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An overview of recent advances on distributed and agile sensing algorithms and implementation

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ABSTRACT

We provide an overview of recent work on distributed and agile sensing algorithms and their implementation. Modern sensor systems with embedded processing can allow for distributed sensing to continuously infer intelligent information as well as for agile sensing to configure systems in order to maintain a desirable performance level. We examine distributed inference techniques for detection and estimation at the fusion center and wireless networks for the sensor systems for real time scenarios. We also study waveform-agile sensing, which includes methods for adapting the sensor transmit waveform to match the environment and to optimize the selected performance metric. We specifically concentrate on radar and underwater acoustic signal transmission environments. As we consider systems with potentially large number of sensors, we discuss the use of resource-agile implementation approaches based on multiple-core processors in order to efficiently implement the computationally intensive processing in configuring the sensors. These resource-agile approaches can be extended to also optimize sensing in distributed sensor networks.

1. Introduction

Traditional sensor systems used to have limited interconnection and processing capabilities on a central terminal. As technology improved, sensor systems acquired embedded signal processing and communication, though still over a single core architecture. Advancements in hardware embedding technology and distributed computing have resulted in distributed sensor systems [1,2]. Such systems have interconnected multi-sensors that are intelligently designed to process collective data, share information or adapt to variable operating conditions. There are many elements that need to be considered in the design of an intelligent distributed sensor system. Some of these elements, which are reviewed in this paper and integrated in Fig. 1(a), include the development of information inference approaches in the sensor network; the design and testing of wireless networks between interconnected sensors; implementation advancement under resource-aware considerations; and development of adaptive agile-sensing methodologies for performance optimization.

Developments in independent and self-contained sensor devices have led to the use of distributed sensing in wireless sensor networks [3–7]. Depending on the application, each network sensor can share information with all other sensors and the base station. The challenge is to develop distributed and collaborative methods that are optimized for the particular application and hardware platform. A wireless sensor network consists of spatially distributed sensors that are capable of monitoring the environment and share information. They are now used in many areas, including military and healthcare applications, habitat monitoring, traffic control and space exploration [3,5]. With recent advances in hardware technology, it is now possible to deploy a large number of devices that are able to sense and communicate information and actuate systems. Although wireless sensors typically have limited processing and communication capabilities due to limited battery power, the fusion center of a wireless sensor network can inte-

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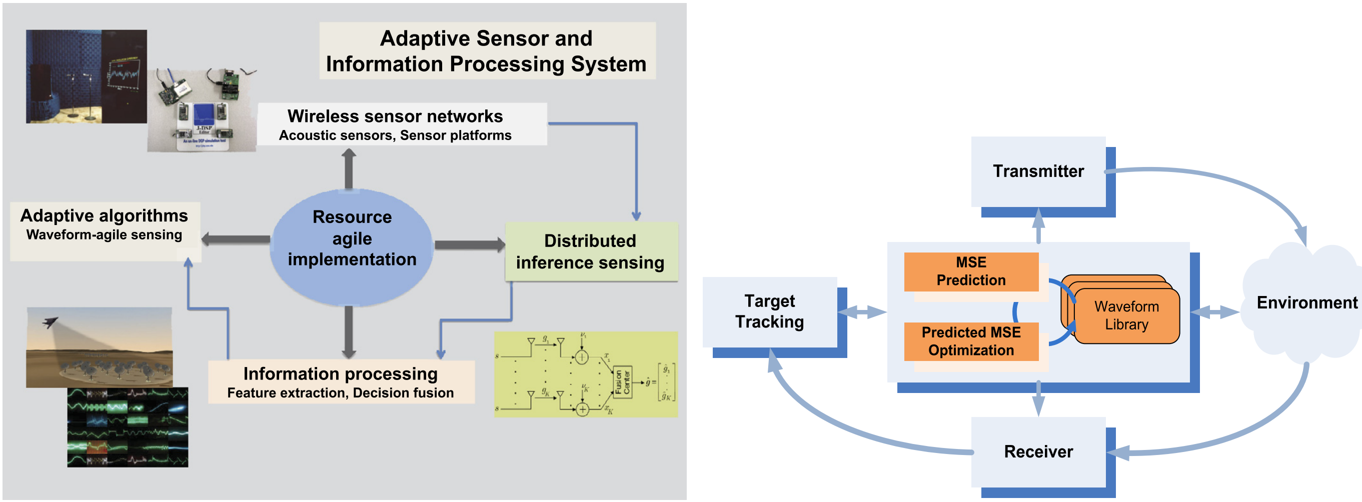

