Wireless Sensor Networks

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Abstract

Sensor networks consist of a set of sensor nodes, each equipped with one or more sensors, communication subsystems, storage and processing resources, and in some cases actuators. The sensors in a node observe phenomena such as thermal, optic, acoustic, seismic, and acceleration events, while the processing and other components analyze the raw data and formulate answers to specific user requests. Recent advances in technology have paved the way for the design and implementation of new generations of sensor network nodes, packaged in very small and inexpensive form factors with sophisticated computation and wireless communication abilities. Although still at infancy, these new classes of sensor networks, generally referred to as wireless sensor networks (WSN), show great promise and potential with applications ranging in areas that have already been addressed, to domains never before imagined. In this article we provide an overview of this new and exciting field and a brief discussion on the factors pushing the recent flurry of sensor network related research and commercial undertakings. We also provide overview discussions on architectural design characteristics of such networks including physical components, software layers, and higher level services. At each step, we highlight special characteristics of WSNs and discuss why existing approaches and results from wireless communication networks are not necessarily suitable in WSN domains. We conclude by briefly summarizing the state of the art and the future research directions.

Keywords

Wireless, Ad-hoc, Multi-hop, Sensor Networks, Location Discovery, Sensor Coverage, Localized Algorithms.

I. INTRODUCTION

In the last decade, the sustained high pace of technological advances paved the way for the exponential growth of the Internet. We can trace the development of two implementation technologies as prime enablers of this growth: The first was the dramatic reduction in the cost of disks, i.e. massive long-term storage. The second was the huge reduction in the cost of optical communication and its simultaneous capacity increase. More specifically, in the last eleven years, the capacity of a $100 disk increased by a factor of 1200, while during the same period, the bandwidth of optical cable doubled every nine months. The Internet, as we know it today, is an exceptional educational, research, entertainment, and economic resource which enables information to be available at the touch of a mouse. There is a wide consensus that the Internet will continue to grow rapidly both in quantitative and qualitative terms. At the same time, it appears that we are on the brink of the next technological revolution that may have even more profound impact on our lives. This revolution, that will enable any time, anywhere, communication and connection between the physical and computational worlds, is due to the advancement of wireless communication technology and sensors. While in the early 1990's wireless technology was mainly stagnant, in the last six years, it has experienced an exponential growth. Wireless bandwidth in industrial offerings has gone up by a factor of 28 in the last five years alone. On the other hand, recent progress in fabrication of micro-electromechanical systems-based (MEMS) sensors has opened new vistas in terms of cost, reliability, accuracy, and low energy requirements. While most of the MEMS-based sensors are still in the research phase, a boom in government funding in this area has resulted in amazing progress. For this field, in 1991, the total funding was $2 million, in 1995, $35 million, while in 2001 it was estimated to have been $300 million worldwide. With such advancement, there is currently a need for methodologies and technologies that will enable efficient and effective use of wireless embedded sensor network applications. The motivational factors pushing for these applications include the mobility of computational devices, such as cellular phones and personal digital assistants (PDAs), and the ability to embed these devices into the physical world.

Almost all of the modern science and engineering has been built using compound experiment-theory iteration steps. Typically, the experiments have been the expensive and slow components of the iterations. Thus, the existences of flexible yet economic experimentation platforms often result in great conceptual and theoretical breakthroughs. For example, advanced optical and infrared telescopes enabled spectacular progress in the understanding of large scale cosmology theory. Particle accelerators and colliders enabled great progress in the understanding the ultra small world of elementary particles. Furthermore, the progresses in computer science, information theory, and nonparametric statistics have been greatly facilitated by the ability to compile and execute programs quickly on general purpose computers. Sensor networks will enable the same type of progress in better understanding many other sciences, not just by information processing, but also through new connections between the sciences and the physical, chemical, and biological worlds.

