Current and Future Trends in Sensor Networks: A Survey

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Abstract

Sensor networks consist of a large number of very small nodes that are deployed in some geographical area. The purpose of the network is to sense the environment and report what happens in the area it is deployed in. Sensor networks are used in many applications. In military applications they are used for surveillance and target tracking. In industrial applications, sensor networks are used in monitoring hazardous chemicals. They are also used in monitoring the environment and in early fire warning in forests as well as seismic data collections. Sensor networks face new challenges not known in cellular and ad-hoc wireless networks. In this paper, we report on currents and new trends in sensor networks. We also present some of the challenges and future work in sensor networks.

1 Introduction

Recent advances in VLSI technology, and MEMS (Micro-Electro-Mechanical Systems), as well as in wireless communication technology made it possible to manufacture sensor networks where very large numbers of very small nodes are scattered across some environment in order to sense and report to a central node (user). Sensor networks have many applications. In military, they are used for battlefield surveillance, and object tracking. They are used for seismic data collection and reporting, in addition to factories and warehouses for tracking and monitoring. It is also used in monitoring weakness in building structure or vehicles and airplanes.

Before reviewing sensor networks, we will briefly describe the different types of wireless networks in order to show why sensor networks are different. Wireless networks could be in one of three types, cellular, ad-hoc, or sensor networks.

Cellular networks, best exemplified by the cellular phones consist of mobile devices roaming an area that is divided into cells, with a base station located in every cell in order to serve the devices in that cell. The cell radius ranges from few kilometers (in old networks) to few tens of meters for modern networks. The mobile devices communicate by establishing a connection to the base station; all the base stations are connected to the phone network. The base station acts as a gateway to make and receive phone calls. Traditionally, the cellular networks use circuit-switching mode of operation. However, recently a movement towards packet switching is gaining acceptance.

Ad-hoc networks are networks that are deployed without an existing infrastructure. Mobile devices communicate among themselves by relaying the message over many devices. In this case, each mobile device works as a user and a routing switch at the same time. Usually, ad-hoc networks are networks that are established on a small geographical area in emergency situation. However, there are some proposals for wide area ad-hoc networks [12]. Since both cellular and ad-hoc networks use mobile devices, low power circuits are very important. However, the mobile devices are rechargeable. As we will see shortly, sensor nodes may not be rechargeable, the network works as long as the power supply is working, and then it ceases to work when the power supply is drained off.

Sensor networks consist of very small devices that could be deployed in some areas. Each node is equipped with a sensor in order to perform monitoring, tracking, or surveillance and reports its finding to some central node. Most of the time the batteries in the nodes are not rechargeable, the networks operates as long as the power supply is O.K. when the power is off, the network ceases to operate. Thus low power is of utmost important in sensor networks.

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In this paper, we review and report on current and future trends in wireless sensor networks. We also describe the main challenges in designing sensor networks compared with other type of networks. The next section introduces the sensor networks and outlines the main challenges in its design. Section 3 reports on routing and medium access protocols in sensor networks. Section 4 deals with the communication aspects of wireless networks. Section 5 discusses the different data aggregation techniques in sensor networks. Section 6 discusses the design of the processor and memory in sensor networks. Finally the paper ends with a conclusion.

2 Sensor Networks

Sensor networks consist of very small nodes (sensors) that are deployed in some geographical area. Sensor networks are used to measure temperature or pressure, or it could be used for target tracking or border surveillance. It could be also deployed in factories in order to monitor toxic or hazardous materials. It is also used to measure the weakness in building structures, or in vehicles and airplanes.

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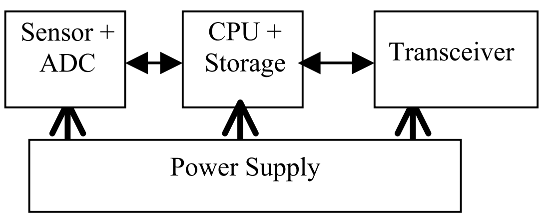

Figure 1: The architecture of a sensor node.

A typical sensor node consists of 4 main parts. Power supply, sensor and analog to digital converter (ADC), processor and storage memory, finally, transceiver to send and receive data as shown in Figure 1

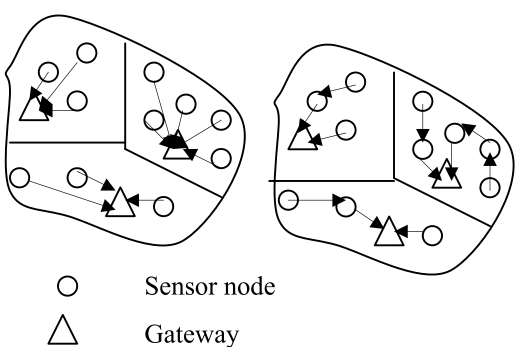

Figure 2: two configurations for sensor networks

The power supply is to power the node. The sensor circuitry can transform physical quantities into an electric signal. The ADC changes the analog signal generated by the sensor into a digital signal and sends it to the processor. The processor can perform simple operations on the received digital signal, and can store it into memory. Finally, the transceiver sends and receives data.

