System-Architectures for Sensor Networks Issues, Alternatives, and Directions

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Abstract

Our goal is to identify the key architectural and design issues related to Sensor Networks (SNs), evaluate the proposed solutions, and to outline the most challenging research directions. The evaluation has three scopes - individual components on SN nodes (processor, communication, storage, sensors, actuators, and power supply), node level and networked system level. The special emphasis is placed on architecture and system software, and on new challenges related to the usage of new types of components in networked systems. The evaluation is guided by anticipated technology trends and both current and future applications. The main conclusion of the analysis is that the architectural and synthesis emphasis will be shifted from computation and to some extent communication components to sensors and actuators.

1. Introduction: Motivation and Objectives

Embedded wireless sensor networks (SNs) are systems consisting of a large number of nodes each equipped with certain amount of computational, communication, storage, sensing, and often actuation resources [Est99]. SNs aim to provide efficient and effective bridge between physical and computational worlds. Furthermore, they have high potential economic impact in many fields, including military, education, monitoring, retail, and science. At the same time, SNs pose numerous new researches and development challenges, including low power, low cost, small size, error and fault resiliency, flexibility, security and privacy, and a need for new types of I/O operations. But, before any of these challenges can be properly addressed, one has to have the sensor network in place: the network has to be designed and implemented, and there has to be mechanisms and means for their efficient and convenient use. Hardware and software architecture will decide to significant extent the effectiveness of SNs. Also, SN design methodology will have primary impact on the cost and performance of SNs. The third aspect with major potential impact, algorithms for SN are mainly out of the scope of this paper.

Our overall strategic goal is to summarize what is currently known about architecture and synthesis techniques for sensor networks and to provide a starting point and impetus for research and development of new architectures and synthesis tools for sensor networks. More specifically, the emphasis is on:

* *Identifying Requirements for Typical SN Application.* Traditionally, design of new computer architectures have been based on comprehensive and representative benchmarks suites for typical target applications. It is of exceptional importance to create such benchmarks for sensor networks. In addition, it is important to predict the nature of future SN applications.

* *Identifying Relevant Technological Trends.* It is well known that many electronics and optical systems follow exponential performance growth rates. SN systems are heterogeneous and complex, therefore it is important to anticipate which design and the cost bottlenecks are intrinsic, and which one will be resolved due to technological progress.

* *Balanced Design.* The first instinct could be to optimize each and every component to the maximal extent. From the research and economic point of view, it is important to identify where to put the main optimization effort. In addition, new computational models are needed, but one has to keep in mind that they are not the ultimate goal per se.

* *Techniques for Design and the usage of the Design Components*. The six components of SN node can be grouped in two categories according to their maturity. Power supplies, and in particular storage and power supply are mature technologies. On other hand, ultra low power wireless communication, sensor and actuators are technologies waiting for major technological revolutions. It is important to identify which techniques, architectures, and tools can be reused, and where the new design effort is required.

* *Overall Node Architecture and Trade-offs.* One can envision a number of possible trade-offs. For example, TinyOS approach [Hil00] advocates aggressive communication strategy in order to reduce complexity of computation and storage at local sensor nodes. On other hand sensor-centered approach [Fen02] advocates

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aggressive sensor data processing, filtering, and compression in order to reduce communication.

2. SNs - Global View and Requirements

We have identified a number of characteristics of sensor networks that have direct impact on architectural and design decisions. These characteristics rise naturally from application requirements and technology limitations. Typical SN applications include contaminant transport monitoring, marine microorganisms analysis, habitat sensing, and seismic and home monitoring [Cer01]. It indeed shows a great deal of diversity. Nevertheless, a number of general characteristics are shared among all SN applications regardless of the usage. These characteristics include low cost, small size, low power consumption, robustness, flexibility, resiliency on errors and faults, autonomous mode of operation, and often privacy and security.

SNs have six components: processor, radio, local storage, sensors, actuators, and power supply. There are a number of relevant technology trends that have to be considered. For example, a huge variety of powerful low-powers, low-cost processors, and low-cost memory technologies are wildly accessible. Also, both memory and processor are growing more and more powerful according to Moore's Law, and wireless bandwidth has increased by a factor of more than 25 in the last five years; the capacity of batteries is only growing at a rate as low as 3% per year. The cost of application-specific designs is growing rapidly: only masks cost one million dollars and keep increasing by the factor of two every two years. Sensors and actuators are relatively young industrial fields and predictions are still uncertain.

Due to these application requirements and technology constraints, we identify the following architectural and design objectives:

* *Small physical size.* Reducing physical size has always been one of the key design issues. Therefore, the goal is to provide powerful processor, memory, radio and other components while keeping a reasonably small size, dictated by a specific application.

