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Adaptation and Learning over Complex Networks

The topic of this special issue of *IEEE Signal Processing Magazine* is timely and deals with a subject matter that has been receiving immense attention from various research communities, and not only within the signal processing community. Extensive research efforts on information processing over graphs exist within other fields such as statistics, computer science, optimization, control, economics, machine learning, biological sciences, and social sciences. Different fields tend to emphasize different aspects and challenges; nevertheless, opportunities for mutual cooperation are abundantly clear, and the role that signal processing plays in this domain is of fundamental importance. This is because, in all these fields, there is growing interest in performing inference and learning over graphs, such as deducing relationships from interconnections over social networks, modeling interactions among agents in biological networks, performing resource allocation distributively, passing information over networks, optimizing utility functions over graphs, adapting and learning over graphs, etc. Commonalities and significant signal processing run across all these applications. The articles in this special issue help highlight this interplay among disciplines and the significant role that signal processing plays in this domain.

TWO SPECIAL ISSUES

Due to the highly cross-disciplinary nature of complex networks, the tutorial articles in this issue of *IEEE Signal Processing Magazine* are coupled with high-quality technical articles covering new advances in the field, which appear in a second special issue: the April 2013 issue of *IEEE Journal of Selected Topics in Signal Processing (JSTSP)*, organized by the same guest editors. In this way, the survey articles in the magazine help introduce readers to advances in important relevant domains, while the more focused technical articles in *JSTSP* cover state-of-the-art advances in the field. Through this combination of tutorial and technical articles in both the journal and the magazine, readers will become better acquainted with the challenges and opportunities that the broader field of network science has to offer across the specialties of information sciences, system science, computer science, biological sciences, physics, economics, machine learning, and optimization theory. Complex networks represent a typical paradigm that helps demonstrate well how barriers among seemingly different disciplines are becoming more transparent.

[THE ARTICLES IN THIS SPECIAL ISSUE HELP HIGHLIGHT THIS INTERPLAY AMONG DISCIPLINES AND THE SIGNIFICANT ROLE THAT SIGNAL PROCESSING PLAYS IN THIS DOMAIN.]

THE WORLD OF COMPLEX NETWORKS

Self-organized and complex patterns of behavior are common in many biological networks, where no single agent is in command and yet remarkable forms of self-organization and decentralized intelligence are evident. Examples include fish joining together in schools, birds flying in formation, bees swarming toward a new hive, and bacteria diffusing toward a nutrient source. While each individual agent in these biological networks is not capable of complex behavior, it is the combined coordination among multiple agents that leads to the manifestation of sophisticated order at the network level. The study of these phenomena opens up opportunities for collaborative research across several domains to address and clarify several relevant questions such as how and why organized behavior arises at the group level from interactions among agents without central control; what communication topologies enable the emergence of order at the higher level from interactions at the lower level; and how information is processed during the diffusion of knowledge through the network. Several disciplines have been concerned in elucidating different aspects of these questions including evolutionary biology, animal behavior studies, physical biology, and even computer graphics. In the realm of signal processing, these questions motivate the need to study and develop decentralized strategies for information processing that are able to endow complex networks with real-time adaptation and learning abilities.

Complex networks are prevalent in modern science, and their reach extends beyond biological networks. For example, these networks can help model and study how individuals are linked over social networks; they can describe the range of activities in macroeconomies, or even model pathways defined over

Digital Object Identifier 10.1109/MSP.2013.2240191
Date of publication: 5 April 2013

complex power grids, transportation grids, and communication grids. In many such complex systems, especially those encountered in nature, it is common for emergent behavior to arise from the interaction among individual agents, as happens with fish schooling or bird flight formations. Research efforts to decipher the intricacies of such complex networks have been progressing steadily in the sciences and a close synergy has been evolving between, for example, studies on self-organization in the social and biological sciences and studies on adaptive networks in the information and system sciences. There are ample opportunities for cross-disciplinary research to understand and reverse-engineer the decentralized intelligence encountered in social, economic, or biological networks. Although biological networks provide inspiration for the design of powerful engineered networks, the resulting theory and algorithms are applicable to a broader context including machine learning applications, distributed optimization problems, and cooperative processing over cognitive networks.

ADAPTIVE NETWORKS

Adaptive or cognitive networks consist of spatially distributed agents that are linked together through a connection topology. The topology may vary with time and the agents may also move. The agents cooperate with each other through local interactions and by means of in-network processing. Such (distributed adaptive) networks are well suited to perform decentralized information processing, decentralized optimization, and decentralized inference tasks. They are also well suited to model and understand self-organized and complex behavior encountered in nature and in social and economic networks. The articles included in this issue of *IEEE Signal Processing Magazine* cover a wide range of topics that are relevant to the study of complex networks such as:

1) "Models for the Diffusion of Beliefs in Social Networks" by Chamley et al. The article describes some basic mathematical models used in economics and uses them to gain insight into social behavior and to explain how individuals influence each other decisions in society.
2) "Learning in Network Games with Incomplete Information" by Eksin et al. The authors examine opinion dynamics over social networks when complete information about the state of the environment is not available, and they describe algorithms for social learning.
3) "Social Learning and Bayesian Games in Multiagent Signal Processing" by Krishnamurthy and Poor. The authors provide an overview of Bayesian games in adaptive sensing problems over graphs and examine their global behavior.
4) "Machine Learning with Brain Graphs" by Richiardi et al. This article explains how graphs provide a useful tool to represent the spatiotemporal dynamics within the brain and discusses the use of machine learning techniques for brain connectivity data.
5) "Seeing the Bigger Picture" by Bertrand and Moonen. The authors describe distributed techniques that enable nodes to infer the network topology from in-network distributed processing.
6) "The Emerging Field of Signal Processing on Graphs" by Shuman et al. The authors discuss graph spectral properties and review techniques to extend classical signal processing operations such as filtering, translation, modulation, and downsampling to the graph setting.
7) "Consensus + Innovations Distributed Inference over Networks" by Kar and Moura. Consensus strategies for inference over graphs are described where agents interact locally without any central coordination.
8) "Nonparametric Bayesian Modeling of Complex Networks" by Schmidt and Mørup. The article provides an overview of useful techniques that enable users to derive nonparametric models for complex networks from observed data.
9) "Dynamic Network Cartography" by Mateos and Rajawat. The article surveys signal processing techniques to model, monitor, and manage dynamic network behavior to construct network state maps and to reveal network anomalies.
10) "Swarming Algorithms for Distributed Radio Resource Allocation" by Di Lorenzo and Barbarossa. The authors describe useful mathematical swarming models that endow communication networks with efficient and robust decentralized radio resource allocation mechanisms.
11) "Diffusion Strategies for Adaptation and Learning over Networks" by Sayed et al. The article describes strategies for adaptation and learning over graphs and considers applications in distributed sensing, biological networks, intrusion detection, machine learning, and optimization.

We express our deep gratitude to the many reviewers who have helped us improve the quality of the final articles. We are confident that readers will find this collection of articles interesting and appealing. Readers are encouraged to consult the technical articles in the accompanying April 2013 special issue of *IEEE JSTSP* for an even broader perspective on the field.

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