Sensor networks consist of a set of sensor nodes, each equipped with one or more sensors, communication subsystems, storage and processing resources, and in some cases actuators. The sensors in a node observe phenomena such as thermal, optic, acoustic, seismic, and acceleration events, while the processing and other components analyze the raw data and formulate answers to specific user requests. The recent advances in technology mentioned above, have paved the way for the design and implementation of new generations of sensor network nodes, packaged in very small and inexpensive form factors with sophisticated computation and wireless communication abilities. Once deployed, sensor nodes begin to observe the environment, communicate with their neighbors (i.e. nodes within communication range), collaboratively process raw sensory inputs, and perform a wide variety of tasks specified by the applications at hand. The key factor that makes wireless sensor networks so unique and promising both in terms of research and economic potentials, is their ability to be deployed in very large scales without the complex pre-planning, architectural engineering, and physical barriers that wired systems have faced in the past. The term "ad-hoc" generally signifies such a deployment scenario where no structure, hierarchy, or network topology is defined a priori. In addition to being ad-hoc, the wireless nature of the communication subsystems that rely on radio frequency (RF), infrared (IR), or other technologies, enable usage and deployment scenarios that were never before possible.

To illustrate the key concepts and a possible application of wireless ad-hoc sensor networks (WASNs), consider the environmental monitoring requirements of large office buildings. Such buildings typically contain hundreds of environmental sensors (such as thermostats) that are wired to central air conditioning and ventilation systems. The significant wiring costs limit the complexity of current environmental controls and their reconfigurability. Furthermore, in highly dynamic corporate environments, cubicle offices may continuously be added, removed, and restructured which makes environmental control rewiring an intractable task. However, replacing the hard-wired monitoring units with inexpensive ad-hoc wireless sensor nodes will easily improve the quality and energy efficiency of the environmental system while allowing unlimited reconfiguration and customization in the future. In addition to the classic temperature sensing, senor nodes with multiple modalities (i.e. equipped with several different types of sensors) can significantly enhance the abilities of such a system. For example, motion or light sensors can detect the presence of people and even adjust the environmental controls using actuators, according to pre-specified user preferences. In many instances, the savings in the initial wiring costs alone may justify the use of such wireless sensor nodes.

Although the environmental monitoring example above is an application of WASNs to a task that has existed for a long time, many new applications have also started to emerge as direct consequences of WASN developments. Such applications range from early forest fire detection and sophisticated earthquake monitoring in dense urban areas, to highly specialized medical diagnostic tasks where tiny sensors may even be ingested or administered into the human body. As mentioned above, personal spaces such as offices and living rooms can be customized to each individual by sensors that detect the presence of a nearby person and command the appropriate actuators to execute actions based on that person's preferences. In essence, WASNs provide the final missing link connecting our physical world to the computational world and the Internet. Although many of these sensor technologies are not new, technological barriers and physical laws governing the energy requirements of performing wireless communications have limited their feasibility in the past. A few highlights and benefits of the newer, more capable sensor nodes are their abilities to:

- Form very large-scale networks (thousands or more nodes);
- Implement sophisticated networking protocols as well as distributed and localized analysis algorithms;
- Reduce the amount of communication required to perform tasks by distributed and/or localized computations;
- Implement complex power saving modes of operation depending on the environment, current tasks, and the state of the network.

In the following sections, we describe the generic components that form a wireless sensor network and highlight the key issues and characteristics that differentiate sensor networks from traditional peer-to-peer and ad-hoc wireless communication networks. Section II lists the architectural and hardware related components while in section III the focus is on higher level services and software issues. Section IV provides a brief overview of the state of the art and the challenges ahead.

II. ARCHITECTURE AND HARDWARE

Similar to classical computer architectures, the main components of the physical architecture of WSN nodes can be classified into four major groups: (a) processing, (b) storage, (c) communication, and (d) sensing and actuation (I/O). The following is a brief summary of the main issues involved and some related topics for each of these components.

A. Processing

Two key constraints for processing components are energy and cost. Essentially all current WSN processors are those used for mass markets. This is in large part due to the advantages of the economies of scale and the availability of comprehensive and mature software development environments for such processors. Since the processing in a node has to address a variety of different tasks, many nodes have several types of processors: microprocessors and/or microcontrollers, low power digital signal processors (DSPs), communication processors, and application specific integrated circuits (ASICs) for certain special tasks. The standard complementary metal oxide semiconductor (CMOS) process will be the technology of choice for sensor node processors at least for the next decade.