* *Low power consumption.* The capability, lifetime, and performance of the sensors are all constrained by energy. The sensors have been able to be active for a reasonable long period of time without recharging the battery, because maintenance is expensive.

* *Concurrency-intensive operation.* In order to achieve the overall performance, the sensor data have to be captured from the sensor, processed, compressed, and then sent to the network simultaneously in pipelined processing mode, instead of sequential action. There are two conceptual approaches to address this requirement: (i) partitioning the processor into multiple units where each is assigned to be responsible for a specific task; and (ii) reduction of the context switching time.

* *Diversity in design and usage.* Since we want each node to be small in size, low on power consumption, and have limited physical parallelism, the sensor nodes tend to be application specific. However, different sensors have different requirements. For example, cameras and simple thermometers are the two extremes in terms of the functionality and complexity. Therefore, the design should facilitate trade-offs between reuse, cost and efficiency.

* *Robust Operations.* Since the sensors are going to be deployed over a large and sometimes hostile environment [forests, military usage, human body], we expect the sensors to be fault and error tolerant. Therefore, sensor nodes need abilities to self-test, self-calibrate, and self-repair [Kou02].

* *Security and Privacy.* Each sensor node should have sufficient security mechanisms in order to prevent unauthorized access, attacks, and unintentional damage of the information inside of the SN node. Furthermore, additional privacy mechanisms must also be included.

* *Compatibility.* The cost to develop software dominates the cost of the overall system. In particular, it is important to be able to reuse the legacy code through binary compatibility or binary translation.

* *Flexibility.* There is a need to accommodate functional and timing changes. Flexibility can be achieved through two means: (i) programmability - by employing programmable processors such as microprocessors, DSP processors and microcontrollers; and (ii) reconfiguration by using FPGA-based platforms. We envision that flexibility will be mainly achieved by programmability due to low power consumption.

3. Individual Components of SN Nodes

SN nodes have six components: processor, storage unit, radio, sensors, actuators, and power supply subsystems. It is apparent that standard processor, possibly augmented with DSP and other co-processors and some ASIC units will provide processing capabilities. Also, the state-of-the-art of the actuators is such that they are still not used in the current generation of SN nodes. Therefore, we focus our attention on the other four components.

* *Storage.* Depending on the overall sensor network structure, the requirement for storage at each node should be sharply different. For example, if one follows the architecture where all information is instantaneously sent to the central node, then there is very little need for local storage on each individual node. However, in a more likely scenario, where the goal is to minimize the amount of communication, there will be significant requirement for local storage. There are at least two alternatives for storing data in a local node. In addition, in the case where the node is physically larger, one can store the data in micro disks [Die00]. The first option is to use flash memory. Flash memory is very attractive in terms of cost and storage capacity. However, it has relatively severe limitations in terms of how many times it could be used for storing different data in same physical locations [Ish01]. The second option is to use nano-electronics -based MRAM [Sla02]. It is expected that MRAM will soon significant applications in a number of areas.

It is important to note that historically, both non-volatile semiconductor and disk storage capacity have been growing at the rate that is higher than the Moore's law. We envision at least two major challenges for the use of non-volatile memory in sensor nodes: partitioning for power reduction and developing memory structures that will fit short, word-length of data produced by sensors.

* *Power Supply.* There is a wide consensus that energy will be one of the main technological constraints for SN nodes. The current generation of smart badges enables continuous operations for only a few hours. There are at least two conceptually different ways that energy supply can be addressed. The first is to equip each sensor node with a (rechargeable) source of energy. Currently, the dominant option is to use high-density battery cells [Ful94] [Lin95]. The other alternative for this option is to use full cells [Fir01]. Full cells provide exceptional high density and clean source of energy. However, currently they are not available in physical format that are appropriate for SN nodes. The second conceptual alternative is harvesting energy available in the environment [Rab00]. In addition to solar cells, which are already wildly used for mobile appliances such as calculators, there are a number of proposals for converting vibration to electric energy [Men01].

* *Sensors.* The purpose of sensor network nodes are neither computing, nor communicating, but rather sensing. The sensing component of SN nodes is the current technology bottleneck. The sensing technologies are not progressing as fast as semi-conductors. Also, sensors are being applied to the real physical world, while the computing and communicating units are dealing with a somewhat controlled environment. Transducers are front-end components in sensor nodes and are being used to transform one form of energy into another. Design of transducers is considered out of scope of system architect. In addition, sensors may have four other components: analog, A/D, digital, and micro-controller.

The simplest design option includes only the transducer itself. However, the current trend is to put more and more "smartness" into sensor network nodes. Therefore, a significant processing and computing abilities are being added to sensor nodes [Mas98].