Figure 2 shows two different configurations for wireless sensor networks. In both configurations the nodes are scattered in a geographical are, the area is divided into clusters with a gateway in each cluster. Nodes in each cluster communicate with the gateway. The gateway collects the data and forwards it to the user. In (a) nodes directly communicate with the gateway in its cluster, while in (b) nodes use chaining in order to communicate with the gateway. Using chaining reduces the energy used in transmission, but increases the energy used in processing since each node should receive and forward the message to and from other nodes. Some sensor networks may have more than one level of aggregation.

Typically, sensor networks works in one of two modes. Continuous operation, or query mode. In continuous operation mode, the node is continuously sensing the environment and sending the data (or the processed data) to neighboring or a central node. In query mode, the node is usually powered down waiting for a command from a central node, or neighboring node. When the node receives the commands (usually on the form of report on so and so). It collects data from the sensor, processes it and sends it to the requesting node.

2.1 Design Factors

Because of the way sensor networks are envisioned, it is different than regular wireless networks. The design of sensor networks must concentrate on the challenges that are inherent to sensor networks. The most important design factors are fault tolerance, scalability, cost, and power consumption.

Fault tolerance: In sensors networks, hundreds, and in the extreme, hundreds of thousands of sensors are deployed in a large geographical area. In some cases dropped from airplanes, or deployed using artillery shells. Requiring that every node must work in order for the network to operate is impossible to achieve. The network must have a high level of fault tolerance in order to be of any practical value [11].

Scalability: As we mentioned above, sensor networks may include from tens to hundreds of thousands of sensors. Some times new nodes are added to the network after some nodes power supplies are completely exhausted. That results in a variable number of nodes. The protocols used in the networks must be scalable in order to survive under these circumstances.

Cost: because of the large number of nodes required, as well as the fact that in most networks the nodes are disposable (work until they drain off their power supply, then, then they are disposed of). The cost is a very important design factor for sensor networks. Having a low cost for sensor nodes is a must.

Power consumption: Power consumption is the most important design factor for sensor networks.

Saving power during the operation of the electronic device could be achieved on more than one level. First, on the circuit or VLSI level, power could be saved by using less power for state transition (capacitor charging and discharging) and state maintenance.

On the architecture level, power could be saved by the proper implementation of the processor, the cache, and the instruction set. A study on the StrongARM110 processor revels that the power dissipation in the instruction cache, data cache, and TLB accounts for almost 60% of the power consumption of the processor that means there is a room for power saving by the proper implementation of the memory system.

Also power could be saved at the medium access control, and network level protocol. Minimizing the number of collisions or the path length results also in energy saving. Transmission and reception of radio signal is another candidate for power minimization. Short distance transmission and simple circuitry for modulation/demodulation results in power saving.

2.2 Batteries

Power supply has always been a problem for mobile devices. The gap between the battery power and processor power requirements is widening every year. Recent research studies show that low power design is not the only solution for this problem. The total energy that could be delivered by the battery depends on how the energy is drawn from the battery. In [15] the authors argue that battery driven design is an important concept for electronic devices that depends on batteries.

There are many types of batteries for use in mobile devices. Nickel Cadmium batteries are one of the oldest battery technology. The new Lithium Polymer batteries with their very thin form factor are a promising technology for tomorrow's mobile devices [14]. Also, some batteries may be rechargeable. Rechargeable batteries could substantially increase the lifetime of a network. However it might not be always easy to recharge batteries in sensor networks.

Another important step in the design of low power devices is how to model the battery energy supply? Batteries could be modeled using analytical model in which the battery is modeled as a reservoir of energy that is drained by a rate depends on the load [17]. Batteries also could be modeled as an electric circuit using standard circuit elements. A spice model to represent a battery is presented in [10]. Batteries also modeled using stochastic models [21], and using electrochemical models [16].

3 Routing and MAC Protocols

Routing in sensor networks has some challenges that are not present in general wireless networks. The two main challenges are the varying topology nature of sensor networks, and the low power requirement on sensor networks [9], [13], [20], [22].

In [26], the authors proposed a medium access protocol for ad-hoc wireless sensor networks. They emphasized in their design that the main objective in wireless sensor networks in the power consumption rather than fairness, throughput, or delay, which are the main concern in user-oriented networks. And they proposed a protocol called S-MAC.

In their design, they assumed that the network consists of many small nodes scattered in an ad-hoc fashion in order to collect some information about the environment. The nodes usually are in the idle mode until some event occurs; in this case, they record the event and send messages to other nodes. Other nodes may process the messages before forwarding it to a monitoring station.

Their protocol depends on the RTS/CTS mechanism of the IEEE802.11 to avoid collisions. However in their protocol nodes alternate between listening and sleeping according to a specific *schedule*. Each node either determines its own schedule and broadcasts it, or follows the broadcast schedule of a neighboring node. They implemented their protocol on the UCB Motes [25], using the Atmel AT90LS8535 microcontroller with 8K bytes of programmable flash and 512 bytes of data memory and they showed that their protocol consumes 2-6 times less power than IEEE802.11.