B. Storage

Currently, sensor nodes have relatively small storage components. They most often consist of standard dynamic random access memory (DRAM) and relatively large quantities of non-volatile (flash) memory. Since the communication is a dominant component of the overall energy consumption is wireless sensor networks, we expect that the amount of local storage at a node will continue to increase. This expectation is further enforced by the fact that in the last decade, the cost of memory was declining much faster than the cost of processors. We also expect that new technologies, in particular Magnetoresistive Random Access Memory (MRAM), will soon be widely used for this type of storage.

C. Communication

The communication paradigms often associated with the current generations of wireless sensor networks are multi-hop communication. Several current results indicate that multi-hop communications scale very well and can significantly reduce the energy consumption in large sensor networks (1). A number of new projects are currently targeting low power communication. This is an area where it is most difficult to predict how technology will impact future architectures, since commercial wireless communication is a relatively new field. It is very important to note here that in typical low power radios used in WASN communication, listening often requires as much energy as transmitting. This is in sharp contrast to the assumptions made in most previous work in ad-hoc multi-hop networking where sending a message was believed to have been the major consumer of energy. These new constraints indicate that the study of complex power saving modes of operation, such as having multiple different sleep states, will be crucial in this field.

D. Sensors and Actuators

One can envision the sensors as the eyes of the sensor network, and the actuators, as its muscles. Although MEMS technology has been making steady progress in the last four decades, it is obvious that it is still in its early phases where development is mainly sustained by research funding and not yet commercial. However, significant results have already been obtained. A good starting point for learning more about sensor systems is reference (2).

III. SYSTEM SOFTWARE AND APPLICATIONS

As described above, the recent advent of WASNs has required completely new approaches for building system software and optimization algorithms, as well as the adaptation of existing techniques. It is interesting and important to analyze why the already existing distributed algorithm techniques were not directly applicable to WASNs. There are at least five major reasons: *(i)* WASNs are intrinsically related to the physical and geometric world and therefore have very special properties. The uses of local and geographic information for example, play key roles in designing efficient, robust, and scalable sensor networks. *(ii)* Relative communication costs are much higher than they were assumed to be in all previous distributed computing research. Since WASN nodes are severely energy constrained, the cost of communication becomes an extremely important factor in the design of WASN software. *(iii)* Accuracy of physical measurements is intrinsically limited and therefore, there is little advantage on insisting on completely accurate results. *(iv)* Energy consumption is a critical system constraint. *(v)* Data acquisition is naturally distributed and error-prone, implying a strong need for new sensing, computation, and communication models.

The relative communication delay in sensor networks is significantly larger than in traditional computational systems. It is interesting to note that in modern deep submicron (DSM) chip designs, delay on a single system-on-chip will be up to 20 clock cycles. However, even the fastest communication protocols in WASNs will have delays in millions of cycles due to technological and physical limitations as well as system software overhead. Furthermore, communication generally dominates both sensing and computation in terms of energy (currently, image and video sensors are exceptions). Again, it is interesting to draw parallels with DSM designs: In DSM, communication will also dominate power consumption, maybe eventually by as high as a 10:1 ratio with respect to computations. In WASNs, technology trends are much more difficult to predict, yet at least in current and pending technologies, this ratio is much higher, often estimated at 1000:1.

Interestingly, several new hardware and architectural characteristics have also come into play that strongly influence WASN communication costs. For example, we have already mentioned that in many of the current low power radios used in WASN nodes, the power requirements for listening or receiving messages is about the same as when transmitting. This is in sharp contrast to the assumptions made in numerous wireless communication research efforts in the past, where transmitting a message was almost always assumed to have required much more power than listening or receiving a message. Consequently, in order to be truly effective, WASN system software must try to maximize the duration of the times when the communication subsystems can be turned off or placed in sleep modes, thus saving precious reserve energy resources.