We see as one of the main challenges of SN selecting the type and the quantity of sensors and determine their placement. This task is difficult because there are numerous types of sensors with different properties such as resolution, cost, accuracy, size, and power consumption. In addition, often, more than one sensor type is needed to ensure the correctness of operation and data from different sensor that can be combined. For example, in the Cricket Compass [Nis01], the orientation and the movement of the studying object can be obtained by measuring the distance between several fixed-location referencing sensors; the location of sensor is crucial to minimize error [Nis01].

Another challenge is to select the correct type of sensors and the way to operate them. The source of difficulty is sensors interaction. For example, consider determining the distance using audio sensors. Since the speed of the sound depends greatly on both temperature and humidity of the environment, it is necessary to take both measurements into count in order to get the accurate distance.

There are also several other design tasks associated with sensors, including fault tolerance, error control, calibration, and time synchronization [Kou02].

* *Radios.* Radios as communication components are exceptionally important because energy budget dedicated to sending and receiving messages usually dominates the overall energy budget [Rab00]. During the design and the selection of radios, one has to concentrate on at least three different layers: physical, media access control (MAC), and network. The physical layer handles the communication between transmitters and receivers though established physical links. The main tasks involve signal modulation and coding of data, so that receivers can decode the received message in presents of channel noises and interferences. In order to efficiently use the bandwidth and to some extent reduce the development cost, often several radios have to share the same interconnect medium. In this situation, there is a need for coordinated access policy. This is a task that is resolved at MAC layer. Finally, the network layer is responsible for figuring out the path that a message has to take through the nodes of the network in order to travel from its source to the destination.

Design of the radio is a topic of great deal of recent research activities. To serious extent, the radio architecture is impacted by the network structure and protocols. The main tradeoff is between relative energy cost of transmitting and receiving. The key observation is that listening to the channel is expensive. Therefore, there is a need to invent schemes that will enable long period of sleep mode for receivers. For example, one option is to use coordinated policy for deciding which node will go to sleep while the connectivity in the node is maintained [Roz01]. The other option is to use two radios. One of them is responsible for data receiving and is power hungry. It is used only when the other ultra low radio invokes him. The ultra low power radio is only used to detect if one wants to transmit data to the node.

4. Sensor Network Node

In this section, we address the key issues related to architecture and synthesis of an individual node. Architecture aspects are discussed along three lines: hardware, software, and middleware, while design is presented from synthesis and analysis point of views.

There have been at least three main directions in which the architectures of SN nodes have been addressed. The first group of efforts is a number of designs of individual sensor nodes and badges [Agr99] [Asa98] [Loc02] [Mag98] [Men01] [Pot00] [Wan92]. The emphasis on this group of effort has been on ensuring working prototype creation and in some cases, pushing state of the art of an individual component (e.g. radio, energy harvesting). The second group was represented by the TinyOS group [Cul01] [Hil00]. It was the first effort that tries to address tradeoffs between various components of the node by developing new OS. The last effort is sensor centered. The emphasis is to exploit relatively inexpensive components in terms of energy in order to reduce dominating communication energy consumption, as well as to introduce and exploit qualitative tradeoffs between node components and in particularly sensors.

It is difficult to anticipate technological trends, but one can easily identify at least some highly impacted research topics. For example, it is apparent there is a need for overall energy consumption balanced architectures. Another impact is sensor organization and development of interface between components. Finally, due to privacy, security and authentication needs, technique such as unique ID for CPU and other components could be in high importance.

In software domain, main emphasis will be on RTOS (Real Time Operating System) [Li97]. There is a need for ultra aggressive low power management due to energy constraints and a need for comprehensive resource accounting due to demands for privacy and security, in a number of cases, also support mobility functions (e.g. location discovery).

Middleware will be in strong demand to enable development of new applications. Tasks such as sensor data filtering, compression, sensor data fusion, sensor data searching and profiling, exposure coverage and tracking will be ubiquitous.

Synthesis of sensor nodes will pose a number of new problems in CAD world. Again, we expect new tasks will be defined and solved. For example, sensor allocation and selection, sensor positioning, sensor assignment, and efficient techniques for sensor data storage are typical examples of pending synthesis tasks. Model of computation is prime important as a clean start point for synthesis of modern computing systems. The sensor nodes will require not just new models of computations, but also new models of physical world. One such example could be Euclidian space with classical physical laws (e.g. Newton's law, Thermo dynamical law). Standard time behavior can form a basis for such models.

It is well known that modern design flow, debugging and verification are the most expensive and time consuming components. Due to the heterogeneous nature, and complex interaction between components, we expect that the same will be true for sensor nodes. In particular, we expect that the techniques for error and fault discovery, testing collaboration will be of prime important.

5. Wireless SNs as Embedded Systems

For the networking of the wireless devices and appliances, several communication schemes have been proposed, such as satellite, WLAN, cellular, and ad-hoc multihop architectures. Based on the different architectures, the communication between the nodes can be all low power (ranges in meter), high power (ranges in Mega meters) or medium power (ranges in Kilometers).

