IEEE Signal Processing Magazine, March 2002, to appear

Collaborative Signal and Information Processing in Micro-Sensor Networks

Sri Kumar, David Shepherd, and Feng Zhao[1], Guest Editors

[1] Feng Zhao is Principal Scientist at Xerox Palo Alto Research Center (Xerox PARC); David Shepherd is Senior Engineer at Strategic Analysis, Inc.; Sri Kumar is Program Manager in the Information Technology Office at Defense Advanced Research Projects Agency (DARPA). Opinions expressed in this article are of the authors, and do not necessarily reflect the views of the organizations or affiliation of the authors.

Introduction: The purpose of this special issue is to provide a source of reference for the ongoing and future research in collaborative signal and information processing (CSIP) in distributed micro-sensor networks, by collecting the new intellectual directions and presenting the current and expected challenges facing CSIP.

Networked microsensors technology is a key technology for the 21st century. Cheap, smart devices with multiple on-board sensors, networked through wireless links and the Internet and deployable in large numbers, provide unprecedented opportunities for instrumenting, and controlling to our advantage, homes, cities, the environment, and battlefields.

Networked micro-sensors is a technology opportunity for a broad spectrum of applications and new capabilities, for environmental monitoring (e.g. traffic, habitat, security), industrial sensing (e.g. factory, appliances), infrastructure integrity (e.g. power grid), and battlefield tactical applications (e.g. target tracking). Micro-sensors can be deployed almost anywhere: on ground and in air, on bodies and inside buildings, on vehicles and under water - all networked to detect and track spatio-temporal events of interest.

Sensor nodes have embedded processing capability, multiple on board sensors such as acoustic, seismic, IR, magnetic, imaging, micro-radar, etc., and storage. Sensor nodes can be ad hoc deployed, utilizing wireless links to neighboring nodes and location and positioning capability through GPS or local positioning algorithms. As these devices need to be operated with small batteries and energy constraints, the software needs to be energy efficient.

Realizing the potential of micro-sensor networks presents a number of challenges. These include i) methods for rapid networking of these sensor devices, and ii) leveraging the distributed computing environment provided by these devices for extraction of reliable and timely information from the data collected from them. The latter includes the programming challenges for sensor networks, including querying and tasking the sensor network, ensuring multi-tasked and multi-user operation as well as networked computing that blends the processing of data that sensors collect from the physical world with the needs of users.

A number of research efforts are currently under way to address the issues surrounding these challenges. For example, the DARPA Sensor Information Technology (SensIT) Program [1] is developing ad hoc networking of fixed and mobile devices, methodologies for micro-databases to collect, store, and process data in the sensor network, methods to compile and execute queries and tasks, and mechanisms to deliver the results to end users, who may be mobile. One of the most critical areas is the distributed processing of the data collected from the devices, which is the focus of this special issue.

CSIP Challenges: CSIP in distributed micro-sensor networks is an emerging interdisciplinary research area, drawing upon traditionally disparate disciplines such as lower-power communication and computation, space-time signal processing, distributed and fault-tolerant algorithms, adaptive systems, and sensor fusion and decision theory. CSIP research into micro-sensors has focused on developing new methods and algorithms for representing, storing, and processing spatially distributed, multi-modal information.

The processing of data collected in the sensor network presents a new challenge, and a new paradigm, to the signal and information processing research community. In addition to considerations of single-platform signal processing, the networked information processing is further constrained by application requirements on energy efficiency, network latency, and fault tolerance. With these factors in mind, the primary research challenges in CSIP may be summarized as follows:

1. The micro-sensor networks enable dense spatial sampling of phenomena of interest. For example, multi-modal sensors on tens of thousands of devices could be collecting data on a major transportation grid. The challenge is to combine the distributed data, first at each node and then with collaboration among the relevant devices in the network, to produce meaningful global results.
2. Distributed processing in a wireless network typically is asynchronous. For example, data from other nodes may arrive out of order at a sequential state estimator. The challenge is to design the relevant signal and information processing and fusion algorithms for asynchronous execution.
3. Due to the energy constraints of battery-powered micro-sensors, power-aware signal processing and communication methods are needed to provide progressive accuracy, *i.e.* anytime algorithms that can be terminated at any time with graceful degradation in results.

4. To meet the energy constraints and effectively support end-to-end applications, an ad hoc sensor network must optimize processing and communication among signal processing, data fusion, querying, and routing tasks. For example, diffusion of data through the network may be directed by considering both information gain from signal processing applications and resource usage, thus breaking the traditional abstraction barrier between signal processing and network routing.

This Special Issue: The articles in this special issue provide a snapshot of the state of the art in CSIP research for sensor networks, and attempt to address some of the diverse views associated with CSIP. This special issue grew out of the 1st CSIP Workshop held at Xerox Palo Alto Research Center in January 2001 [2], which gathered about 50 academia, industry, and government researchers active in various research fields central to CSIP.

The subjects of the special issue articles range from detection, classification, and tracking of targets to energy efficiency, distributed compression, active sensor querying, and high-level information processing. The first paper, by Li *et al.*, describes a framework for target detection, classification, and tracking. They argue that classification of space-time signatures of events plays a key role in tracking multiple targets, and present several classifier algorithms and their performance on experimental data sets. The paper by Chen *et al.* provides a comprehensive introduction to various methods for source location and direction estimation, using intra-node or inter-node collaboration. The introduction covers conventional array signal processing as well as blind beamforming algorithms, and it also describes the use of Cramer-Rao bound to characterize the performance of direction-of-arrival (DOA) estimators. Raghunathan *et al.* consider an important aspect of CSIP, the optimization of energy consumption in a sensor network. Their paper describes a suite of techniques for managing node-level as well as network-wide energy usage to maximize the lifetime of a network. Pradhan *et al.*'s paper presents a decentralized technique to compactly encode sensor information, thus removing spatial redundancy and minimizing storage and communication requirements. Their method relies on the structured error correcting coding used in communication and signal processing and requires minimal inter-node communication. Zhao *et al.* introduce an information utility-based CSIP method that dynamically defines regions of sensor collaboration by optimizing information gain while minimizing network resource usage. Their algorithm is presented in the context of tracking a moving target. Finally, Guibas describes a framework for tracking relations among a set of targets rather than individual targets alone. The paper argues, using several examples, that sometimes it is more useful, and more economic, to track high-level relational information than to locate each individual target.

Acknowledgement: We would like to thank the anonymous referees for their work in evaluating the submissions.

References

[1] DARPA Sensor Information Technology Program, http://www.darpa.mil/ito/research/sensit/index.html. See also http://www.darpa.mil/DARPATech2000/presentation.html.

[2] Workshop on Collaborative Signal and Information Processing, http://www.parc.xerox.com/cosense/csp, chaired by Feng Zhao and Sri Kumar, Xerox Palo Alto Research Center, January 2001.