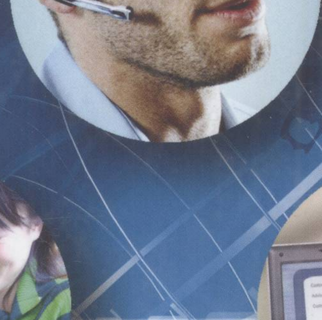
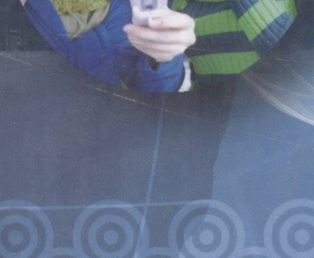
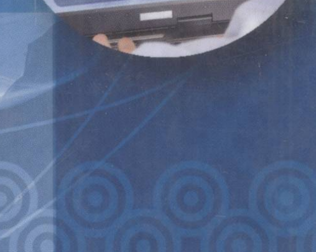
Edited by **Qusay H. Mahmoud**

COGNITIVE NETWORKS

Towards Self-Aware Networks







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COGNITIVE NETWORKS

To the authors of the individual chapters, without whom this book would not exist.
And to readers of this book, who will be the future innovators in the field

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Foreword 1

Professor Qusay H. Mahmoud ('Q') has contributed a landmark to the evolution of cognitive radio technologies with the publication of his text, *Cognitive Networks*. Specifically, this text clearly marks the beginning of the transition of cognitive radio from enabling technologies in relatively abstract, academic and pre-competitive settings to more clearly address what might be called the critical business-case enablers for broad market relevance. From its introduction at KTH, The Royal Institute of Technology, Stockholm, in 1998, cognitive radio has been about market relevance, overcoming the superficial lack of radio spectrum by pooling, prioritization and space–time adaptation to not just the radio frequency (RF) situation, but also to the needs of the users in the scene. Textbooks to date, however, have contributed more significantly to the foundations of the technology or to relatively small market segments such as secondary spectrum or ad hoc networks than to the broader Internet-scale wireless markets of increasingly heterogeneous cellular services and commodity consumer electronics. Communications networks for these broader real-world markets typically must be (or become) secure, scalable, reliable, controllable, interoperable and, of course, billable. It is difficult to state the importance of Q's book in a few words. Although a few chapters (like my own) are more foundational than transitional, most of the chapters move cognitive networks solidly along a transition from theory to practice.

Let me offer a few highlights that qualify as paradigm shifts. First, Hervé Debar's (France Télécom) chapter (Chapter 12) on intrusion detection in cognitive networks draws on the IETF's intrusion detection working group to characterize the problem of knowledge attack and to structure management and policy plans with operations that define a paradigm shift in network security. Since cognitive networks are inherently flexible in the extreme, it would be difficult or impossible for cognitive wireless networks (CWNs) to transition from theory and niche applications to broadly applicable practice without a solid handle on security. This chapter addresses in a systematic way, the intrusion detection aspect of information security framed comprehensively by Mathur and Subbalakshmi in their companion chapter on security issues, which characterizes security issues from availability and access to privacy and non-repudiation, along with classes of attack that would be problematic for CWNs in the literature. Although Debar's chapter addresses only intrusion detection in detail, this pair of chapters set a high standard indeed for the articulation of a critical transition issue – security – and the related contribution that shows the way towards transition.

In another important chapter (Chapter 2), Motorola calls the foundational layers of reconfigurable wireless networks the 'autonomic' layers, adapting IBM's term, an allusion to the autonomic nervous system of mammals that controls involuntary actions such as heart beat and respiration. Although I prefer my own original cognition cycle – observe, orient, plan, decide, act and learn – to the simpler Motorola–IBM cycle – monitor, analyze, plan and execute (with knowledge in the middle, but without learning) – their FOCALE architecture that realizes the cycle in cognitive networks ties learning to business goals. That's a big improvement on my own OOPDAL loop, which wasn't explicitly tied to the inevitable business logic from which the revenue comes. This chapter, like several others, also introduces 'layers' and related objects and relationships for services, management and the control of the foundational reconfigurable networks. I found the differences in device interface language for controlling different kinds of routers compelling evidence for what I call computational semantics interoperability: they proposed an ontology-mapping construct as essential for the transition towards practical cognitive networks.

The MITRE chapter by Ginsberg, Horne and Poston (Chapter 10) develops this notion of semantic interoperability among heterogeneous networks further, drawing on the web ontology language (OWL) from the semantic web community, in some sense a technology looking for a problem that may in fact have found a home in the creation of machine-readable specifications. When I teach radio engineering courses in the US, almost no radio engineers have used Z.100, the International Telecommunications Union's standard specification and description language (SDL) for digital systems, particularly for the state machines and message sequence charts (MSC) of radio. Not so in Europe where Z.100 was invented so that engineers from across the EC could collaborate in the mathematical language of SDL. For me, it was a watershed event when a few years ago, the GSM MoU committee determined that the machine-readable SDL would be normative while the human-readable text would be explanatory, reversing decades-long practice that the natural language text of a specification be normative while the figures and computer-readable code in the specification be illustrative.