For example, the wireless sensor networks is the widely used cellular wireless network. In this architecture, a number of base stations are already deployed within the field. Each base station forms a cell around itself that covers part of the area. Mobile wireless nodes and other appliances can communicate wirelessly, as long as they are at least within the area covered by one cell. An example of such a network is shown in Figure1. The communication requires medium power, although the fixed and immobile base stations are consuming a large amount of power to cover a large area and to communicate to and from the lower power mobile wireless nodes. However, the cellular wireless architecture has the drawback that not only it has to be implanted in the field, but also cells should be carefully designed to have full coverage and transparency with respect to the cells.

Wireless local area network (WLAN) is built for high frequency radio waves. The WLAN also need its own infrastructure within the designated local area. It is very well suited for local private areas, such as offices, campuses and buildings. In some of the applications of the sensor network, like smart buildings, connecting the sensor networks to the WLAN implanted within the area is very suitable. The power consumption in LAN is also medium, although again, the fixed part of the infrastructure is naturally higher powered.

In order to overcome the difficulties caused by the infrastructure settings for Wireless Satellites, WLAN and Cellular networks, a new generation of wireless networks architecture has emerged - the wireless multihop ad-hoc networks. In such networks, the infrastructure architecture is not needed and the nodes can configure themselves to communicate to other nodes within their communication range on the fly.

The nodes are short range and therefore all of the communications are low power. If two nodes that are not within each other's range need to communicate to each other, they use the intermediate nodes as the relays. There are at least four reasons why the multihop ad-hoc wireless sensor network architecture appears as an attractive alternative to the WLAN and cellular technologies. The first reason is the on demand formation of the network that does not require pre-deployed architecture. The second reason that the multihop routing, can save orders of magnitude of power consumption, when compared to the long range routing for the same distance [Rab00]. The third reason is the bandwidth. Since the communications between the nodes are short-range and local, the bandwidth is re-usable, as opposed to the long-range communications. The fourth reason is the fault tolerance [Cer02]. Sensor network are envisioned to have a lot of inexpensive nodes embedded in the environment. The ad-hoc multihop architecture supports the advent of the new nodes and departure or failure of the old ones.

Most of the current sensor network literatures have been advocating the ad-hoc multihop architecture [Aky02] [Est99] [Hil00] [Kah00] [Rab00] [Ye02]. Nevertheless, there are no indications that the ad-hoc multihop architecture would be the best architecture for all of the sensor network applications. Because of the quantity of the radios and the number of the packets flowing in the network, there is a natural asymmetry in the multihop ad-hoc implementation. In fact, for some application such as smart buildings or scientific experimentations, where the network does not change over the space, having a number of static components in the network is natural solution. The static parts would be connected to the constant power supply, so that wireless

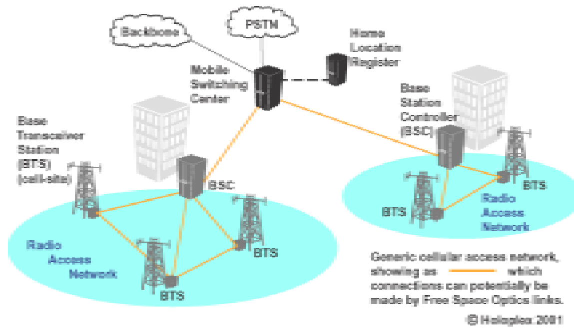

Figure 1 – Wireless cellular network architecture
(Source: http://www.holoplex.com/technology_backhaul.html)

parts can use low power to communicate to them and also nodes can go in the standby mode from time to time.

Another important issue related to the sensor networks is the topology of the network [Cer02]. The question is how to distribute the nodes within the field to achieve the best range and coverage from the sensors. This question is a variation of the well-known art-gallery problem [O'R87], where the new constraints on the nodes are that they are short communication range. The other big issue in the topology consideration is that not all of the nodes should be uniformly distributed, as is the assumption in the current literature and simulations for sensor networks. Furthermore, the network architecture should address the concerns of the various layers of the network. There is still a need for the better components in the physical layer [Kah99], power control and MAC layer [Ye02], and the routing protocols [Est99] at the network layer. The only proposed operating system for the sensor network is TinyOS that is an operating system at the node level [Hil00]. There is a need for a more complex network operating system (NOS) that can facilitate (1) the autonomous mode for the ad-hoc multihop architecture, (2) address the privacy and security concerns, and (3) efficient execution of the localized algorithms.

6. Conclusion

We surveyed the architectural and synthesis issues related to sensor networks. We identified the main design objectives, the current trends, and their relative advantages and limitations. The special emphasis was placed on formulating the highest impact architectural and synthesis challenges.

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