too big to fit into the limited available memory).

A real problem is how to control the sensor network itself. The sensor nodes will be too many to be individually accessible to a single user and might also be deployed in an inaccessible environment. By control we understand issues, such as deployment and installation, configuration, calibration and tuning, maintenance, discovery, and reconfiguration. Debugging the code running in the network is completely infeasible, as at any point inside, the user has access only to the high-level aggregated results. The only real debugging and testing can be done with simulators that prove to be invaluable resources in the design and analysis of the sensor networks.

31.5 Conclusions

This chapter was a brief introduction to the new field of wireless sensor networks. It provided a short overview of the main characteristics of this new set of tools that will soon enhance our perception capabilities regarding the ambient world.

The major challenges have been identified, some initial steps have been taken and early prototypes are already working. The following chapters of the book will focus on particular issues, giving more insight into the current state of the art in the field. The research in this area will certainly continue and there may come a time when sensor networks will be deployed all around us and will become regular instruments available to everyone.

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