INTRODUCTION

Sensor network algorithms and applications

BY NIKI TRIGONI1 AND BHASKAR KRISHNAMACHARI2,*

1Department of Computer Science, University of Oxford, Wolfson Building, Parks Road, Oxford OX1 3QD, UK
2Viterbi School of Engineering, University of Southern California, Los Angeles, CA 90089, USA

A sensor network is a collection of nodes with processing, communication and sensing capabilities deployed in an area of interest to perform a monitoring task. There has now been about a decade of very active research in the area of sensor networks, with significant accomplishments made in terms of both designing novel algorithms and building exciting new sensing applications. This Theme Issue provides a broad sampling of the central challenges and the contributions that have been made towards addressing these challenges in the field, and illustrates the pervasive and central role of sensor networks in monitoring human activities and the environment.

Keywords: networks; sensors; wireless; algorithms; protocols; applications

1. Introduction

The Issue is organized into three main themes: the first theme focuses on the problem of network configuration and software, and introduces algorithms for node scheduling, time synchronization and energy management, as well as operating systems and network protocols. The second theme covers a range of signal-processing techniques developed for sensor node localization, event detection and tracking, as well as in-network data compression. The third theme provides a taste of sensor network applications and covers a variety of set-ups, from monitoring controlled building environments to sensing challenging underwater environments, and from traditional fixed sensor topologies to new domains of mobile participatory sensing.

2. Network configuration and software

In a typical sensor network, nodes can collect data from local sensors, perform local computations and communicate wirelessly with other nodes by radio. Given the limited radio communication range, each node can directly exchange messages

*Author for correspondence (bkrishna@usc.edu).

One contribution of 11 to a Theme Issue ‘Sensor network algorithms and applications’.
with a limited number of neighbouring nodes. Thus, a sensor network can be viewed as a distributed system, in which nodes must carefully coordinate their communication and computation tasks in order to efficiently achieve a monitoring goal. Lenzen & Wattenhofer [1] highlight the power of distributed algorithms in solving network coordination tasks, such as carefully scheduling radio transmissions to avoid interference and synchronizing the clocks of sensor nodes. They highlight important differences between a wireless sensor network and an idealized distributed system, and discuss how these differences affect the design of distributed algorithms and their complexity. They show that the underlying communication model, which governs how nodes communicate and interfere with each other, is key to designing distributed algorithms for sensor networks, and has sparked new interest in the area of distributed computing.

The fact that sensor nodes are embedded within a physical space gives rise to interesting geometrical structures, and motivates the study of a special class of algorithms, referred to as geometric algorithms. Gao & Guibas [2] identify four distinct areas in which geometric structures can be exploited to configure sensor network operation. First, they can be used in network localization, i.e. to infer the locations of sensor nodes from local measurements, such as distance and angle estimations between neighbouring nodes. The authors give an overview of distributed and centralized localization algorithms, explain the challenge of localization ambiguity (multiple localization solutions that satisfy the distance/angle constraints) and summarize key theoretical results on graph rigidity and network localizability. Second, geometrical information can be used in routing. The authors discuss how physical and virtual coordinates of sensor nodes can be used to determine the path that a packet follows to a destination. They also overview routing techniques that aim to balance the network communication load, as well as landmark-based routing schemes in which a small subset of nodes is selected as the landmark and routing decisions take into account distances to landmarks. Third, geometrical information can be exploited to design information brokerage mechanisms, which enable information consumers and information sources to discover each other in a communication-efficient manner. Finally, the authors highlight the use of geometrical algorithms in discovering and representing non-trivial network topologies with ‘hole’ structures.

A key aspect of designing network configuration algorithms is to conserve energy and prolong the lifetime of the network. Stankovic & He [3] survey the area, and present three distinct approaches to energy management. The first approach focuses on the hardware side, and highlights ways of scavenging and storing energy at the sensor nodes. The authors also discuss differences in energy consumption in various types of sensor hardware, and controls over hardware components to allow trade-offs between energy and performance. The second approach, referred to as energy management in the small, concerns energy management solutions that are targeted at specific layers of sensor node functionality, for example medium access control, routing, localization and time synchronization. The third approach, referred to as energy management in the large, comprises efforts to build system components that are specifically dedicated to energy management. Such components typically orchestrate sensor activation patterns, taking into account the sensing range and density of sensor nodes, as well as the nature of the monitored events (e.g. their duration, shape, mobility, and so on).
Network protocols define the overall communication process in a sensor network, and require an operating system at each node to provide a software abstraction to manage its resources. Dunkels & Dutta [4] provide an overview of developments in the design of operating systems and network protocols for sensor networks. Focusing first on operating systems, the authors identify challenges pertaining to resource constraints and the sheer diversity of both hardware and applications, and discuss how these challenges have been addressed in the literature. They highlight the design issues pertaining to concurrency and execution models, memory allocation, storage, energy and the communication architecture provided by sensor network operating systems. Then, they present network protocols for low-power medium access, routing and reliable transfer. As sensor networks mature and transition to industrial practice, there is an increased effort on the standardization of network protocols. The authors describe some of the ongoing efforts by the Internet Engineering Task Force to enable Internet protocol-based sensor networks.

3. Signal processing

Once sensors self-configure into a network, they must set off to address the monitoring task at hand. This involves activating their sensors, and processing sensor signals to infer events of interest. These events are then stored locally or communicated wirelessly through the network. Signal processing has a number of interesting applications, from localizing sensor nodes to detecting and tracking events of interest and compressing data within the network prior to data propagation.