(a) (b)

Fig. 1. (a) Integrated distributed and agile sensing. (b) Waveform-agile sensing for target tracking.

grate and process information from multiple sources and make inferences from the combined observations. Distributed inference in the form of signal detection and parameter estimation tasks in a sensor network has garnered significant interest in recent years [8–14]. These tasks can be performed with reduced communication bandwidth requirements, increased reliability, and reduced cost. This is different from centralized sensor networks, where all the sensors are wired to the fusion center.

As fusion centers in decentralized networks receive condensed information from the sensors, they can exhibit a loss in performance when compared to centralized systems. However, this performance loss can be minimized by developing computationally efficient algorithms to optimally process the sensor measurements locally as well as the fusion center. Modern sensor signal and information processing relies heavily on both intensive and efficient computation capabilities. Intensive computation requires a high-bandwidth data access rate whereas real time computing requires efficient implementation of processing algorithms. Recent advances in integrated circuits enable us to exploit the development of both computationally intensive and efficient devices using multicore processors [15,16]. Multicore processors are now being used in many areas including communications [17–19], multimedia and image processing [20,21], radar [22–24], and biomedical engineering [25,26].

An important aspect of distributed sensor systems is the use of adaptive processing algorithms to optimize sensing performance. Agile sensing refers to adapting sensing strategies based on environmental conditions or sensing objectives. Specifically, waveform-agile sensing techniques dynamically select the transmitted waveform to optimize a performance metric such as probability of detection or tracking estimation error in radar applications (see Fig. 1(b)) [27–33]. An example of a distributed sensor network with agile sensing is a passive acoustic sensor system used to track a sound source in shallow water [34]. When a sensor locally detects a sound source, it extracts features and transmits them to the fusion center. The features from all the sensors are then processed to estimate the sound source parameters. Also, the predicted estimation error at the next time step is minimized at the fusion center to optimally select and transmit working parameters to each sensor.

In this paper, we provide an overview of recent work on distributed and agile sensing algorithms and their implementation. We examine distributed detection and estimation algorithms for real time scenarios. We also study waveform-agile sensing, specifically concentrating on radar and underwater acoustic signal transmission environments. For systems with potentially large number of sensors, we discuss the use of resource-agile implementation approaches based on multi-core processors in order to efficiently implement the computationally intensive algorithms.

The rest of the paper is organized as follows. In Section 2, we present recent advances in distributed and agile sensing algorithms. Specifically, in Section 2.1, we discuss distributed inference sensing methodologies for detection and estimation at the fusion center. Section 2.2 reviews waveform-agile sensing for radar and underwater matched field processing applications. In Section 3, we discuss implementation issues and applications of distributed and agile sensing. The design and testing of wireless networks between interconnected sensors is considered in Section 3.1. We present the parallelized implementation of different algorithms on multicore processor platforms and modifications to minimize communication overhead in Section 3.2. A specific application of distributed sensors to the smart grid network is discussed in Section 3.3 for diagnosing faults.

2. Distributed and agile sensing algorithms

2.1. Algorithms for distributed inference in sensor networks

Distributed inference algorithms refer to two classes of problems: distributed detection and distributed estimation. Traditionally, distributed detection algorithms focus on perfect but bandwidth-constrained communication channels. The focus is mainly on issues such as conditional independence [35,36] versus correlated sensor measurements at the sensing stage [37–40]. The bandwidth-constraint problem is often formulated in the form of calculating the number of bits per sensor and finding the optimal bit allocation amongst sensors given the total number of bits that can be transmitted by the sensor to the fusion center under the assumption of lossless communication [41–46,4,47]. Fusion algorithms for such cases have also been studied in [48–50].

More recently, channel-aware signal processing algorithms that account for non-ideal transmission channels, assuming perfect channel information both at the sensors and the fusion center, were studied in [51–53]. In [54], by relaxing the lossless communication assumption, fusion algorithms combined local decisions that were corrupted during the transmission process due to channel fading. Also, a new likelihood ratio based test was proposed that did not require instantaneous channel state information but only