Predictable and Controllable Wireless Sensor Networks

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Abstract: Research activity in the area of wireless sensor networks has grown dramatically in the past few years, driven by advances in miniaturized hardware, and motivated by a vast array of potential applications. Only a small number of sensor networks have been deployed, and these are mainly used for research purposes. Early experiences highlight a lack of predictability in relation to cost, performance and reliability, raising concerns over their use in scenarios like mission critical production environments. This paper motivates the necessity of predictable and controllable wireless sensor networks. The key parameters that need to be predicted and controlled are identified. Furthermore, recent research results from UCC's Mobile & Internet Systems Laboratory are presented. These results show a) the building blocks needed to form a predictable and controllable sensor network and b) the methods that allow us to control and predict the sensor network behavior.

1. Introduction

Wireless Sensor Networks (WSNs) are a topic of growing attention because of the vast array of potential applications that they enable. In a European context, a synopsis of related work in the E-NEXT project was recently presented at the European Workshop on Wireless Sensor Networks [1]. The volume of activity is further illustrated by recent IEEE magazines that are dedicated to WSNs, the early appearance of relevant books, such as [2], and the first international forum to discuss experiences with real WSN systems and deployment [3].

1.1 Background

A WSN comprises a collection of autonomous sensing nodes, each equipped with modest computing ability and memory, a wireless transceiver, power source, and physical sensors. There exist a wide range of possible sensors, including those for temperature, humidity, motion, light, position as well as acoustic and pressure sensors, etc. Obviously the choice of sensor is dependent on the physical phenomena that it is desired to measure or monitor. Wireless communication is typically achieved using radio frequency (RF). A battery usually provides power for a node. In some cases a node can function as an actuator rather than (or in addition to) a sensing node. It is expected that sensor nodes will be inexpensive and that large deployments will comprise many thousands of nodes.

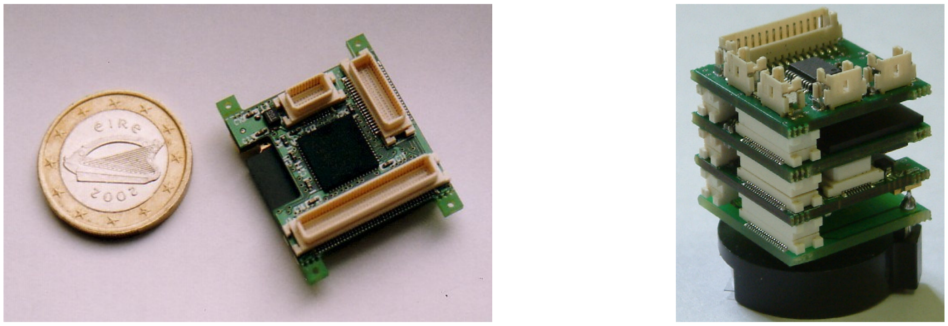

Figure 1 – The UCC Dsystems Node

Figure 1 shows as an example the sensor nodes developed at UCC by MISL and the NMRC.

The potential applications of WSNs are vast and include for example, environmental monitoring, security and surveillance, precision agriculture, utility plant monitoring, health monitoring, military situations, building management and disaster recovery. In general a WSN is considered suitable in situations where there are some physical phenomena to be measured over a relatively large geographical region, or where the location is difficult to access with conventional monitoring approaches. A WSN is an example of a self-organising computer network, underlined by the fact that once deployed and activated, sensor nodes communicate only with their neighbours in order to establish their context and a routing path to the data collection point, usually called the data sink. Nodes are programmable, and can respond to queries issued by a user application attached to the sink node and disseminated through the WSN. Early reported experiments include habitat monitoring [4] and forestry [5].

1.2 Motivation

Today, sensor networks are mainly deployed for research purposes, used either by sensor network researchers to test their designs or other research groups to gather data that was previously inaccessible. An example of the latter category is zoologists that use the network for habitat monitoring. These scenarios share a common characteristic in that they are not considered performance-critical. Lack of predictability, while undesirable, is not a cause of failure.

If sensor networks are to be successful in a commercial environment then they must be predictable, allowing a service to attain some specified quality and/or cost. The cost issue is obviously important for business planning and feasibility, especially in highly cost-sensitive application areas such as agriculture. Service quality is important in many application areas - an obvious example is human medicine.

Sensor networks are not yet used in commercial environments. We believe that one reason for the hesitant deployment of sensor networks is the lack of predictability. It is for example not possible to predict the operational costs of a sensor network. It is difficult to predict the transmission delay of messages in the network. Besides other parameters, the transmission delay of messages defines the achievable service quality the network can provide. Thus, it is our research goal to close this knowledge gap. To achieve this goal, two currently neglected research fields must be explored:

- Building blocks are needed to form a predictable and controllable sensor network. Such building blocks are for example operating systems and communication protocols.
- Methods that allow us to control and predict the sensor network behavior. For example mathematical models are needed to predict service quality in WSNs. Furthermore, methods are needed that allow us to control the network behaviour such that the service quality stays within the desired and predicted bounds.