Lédeczi & Maróti [5] provide an interesting overview of range-based localization methods for wireless sensor networks. They review various approaches to determining the distance between two nodes, by processing radio, acoustic or light signals. They discuss the advantages and disadvantages of ranging using time of flight versus signal strength and phase measurements. The authors then discuss how the collected ranging data and their error distributions can be fused to provide location estimates. They also show how localization techniques can exploit a priori information about the location of some nodes, the environment where the network is deployed and patterns of mobility (in scenarios of localizing mobile nodes). While global positioning system (GPS) technology has largely addressed the problem of node localization in outdoor environments, there is a large number of interesting research challenges that need to be tackled both indoor and in dense urban environments. The authors believe that some of these challenges may be overcome by multi-modal localization, that is, by fusing signals from multiple sensors that measure different physical phenomena (including GPS, cameras, inertial sensors, air pressure sensors, and so on).

Localization is only one instance of a large class of inference problems in the context of sensor networks. Veeravalli & Varshney [6] summarize research developments in the area of distributed inference, with emphasis on dealing with resource constraints, such as limited power, communication range and bandwidth. They discuss three different types of inference problems: distributed detection of events of interest (e.g. the presence of a contaminant), parameter estimation (e.g. the location and intensity of a heat source), and tracking
(e.g. work-in-process tracking in a manufacturing environment). The authors point out that, although significant contributions have already been made in addressing these problems, there remain a lot of open research issues. Fertile areas for future work include distributed inference with conditionally dependent observations, when the observation statistics are unknown or partially known or when observations are made by sensors of different modalities.

Once sensor data are gathered and processed locally at sensor nodes, they typically need to be transmitted wirelessly through the network to special purpose nodes, called *base stations* or *sinks*, to be consumed by the application users. Compressing data as they are transmitted to the sink can significantly reduce the network communication load and increase the lifetime of the network. In their article, Duarte *et al.* [7] review a number of distributed compression techniques for wireless sensor networks. They pay particular attention to spatial compression techniques, which exploit correlations in data generated by neighbouring nodes. They make the key observation that such techniques require raw data to be transmitted from the source nodes to *aggregating* nodes, where spatial correlations are discovered and data are compressed. Existing algorithms vary in the degree of synergy between the coding and communication aspects: from treating routing and compression independently to prioritizing one over the other, or jointly optimizing the two aspects. The importance of distributed compression is likely to increase over the next years, as sensor networks become more ubiquitous, increase in size, density and sampling rates, and bandwidth becomes a scarce resource.

### 4. Applications and new domains

In the last decade, we have seen significant advances in hardware and algorithm design for sensor networks. Together, they have enabled the adoption of this exciting new technology in a variety of interesting applications, from indoor to outdoor sensing, from monitoring human activities to sensing large-scale environmental processes. Owing to space reasons, it is infeasible to provide an exhaustive list of sensor network applications and their specific research challenges. To illustrate the breadth of existing applications, we include three examples with completely different application requirements and network set-ups.

The article by Liu & Terzis [8] describes the unique challenges of using sensor networks to monitor data centres. Data centres can vary in size, from a few server cabinets to large dedicated buildings consuming hundreds of megawatts of electricity. Careful monitoring of large data centres can lead to significant energy savings, and lower maintenance costs. Different servers run different services, and the number of users that access these services may vary significantly over time. Therefore, the physical locations of servers, the kinds of services they run and the time-varying load incurred by each service have an impact on the stress put on the power and cooling systems. Fixed sensor nodes are an attractive method for increasing visibility into a data centre’s operating conditions. They can sample environmental attributes at high temporal and spatial resolutions, notify operators of unsafe operating conditions, trace the source of failures and help control the power and cooling systems.
Data centres, and the large majority of sensor network applications, rely on radio communication to propagate data from sensor sources to data sinks. In contrast, Heidemann et al. [9] discuss the unique challenges of underwater environments, where communication systems mainly rely on acoustic technology. Underwater sensor networks are static, comprising nodes attached to docks or anchored to buoys or to the sea floor, or mobile, with sensors attached to autonomous underwater vehicles (AUVs), low-power gliders or unpowered drifters. Depending on the set-up, power for communications may be plentiful (e.g. for AUVs) or scarce (e.g. for drifters or fixed sensors). The authors explain how the characteristics of the acoustic channel (e.g. long delays, the long reach of acoustic signals, and so on) affect the design of the communication stack, from the physical and media access control (MAC) layers to the routing and transport layers. However, they point out that, so far, there are very few real applications of underwater sensor networks, and there is a need for more testbed deployments and field experiments to test existing approaches and fuel future research.

Data centres and underwater environments are typical examples of sensing applications, where dedicated sensor nodes are tasked to monitor their environment without much human intervention. The recent proliferation of hand-held devices (e.g. smart phones), in-vehicle sensors (e.g. GPS devices) and residential sensors (e.g. power meters) means that the average individual is now in possession of several sensors. At the same time, cell phone connectivity and social network sites provide ample opportunities for sharing sensor data produced by individuals. This has sparked interest in a novel class of applications, often referred to as participatory or human-centric sensing. Srivastava et al. [10] identify several sensing scenarios that require human participation, ranging from contexts where humans collect sensor data for personal use to wider forms of participation in collecting and sharing data within a community. They highlight important research challenges that arise in such applications, such as continuous sensing by hand-held devices with limited battery life, inference of complex human behaviour from raw sensor data and analysis of the behaviour of social sensing systems. They highlight existing approaches to addressing some of these challenges, and point out the need for new interdisciplinary research to develop and understand complex data-centric systems.

5. Conclusion

This Theme Issue provides a sweeping view of the state of the art in wireless sensor networks. The articles show the tremendous diversity of interdisciplinary research that has been undertaken in this area over the past decade. We find that, while much work has been done, there are still many interesting open research problems and challenges to be overcome in every aspect from algorithm design to protocol implementation to the deployment of applications. Further developments in all these dimensions in the coming years will form the basis of the next generation Internet of Things.

References