In [2] the authors proposed a power control extension to the IEEE802.11 MAC protocol. They used a concept similar to the power control in CDMA networks. Their simulation shows an improvement in both energy consumption and network throughput.

In [3], the authors investigated the effect of low energy routing on delay-constrained data, they also proposed a new energy-aware constrained routing for sensor networks. In addition, they used multihop routing to minimize transmission energy. The authors also used a weighted fair queuing packet scheduling methodology in order to achieve a soft real time guarantees. The problem of repositioning the base stations for enhancing the network performance is addressed in [27].

Although many research projects in both industry and universities are being pursued. There is a lot of work to be done in the area of wireless networks protocols. Most of the work in sensor networks assumed the 5 layer TCP model which is very popular for wireline and wireless networks. However, there is no indication that this is the best model for sensor networks. This is almost unexplored area and a lot of work needs to be done especially at the application layer level.

4 Communication

Communication between nodes is done using either light, infrared, or radio transmission. Radio transmission is the most widely used communication medium between nodes, with the ISM (Industrial, Scientific, and Medical) band used in most networks. For wireless communication, the energy required to for the signal to travel a distance of d in free space is d^n, where $2 \leq n \leq 4$ and n depends on the environment and is closer to 4 for short (near earth) antennas which is the case for wireless sensor networks.

That shows how important it is for sensor nodes to communicate over short distance. Multihop communication is widely used in sensor networks. Not only it reduces power consumption, but is more immune to shadowing which makes it an attractive solution in sensor networks.

Another factor to consider is the modulation scheme. M-ary scheme uses less bandwidth and higher data rate than binary scheme. However it uses more complex circuitry for the sender and receiver, which result in more power consumption at the transceiver. That requires a very detailed tradeoff between the different modulation schemes in order to increase the network lifetime.

Ultra Wide Band (UWB) [6], or Impulse radio (IR), is another promising technology for wireless sensor networks. Its resistance to multipath makes it a very good candidate especially for indoor wireless networks. The best physical layer implementation for wireless sensor networks is mainly still an open problem. We expect that it will attract a lot of attention in the near future.

5 Data Aggregation

In wireless networks data are collected by the sensors and reported to an end user. There is always the question of where to do the processing of the data. Doing processing locally and sending only the results increases the energy used by the processor and decrease the energy of data transmission. Sending raw data decrease the energy consumed in processing and increases the energy of transmission. Data aggregation and fusion play a very important role in energy saving. Since there are usually a large number of sensors, some of the data may be redundant. Messages routed through the nodes can be combined to reduce the overall traffic in the network, thus improving the performance and reducing the power used in transmitting messages. The problem of determining the optimal selection and location of aggregation points in a general wireless sensor networks is NP-complete. However many attempts were made to find an approximate solution for the aggregation problem.

The authors in [4] studied the problem of maximizing the lifetime of the wireless sensor networks. They introduced exact and approximate algorithms for data aggregation. They performed data aggregation on two levels. First, local aggregators are used to aggregate data received from local sensors, then an optimal set of master aggregators are chosen to select the second level of data aggregation. Their results show that substantial saving in energy could be achieved using their technique.

[23] studied the quality of the aggregated data. They proposed data aggregation algorithms for clustered-based, and chain-based aggregation. They showed that their protocol reduces the total energy in the network without sacrificing the quality of the data collected. The problem of how long to delay messages in every node to improve aggregation is addressed in [24]. The authors in [7] proposed a heuristic in order to construct and maintain an aggregation tree in wireless sensor networks.

6 Processors

Low power processor design has been an active area of research for a long time. For a review of low power design at the circuit and architecture level the reader is referred to [1]. For sensor networks, there are specific challenges with respect to the size of the node (usually does not exceed the size of a matchbox), as well as the node capabilities and cost.

Relatively unexplored area is the use of FPGA to implement sensor nodes. FPGA does provide a great opportunity for cost reduction. However the main problem with FPGA is the lack of control on switching off parts of the array if not needed. The new advances in low power FPGA seems to be a very good opportunity for use in sensor networks nodes.

Some of the promising techniques for low power processor design are: Frequency scaling [19], where the clock frequency driving the system changes according to the system performance and requirements. Low frequency slows down the system, but saves power. Frequency scaling was extensively studied for processor design, but not specifically for sensor nodes.

Battery-aware task scheduling is another promising technology for sensor nodes [18]. In battery-aware task scheduling, the scheduler takes the state of the battery into account when deciding on the scheduling decision in order to prolong the life of the battery.

7 Conclusion

In this paper, we presented some of the challenges in designing wireless sensor networks, as well as the state-of-the-art and future direction in wireless sensor networks. The field of sensor networks is very recent, and a lot of work needs to be done in it in order to mature and become an acceptable technology.

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