In this paper we present relevant research from UCC's Mobile & Internet Systems Laboratory. We believe that our research provides an important step towards the systematic design of predictable and controllable sensor networks.

1.3 Structure

The remaining paper is organized as follows. Section 2 describes and defines in detail the terms predictable and controllable. There, the parameters that should be predicted and controlled are explained. Section 3 presents our research on building blocks for predictable and controllable sensor networks. Section 4 shows our research on methods that allow us to control and predict the sensor network behavior. Section 5 concludes the paper.

2. Prediction and Control

As motivated in the introduction, a sensor network should be predictable and controllable regarding its *cost* and its *service quality* parameters. As it will be shown later, cost and service quality parameters are interdependent.

2.1 The Cost Parameters

For the commercial viability of WSNs, the monetary costs associated with deployment and operation has to be predictable.

The deployment cost of a sensor network is determined mainly by the cost of an individual node and the cost for deploying all nodes. The deployment costs are often simple to predict. For example, if sensors are dropped by plane, the cost for renting the plane determines the deployment cost. The prediction of the node costs is more difficult. The cost of a sensor node is defined by its technical capabilities such as processing power and memory size. It is difficult to predict how much processing power and memory space are necessary to operate the sensor network, especially if a specific service quality must be achieved at the same time. Thus, the cost parameter deployment cost is linked with the service quality.

The long-term operational cost of a sensor network is determined mainly by maintenance. Sensors are battery powered and have therefore a limited network lifetime. To ensure continuous network operation, batteries will have to be replaced occasionally. This task impacts maintenance costs. To reduce energy consumption and thus maintenance costs, the network behavior can be modified. This however might influence the service quality. This cost parameter is therefore linked with the service quality.

We believe that the aforementioned cost parameters are the main contributors to the total network cost. However, additional parameters might exist and can be integrated in the presented framework.

2.2 The Service Quality Parameters

In most cases, it is necessary to predict the service quality that can be achieved while using a wireless sensor networks. The sensor network is part of a computer system that provides a specific service to its users. The quality of the provided service depends on the quality of the data extracted from the sensors in the field. Thus, the service quality parameters depend on parameters describing the data extraction process in the network. The most important parameters are data transfer delay, data transport reliability and data accuracy. Additional parameters might exist and can be integrated in the presented framework.

In many cases, the sensing data is transmitted hop-by-hop towards a sink. The sink is then subsequently used to analyze the data received from many sensors in the field. The forwarding process in each sensor consumes some time and thus a delay between data gathering and processing exist. If this delay is too high, the quality of the result of the process analyzing the data in the sink might drop. Thus, it is necessary to predict and control the data transfer delay in the network. There is an inverse relationship between delay and energy consumption, see for example [6]. The energy consumption is linked with the lifetime of the sensor and the sensor field and therefore related to the cost parameters of the sensor field. Additionally the forwarding delay influences the memory usage in the node which links this parameter as well with the cost of the sensor network.

The quality of the data analysis process at the sink depends as well on the data transport reliability. If messages sent by the sensors are lost on transit, less data is available for the analysis and hence the quality of the result will drop. The transport reliability in a network can be improved, but this often requires that more energy be used for transmissions [7]. Thus, this service quality parameter is linked as well to the cost parameters.

A sensor network may vary the amount of sensors used to observe a physical phenomenon, based for example of some measure of utility [8]. Depending on the amount of sensors used, the amount of messages in the network varies. With less information available at the sink, the quality of the analysis will drop but less energy is used in the field. Additionally, fewer messages will reduce the data transfer delay, as a smaller number of messages have to be forwarded in each node.

2.3 Summary

Cost and *service quality* parameters need to be predictable and controllable. These parameters are interdependent and appropriate models are needed to capture the dependencies and feed into a systematic design activity.

In a first step towards this goal, technical building blocks are necessary that allow their realisation. Our belief is that a WSN must be comprised of individual components that are themselves predictable, such as nodes and communication protocols. Using these, models and methods can be defined that interrelate the network parameters of interest.

3. Building Blocks for Predictable Sensor Networks

This section describes building blocks needed to form a predictable sensor network. The prediction and control methods described in the next section need the features provided by these blocks.

3.1 Sensor Node Operating Systems

A sensor node is severely constrained regarding its computation, memory and energy resources. Thus, new operating systems for sensor nodes are a focus of research, as existing ones cannot scale or be adapted to operate in such impoverished systems. In comparison to conventional embedded systems, WSN nodes have much greater resource constraints and operate in a collaborative distributed systems environment where they interact with other nodes to attain a system goal. Most of these new operating systems are based on an event abstraction, a well-known example being TinyOS (www.tinyos.net). Activity in the operating system is triggered by an event; after the event is processed, the system retires to an energy efficient sleep state.

Unfortunately, it is currently impossible to predict the time (or even an upper bound) needed to process events in such operating systems. Event based sensor network operating systems with real-time characteristics do not exist yet. However, these are obviously needed to build predictable sensor networks. TinyOS was ported to the D-System nodes developed at UCC by MISL and the NMRC [9], and ongoing research focuses on extending the operating system for real-time performance.