In addition to placing nodes in sleep modes to conserve energy, one can expect that fault tolerance and autonomous operation will be essentially mandatory for large scale WASNs, due to wide-scale deployment and relatively high cost of servicing nodes. During the useful lifetime of a typical WASN, it is not unreasonable to expect that at least some nodes will exhaust their energy supply. Even if latency (real-time constraints), energy consumption, and fault tolerance were not an issue, security and privacy issues would very often mandate that only a subset of nodes participate in a specific task. In addition, sensor nodes are often deployed outside strictly controlled environments, communicate using wireless (insecure) media, and hence are highly susceptible to security attacks. This further indicates that expecting all nodes to always be able to sense, communicate, and compute, is not realistic. Moreover, as WASNs evolve into the Internet-like scale and organization and span the whole Earth and beyond, the only realistic possibility for all tasks will be execution in highly localized scenarios. In localized computation models, only a subset of nodes, which are almost always within geographic proximity, collaborate and participate in formulating results to specific application tasks.

The challenges outlined above can be classified into three major categories: *strict-constraints*, *new mode of operations,* and *interface between physical world, computation, and information theory*. The strict-constraint challenges include problems related to the need for low cost, long life, and reliable infrastructures. Low power operation, wireless bandwidth efficiency, reliability, fault tolerance, high availability, error recovery, distributed synchronization, and real-time operation in unpredictable environments are all important factors that influence the design decisions at this step. In this direction, the current key problem is learning how to scale the already available techniques to the next levels of strictness of constraints.

There are two main research direction related to the *new modes of operation* of WSNs due to their distributed and multi-hop natures: *localized algorithms* and *autonomous continuous operation*. Localized algorithms are algorithms implemented on sensor networks in such a way that only a limited number of nodes communicate, therefore reducing overall energy consumption and bandwidth requirements. Consequently, localized algorithms often operate with incomplete information, noisy data, and almost always under very strict communication and energy constraints.

One way of modeling localized algorithms in WASNs is as follows: One or more nodes initiate a request for a computation (a query). The result of the query is to be sent to one or more sink nodes. Each node can obtain its required information either through its sensors or by communication with neighboring nodes. The goal is to maximize an objective function for the optimization task at hand, in such a way that all constraints are satisfied and the communication cost is minimal. The first and most important difference between the localized algorithm and other traditional methods is the amount of information available to the processing units. In conventional scenarios, the processors have all the information that is needed for their computation tasks. However, in localized approaches, the required information is not complete and thus the communication between components should be interleaved with the computations in different parts so that they compensate for the insufficient information. The other interesting aspect of localized procedures is that although there are many processing units in a pervasive computing environment such as WASNs, for most of the applications, only a few processors are sufficient to carry out the required calculations. This is in contrast to the classical distributed computing paradigms where all processors involved in a computation are actively computing all the time. For centralized algorithms of course, one processing unit handles all of the computations and control. In addition to the localized nature of the optimization algorithms in WASNs, autonomous closed-loop modes of operation are a must for effective use of such networks. Essentially, the applications must execute with minimal or no intervention of a human operator.

Traditional wired and wireless computer communication network designers have typically followed (although often loosely) the International Organization for Standardization (ISO[1]) Open System Interconnection (OSI) Reference Model as the basis for their protocol stack design. The OSI Reference Model specifies seven protocol layers: Physical, Data Link, Network, Transport, Session, Presentation, and Application (3). The following subsections briefly describe two main WASN protocol stack layer functions namely Medium Access Control (MAC) and Routing that are equivalent to what the OSI model classifies as Data Link and Network layer functions respectively. The subsequent sections then describe sensor network specific tasks and problems such as location discovery and coverage.

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[1] ISO is not an acronym. ISO is an international standardization organization with members from more than 75 countries.

A. Medium Access Control (MAC)

Wireless communication media are almost always broadcast in nature and thus are shared among the participants. For example, RF transmissions of one node can be "heard" by any other node that is within communication range. If two nodes that are close together transmit at the same time, their transmissions will most likely "collide" and interfere with each other. Medium access control refers to the process by which nodes determine when and how to utilize a shared communication medium. In WASNs where network communications are multi-hop (often require intermediate nodes to forward packets), the MAC layer is also where specific self organization and autonomous configuration abilities can be introduced into the network.

