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# Resource-Constrained Signal Processing, Communications, and Networking

The primary design objective of computing and communication systems has been performance: the speed of signal processing, the rate of communications, and the optimization of quality of service. For wireless systems and networks deployed on a large scale and untethered to power sources, practical considerations dictate a different design regime, one that should be dominated by energy and bandwidth constraints. If thousands of battery-powered, low-cost sensors are to be used for long-term surveillance of areas inaccessible to humans, and if large-scale sensor networks deployed for various applications are to share the already crowded spectrum with existing wireless services, a fundamental shift in design paradigm is necessary: from focusing on performance to focusing on constraints, from maximizing data rate to maximizing resource efficiency.

The set of eight articles in this special section illuminates the impact of resource constraints on the design methodologies of signal processing, communications, and networking. They offer the viewpoint that, to achieve the efficient use of the two principal resources of energy and radio spectrum, wireless systems and networks should be *distributed, cooperative*, and *opportunistic*. This is in sharp contrast with conventional approaches that rely on centralized architectures, with competing users that are limited by worst-case communication scenarios.

## DISTRIBUTED SIGNAL PROCESSING UNDER RESOURCE CONSTRAINTS

Distributed systems allow local data processing, thus reducing the energy consumption and bandwidth requirement incurred in the communications to a fusion center. The first three articles in this special section demonstrate the advantages as well as challenges in distributed signal processing. Specific topics include detection, estimation, and multitarget tracking in the context of wireless sensor networks.

[TO ACHIEVE THE EFFICIENT USE OF THE TWO PRINCIPAL RESOURCES OF ENERGY AND RADIO SPECTRUM, WIRELESS SYSTEMS AND NETWORKS SHOULD BE *DISTRIBUTED, COOPERATIVE, AND OPPORTUNISTIC.*]

Besides resource constraints, the problem of decentralized detection in a wireless setting is further complicated by the fact that the wireless channel is a shared medium. There are a number of possible methods and system architectures that can be used to address this complication. In the first article, Chamberland and Veeravalli provide an overview of extensions to traditional approaches as well as emerging paradigms for detection problems in a wireless network setting.

The next article by Barbarossa and Scutari focuses on distributed statistical inference in wireless sensor networks. The basic idea is to distribute the decision making and have the nodes reach a consensus decision through local information exchange. Barbarossa and Scutari describe a simple self-synchronization mechanism, which is inspired by biological systems, for achieving such consensus in sensor networks. They derive conditions that guarantee convergence of the consensus algorithms to the optimum centralized decision and address energy consumption issues and robustness to fading and propagation delays. They illustrate their results through the statistical inference applications of hypothesis testing and parameter estimation. They make the case that cross-fertilization between mathematical biology and distributed signal processing has great potential for future emerging applications in distributed systems.

Target tracking is one of the most important application areas for distributed sensor networks, both in the military and civilian contexts. The multitarget tracking (MTT) problem is known to be challenging and difficult, even in the centralized setting where all the observations are available at one location and they can be processed jointly without stringent resource constraints. Sensor networks introduce additional challenges due to resource limitations in terms of power, sensing, communication, and computation. Liu, Chu, and Reich provide a survey of the techniques that have been developed for MTT in sensor networks, including some recent developments. They show that it is possible to design a system that efficiently tracks multiple targets using appropriate fusion mechanisms, sensor utility metrics, sensor tasking, and target identity management. They argue that the key to adapting the MTT paradigm to sensor networks is the dynamic management of sensor, network, computational, and energy resources.

### ENERGY EFFICIENCY VIA COOPERATION AND CROSS-LAYER DESIGN

Conventional approaches to networking focus on competing users and adopt a layered protocol architecture. The next two articles take the viewpoint that introducing cooperation among users and allowing close coupling across layers offers improved performance, especially in energy efficiency.

Cooperative communications exploit the spatial diversity in multiuser systems by allowing users with diverse channel qualities to cooperate and relay each other's messages. Optimal resource allocation, adaptive to the channel conditions of individual users, can further enhance the potential gain of cooperative strategies. Hong, Huang, Chiu, and Kuo examine various power-allocation strategies for cooperative networks based on different cooperation strategies, optimizing criteria, and assumptions on channel state information. They further explore the strong similarities between the system structures of cooperative communications and wireless sensor networks where nodes collectively perform a common task. It is demonstrated that wireless sensor networks provide natural applications of cooperative communication techniques.

Meshkati, Poor, and Schwartz address resource allocation from a cross-layer perspective. Using game theory as a unifying framework, they investigate energy-efficient resource management in a variety of wireless networks. The joint optimization of and the interaction between various parameters across different layers are examined, where the parameters considered include transmission power, data rate, modulation, temporal and spatial signal processing techniques, and delay constraints.

### OPPORTUNISTIC NETWORKING AND COGNITIVE RADIO

Instead of a static approach focusing on the worst-case scenario, an efficient use of limited resources requires an opportunistic and adaptive approach that exploits the inherent dynamics of the wireless infrastructure: the dynamics of spectrum usage and the dynamics of channel conditions. This means accessing the medium by capturing instantaneous spectrum vacancies and communicating only when channel conditions are favorable.

[THE DESIGN OF LARGE-SCALE RESOURCE-CONSTRAINED WIRELESS SYSTEMS REQUIRES A MULTIDISCIPLINARY APPROACH WHERE SIGNAL PROCESSING, COMMUNICATIONS, AND NETWORKING CLOSELY INTERACT.]

The article by Ekpenyong and Huang addresses exploiting the channel-state information (CSI) for adaptive transmission to improve energy and spectral efficiency. The transmitter can adapt the transmission power or the data rate to the channel conditions to guarantee a specific level of quality of service. However, CSI is typically known only at the receiver and must be fed back to the transmitter. Ekpenyong and Huang investigate the effect of feedback constraints on adaptive transmission, where feedback constraints include feedback delay, feedback errors, and the limited data rate of the feedback channel.

The next article by Zhao and Sadler focuses on dynamic spectrum access strategies that aim to resolve the paradox between the apparent spectrum scarcity and the pervasiveness of idle frequency bands in both time and space, as revealed by extensive measurements of actual spectrum usage. Zhao and Sadler provide a taxonomy of the diverse ideas envisioned for dynamic spectrum access and an overview of challenges and recent developments in both technological and regulatory aspects. The interactions across signal processing, networking, and regulatory policies are examined.

The physical platform for opportunistic communications and networking is cognitive radios capable of autonomous reconfiguration by learning from and adapting to the communication environment. Will such reconfigurability, however, come at a price of high energy consumption? The last article of this special section addresses the tradeoff between reconfigurability and energy scalability in cognitive radios. Dejonghe et al. provide an overview of cognitive radio architectures and their building blocks, showing how such architectures can provide benefits over conventional radios.

The design of large-scale resource-constrained wireless systems is complex. It requires a multidisciplinary approach where signal processing, communications, and networking closely interact. The articles in this special section offer only representative examples on the challenges and recent developments in this research area. It is our hope that these articles will stimulate interests in the signal processing community in reformulating and revisiting classic signal processing problems under new constraints and exploring the role of signal processing in exciting new applications such as cognitive spectrum-agile networks. [SP]