The modified operating system will be used as a network element that provides prediction and control regarding *energy consumption* and *event processing time*.

3.2 Communication Protocols

Nodes in a sensor network exchange messages via radio transmission. The forwarding of a message between two nodes consumes time and energy. Furthermore the transmission might have a specific reliability, as wireless channels are naturally prone to interference, errors and loss. The message exchange between nodes must be predictable regarding energy consumption, transmission time and reliability. A predictable network can be built only if predictability on the level of node-to-node communication can be achieved and quality of service issues are given due consideration [10].

The grade of predictability on the level of node-to-node communication is mainly defined by the Media Access Control Protocol (MAC). If for example a simple contention based MAC protocol is used, guarantees on the necessary transmission time and energy cannot be given. Collisions might occur in the channel and the sender might have to back-off several times and retransmit the message. Obviously, this behaviour will make it impossible to predict the necessary transmission time or energy. Our research targets MAC protocols that can be implemented in resource-constrained sensors while still providing predictability. Our protocol, called μ-MAC [11], is novel in its explicit use of application requirements and traffic characterization to schedule medium access, thus enhancing predictability while also conserving energy by avoiding unnecessary idle listening.

Our newly defined MAC protocols provides predictability and control of *message forwarding delay* and *energy usage*.

4. Prediction and Control Methods

This section describes briefly two prediction and control methods that can be used. These theoretical methods need the building blocks described in the previous section to be applied in a real-world scenario.

4.1 Maintenance-Efficient Routing

Communication patterns define the energy depletion profile of a wireless sensor network. In particular, routing defines which areas of the sensor field are subject to a higher traffic load. In these areas, sensor nodes deplete faster than in areas with a low traffic load. As nodes deplete, their batteries have to be replaced, incurring maintenance costs associated with replacing or recharging node batteries. Given the impact of communication in the energy consumption of sensor nodes, the field depletion profile can be greatly influenced by the traffic flow inside the network. Protocols in the network layer can therefore help the shaping of favorable depletion profiles according to some appropriate metric that captures the concept of maintenance efficiency.

Our work on maintenance efficiency [12] defines an analysis framework of routing protocols that can be applied to produce sensor fields that are much less expensive to maintain. The framework is based on a maintenance cost model that is simple, yet flexible enough to capture real world deployment scenarios of WSNs. As an illustration, the framework is used to assess the impact of different forwarding techniques for a known geographical routing protocol on the overall maintenance costs of different sensor fields. The results obtained indicate that a one-size-fits-all approach to the design of maintenance efficient routing protocols does not hold in large deployments of WSNs. However, savings of up to 50% in maintenance cost were observed through simple modifications of the forwarding strategy. Impact on other relevant metrics such as hop-count (and hence latency) is also quantified.

The developed *maintenance cost model* provides the following features:

- It allows us to capture maintenance costs in sensor networks and hence allows us to predict and control this cost parameter.
- It allows us to relate the *maintenance cost* parameter with the service quality parameter *data transfer delay*.

To make use of the maintenance cost model in reality, a predictable node energy pattern is needed. Such a predictable energy pattern can be achieved by using the μ-MAC protocol described in the previous section.

4.2 Sensor Network Calculus

Network calculus is a tool to analyze flow control problems in networks with particular focus on determination of bounds on worst-case performance. In particular, it abstracts traffic regulation and scheduling schemes from which one may derive general results. It has been successfully applied as a framework to derive deterministic guarantees on throughput, delay, and to ensure zero loss in packet-switched networks [13].

Our work tailors the network calculus such that an analytical investigation of performance-related characteristics of wireless sensor networks is possible [14]. The resulting sensor network calculus allows a worst-case analysis of a sensor network taking into account the various trade-offs and interdependencies between the service quality parameters node power consumption, node buffer requirements and information transfer delay.

The developed *sensor network calculus* provides the following features:

- It allows us to capture the service quality parameter data transfer delay and hence allows us to predict and control this cost parameter.
- It allows us to relate the *data transfer delay* parameter with the *cost* parameters as buffer needs and power consumption are related to the cost of a sensor field (see Section 2).

The predictions calculated by using the sensor network calculus can only reflect a real world scenario if a predictable sensor nodes and hop-to-hop communication methods are used. Available building blocks are described in the previous section.

5. Conclusion

The case for wireless sensor networks that are predictable and controllable has been presented, along with a description of some of our work takes us towards that goal. The desire for a systematic approach to the design of WSNs is a critical component of our longer-term strategy in this important research area. Building on the work presented here, we are following several lines of enquiry in the areas of systematic design and network deployment. In doing so we expect to enable applications of this exciting technology in commercial situations where cost and performance must be quantifiable and measurable.

6. Acknowledgements

The D-Systems project is supported by the Informatics Research Initiative of Enterprise Ireland and is in collaboration with the NMRC. The research on Network Calculus is in collaboration with Technische Universität Kaiserslautern.

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