Traditional MAC designs have followed two distinct philosophies: dedicated and contention-based. In the dedicated scenarios, each node receives the shared resource according to a pre-specified scheme. Time-division-multiple-access (TDMA) is one such scheme where each node may only transmit within a small, periodic, time slot. Such MAC strategies are typically not well suited for ad-hoc networks that have no predefined organization and can be very dynamic in nature, i.e. nodes can join, move, or leave the network at any time. In contention-based schemes, nodes attempt to "grab" the medium and transmit when needed. Often, nodes have abilities to sense that a channel is in use and thus determine that they must wait. References (4) and (5) provide an overview of existing techniques and propose new MAC layer schemes that are designed specifically for WASNs.

B. Ad-hoc Routing

Routing refers to the process of finding ways to deliver a message from a source to its destination. In ad-hoc, multi-hop networking scenarios, routing is an especially difficult problem since the nodes must discover the destination and the routes to the destinations subject to extreme energy consumption limitations. Existing works from ad-hoc wireless networking domains provide a solid foundation for WASN routing problems. However, WASNs have unique features that make traditional routing philosophies less relevant. In traditional wired and wireless data communication networks, connections are peer-to-peer. This means that the user at a specific source node must send data (usually in forms of packets) to another user at a specific destination. Consequently, the end-points of communication typically have unique names and specific communications are identified by the source and destination names (addresses). In WASNs however, such peer-to-peer communications are less meaningful. Typically, nodes that sense events, analyze the data, collaborate with neighbors, and communicate processed information to one or more sink nodes. In addition, the information may be processed further along the path to the destination which makes the definition of “routing” very vague in WASNs compared to traditional data communication networks.

Flooding is a well known basic scheme that can be used for routing in any network. When flooding, each intermediate node that receives a packet simply forwards it to all its neighbors until it reaches the destination. In a connected network, the packet will most likely reach the destination, although packet losses due to interference and other transmission errors are always possible. Although for broadcast messages flooding is very effective, the overhead for point to point communication is extremely high. Other more sophisticated approaches have been proposed such as Dynamic Source Routing (DSR) and Ad-hoc On-Demand Distance Vector (AODV) routing that try to discover routes and maintain information about the network topology to eliminate flooding overheads. Reference (6) below provides an overview and detailed analysis of several ad-hoc network routing protocols. However, as stated above, routing schemes from ad-hoc networking do not necessarily work well in sensor networks.

Several schemes have been proposed for routing in WASNs that leverage on sensor network specific characteristics such as geographic information and application requirements. Due to the immaturity of the field, none have established themselves as definitive solutions to WASN routing. Directed diffusion is one example of a generic scheme for managing the data communication requirements (and thus routing) in WASNs. The basic scheme in directed diffusion proposes the naming of data as opposed to naming sources and destinations of data. Data is "named" using attribute-value pairs. Data is requested by name as an "interest" in the network. The request (dissemination) sets up "gradients" so that the named data (or events) can be "drawn". In traditional IP-style communication, nodes are identified as "end-points" and the communication is layered as an end-to-end service. In directed diffusion in contrast, named data flows towards the originators of their corresponding interests along multiple paths with the network "reinforcing" one or multiple such paths (7). However, as stated above, WASN nodes may process the data at intermediate steps and the specific routing solution may be tightly coupled with application tasks (as opposed to layered).

C. Location Discovery

Geographical information is an integral attribute of any physical measurement. Thus, the knowledge of node locations is fundamental in proper operations of sensor networks, especially for WASNs. The ad-hoc nature of WASN deployment necessitates that each node determine its location through a location discovery process. The Global Positioning System (GPS) is one method that was designed and is controlled by the United States Department of Defense for this purpose. The GPS system consists of at least 24 satellites in orbit around the earth, with at least 4 satellites viewable from any point, at a given time, on Earth. They each broadcast time-stamped messages at periodic intervals. Any device that can hear the messages from 4 or more satellites can estimate its distance from each satellite and thus perform trilateration to compute its position.

Although GPS is an elegant solution to the location discovery process, it has several limitations that hinder its use in WASN applications. First, GPS is costly both in terms of hardware and power requirements. Second, GPS requires line-of-sight between the receiver and the satellites and thus does not work well when obstructions such as buildings, trees, and mountains block the direct “view” to the satellites. Thus, other techniques have been proposed to dynamically compute the locations of the nodes in WASNs. In several location discovery schemes, the received signal strength indicator (RSSI) of RF communication is used as a measure of distance between nodes. In other schemes, the time difference in arrival of RF and acoustic (ultra-sound) signals are used to approximate node distances. Once nodes in a WASN have the ability to estimate distances between each other (ranging), they can then compute their locations using the simple trilateration method. In order for a trilateration to be successful, a node must have at least three neighbors who already know their locations. This requires that at least a subset of nodes determine their locations through other means such as by using GPS, manual programming, or deterministic deployment (placing nodes at specified coordinates). References (8) and (9) provide detailed discussions on location discovery techniques and algorithms.

D. Coverage

Several different coverage formulations arise naturally in many domains. The Art Gallery Problem for example, deals with determining the number of observers necessary to cover an art gallery room such that every point is seen by at least one observer. This problem has several applications such as for optimal antenna placement problems in wireless communication. The Art Gallery problem was solved optimally in 2D (10) and was shown to be computationally intractable in the 3D case. Coverage in the context of sensor networks can have very new semantics. The main question at the core of coverage is trying to answer how well the sensors observe a physical space. References (11) and (12) present several formulations of sensor coverage in sensor networks. The formulations include calculations based on best- and worst-case coverages for agents moving in a sensor field and exposure-based methods. In the best- and worst-case formulations, the distance of the agent to the closest sensors are of importance while in exposure-based methods the detection probability (observability) in the sensor field is represented by a path dependent integral of multiple sensor intensities. In both of these schemes, the types of actions that the agent performs impact the coverage metric. For example, the sensor field may have a different coverage level if an agent is traveling west to east as opposed to north to south, or along any other arbitrary paths. The actual physical characteristics and abilities of WASN nodes will play crucial roles in building practical, accurate, and useful coverage models and analysis algorithms.

IV. FUTURE DIRECTIONS

We conclude by summarizing some important future challenges in wireless sensor networks:

QoS: For quality of service (QoS), one can define both syntactic and semantic interpretations. On the syntactic level, one can consider dimensions such as coverage, exposure, latency, measurement and communication errors, and event detection confidence. On the semantic level, one can define utility and cost functions to enable the analysis of how particular data can help in the construction of more accurate models of the physical world or more efficient algorithms.

Scaling: Scaling has been the key metric in analyzing both graph theoretic and physical phenomena. The goal will be to develop new methods that are based on statistical techniques instead of traditional probabilistic ones. Existing techniques such as state transitions and percolation will be key factors in analyzing and building very large systems and optimizing their performance.

Profilers, Recommenders, and Search Engines: Profilers, recommenders, and search engines rapidly emerged as mandatory systems enabling efficient use of the World Wide Web (WWW) and the Internet. There are clear needs to develop such systems for sensor networks. New dimensions and challenges include ways to include information and knowledge, not just about physical location and physical time, but also about the physical, chemical, and biological worlds. There are needs for profilers of events, objects, areas, sensors, and users, among other things.

Foundations and Theory: There is a need to develop new theoretical foundations, new models, new algorithmic complexity theory and practice, new programming models, and languages for embedded sensor networks. For example, new models of sensor networks will encompass the already existing Markov models, interacting particle models (e.g. the Ising Model), bifurcation-based models, fractals, oscillations, and space patterns models. In addition, there will be a need to create new models unique to wireless sensor networks. As another example, the VLSI theory field was built based on two lasting premises: first, that integrated circuits are planar, and second, that features are of small size, yet limited in quantity. There is a need to explore such lasting features in sensor networks. Examples of such rule-based modeling are: "energy spent on communication is dominant and distance dependent", "all measurements have intrinsic errors", and "storage space on nodes is very limited".

Other potential research directions include: validation and debugging, data compression and aggregation, real-time constraints, distributed scheduling and assignment, pricing, and privacy of actions.

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