In this context, Boutaba and Xiao's chapter (Chapter 4) on self-managing networks shows how the technical ideas of semantic interoperability have substantial cost leverage: 80% of information technology is expended on operations and maintenance, with nearly half of service outages caused by human error. Although the telecommunications industry continues to automate, it is on the edges of heterogeneous networks – the wired and the wireless, the multi-standard to the core network – that the contribution of cognitive networks becomes most evident. Lu *et al.* survey a broad scope of ideas, approaches and architectures for self-management in Chapter 3 on adaptive networks. One of the more intriguing is the ant colony idea developed in greater detail by Liebnitz *et al.* in Chapter 1 on biologically inspired networking. Behavior, after all, is crucial. Their first figure shows how the price of scaling up to Internet-sized networks is a loss of determinism because the overhead of centralized control becomes prohibitive as network size increases into the millions and billions of nodes. Reminiscent of foundational work in artificial life by Stuart Kaufman (*At Home in the Universe* and the Artificial Life proceedings of the Santa Fe Institute), Leibnitz *et al.* remind us that biologically inspired architectures may fall short of optimal in some respects, but also may be more robust in dealing with catastrophe. Their mathematical treatment and simulations each relate back to important properties of cognitive networks that enable transition to Internet scale.

Not to condemn with faint praise, all of the chapters, including those not yet mentioned in this brief note, each contribute importantly to critical issues in cross-layer optimization, coding, distributed learning and overall cognitive network robustness. I'm sure the growing community of cognitive radio will benefit greatly from this important work.

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Foreword 2

Cognitive networking is being hailed as the next holy grail of (and a potentially disruptive technology in) wireless communication. Although it is a very broad term, it simply means an intelligent communication system (consisting of both the wireline and/or the wireless connections) that is aware of its environment, both internal and external, and acts adaptively and autonomously to attain its intended goal(s). This implies that all the network nodes and the end devices are self-aware and context-aware all of the time. This is a grand long-term vision; still, for a good period of time, policy-based approaches will continue to rule in large parts of the solution while cognitive approaches slowly make their inroads, which is already happening today. The interest in cognitive networking is mainly driven from the need to manage complexity and the efficient utilization of available resources to deliver applications and services as cheaply as possible.

Increasing complexity of the communication networks is a growing challenge for network designers, network operators and network users. It would seem that the recent advances in cognitive radio and networks might offer the perfect solutions to these problems, even though the Internet certainly continues to enable the integration of a wide-range of transport mediums, connecting billions of mobile and fixed terminals, devices and sensors at homes and businesses. (The estimates are that by the year 2017, there will be roughly 7 trillion wireless devices serving 7 billion people around the globe – *Technologies for the Wireless Future, WWRF,* John Wiley & Sons, Ltd, 2006). With the applications and use cases growing unabatedly across body, personal, home, business, vehicle and wide area networks, the spatio-temporal complexity and traffic dynamics continue to increase. These are increasing the burden on the available network resources and their operational management, making the lives of the network administrators and users cumbersome. This begs the answer to the question of how this increased complexity can be reasonably managed without adding more complexity while also distancing the users and the network owners from spending their time on network operations and management.

Until now, cognitive networking has been mostly studied from the spectrum and radio perspective. Recently much interest has arisen in applying the concepts from other fields, such as machine learning, semantics, complex network theories from the natural systems, statistical physics, chemistry, evolution, ecology, mathematics and economics, that mimic the behavior of the communication networks of today. The latter constitutes a more revolutionary approach to cognitive networks. After all, the natural systems embody complex communication networks that are self-healing and robust. This attempt to cross-fertilize the ideas is clearly in an embryonic stage and most of the actual work still lies ahead of us. Nevertheless, I believe that such an effort is well warranted to bring an order of magnitude of improvement in the performance, improvement in the reliability and robustness, improvement in the utilization of resources, reduction in the cost of operations, and lowering of the cost of services to the user.

This is the first book of its kind that brings together the ideas from very different fields in one place to show the interplay between them and how can they be used to build the cognitive networks of the future that we envision. I am glad to see chapters on biologically inspired networking, autonomic networking, adaptive networking, self-management, machine learning, cross-layer design, distributed learning and reasoning, semantics and security, all of which open up new vistas to research in cognitive networks. I congratulate Dr. Mahmoud for successfully assembling the well-known experts in those fields to provide a cohesive and step-by-step approach to cognitive networks. I have enjoyed reading the manuscript, and I am sure you will too!

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Preface

Networks touch every part of our lives, but managing such networks is problematic and costly. Networks need to be self-aware to govern themselves and provide resilient applications and services. Self-awareness means that learning is a crucial component to reduce human intervention, and hence the need for biologically inspired, or non-deterministic, approaches. While some of the existing breakthroughs in machine learning, reasoning techniques and biologically inspired systems can be applied to build cognitive behavior into networks, more innovations are needed.

In the wireless space, the Industrial/Scientific/Medical (ISM) band has inspired impressive technologies, such as wireless local area networks, but interference is becoming increasingly problematic due to the overcrowding in this popular band. In addition, the cellular wireless market is in transition to data-centric services including high-speed Internet access, video, audio and gaming. While communications technology can meet the need for very high data link speeds, more spectrum is needed because the demand for additional bandwidth is continuously increasing due to existing and new services as well as users' population density. This calls for intelligent ways for managing the scarce spectrum resources.

The cognitive radio terminology was coined by Joseph Mitola III and refers to a smart radio that has the ability to sense the external environment, learn from the history and make intelligent decisions to adjust its transmission parameters according to the current state of the environment. Cognitive radio leverages the software defined radio (SDR), which offers a flexible configurable platform needed for cognitive radio implementation. Cognitive radio offers the potential to dramatically change the way spectrum is used in systems and increase the amount of spectrum available for wireless communications.

Cognitive (wireless) networks are the future, and they are needed simply because they enable users to focus on things other than configuring and managing networks. Without cognitive networks, the pervasive computing vision calls for every consumer to be a network technician. The applications of cognitive networks enable the vision of pervasive computing, seamless mobility, ad hoc networks and dynamic spectrum allocation, among others.

This is the first book on cognitive networks which clearly indicates that cognitive network design can be applied to any type of network, being wired or wireless. It provides a state-of-the-art guide to cognitive networks and discusses challenges for research directions. The book covers all important aspects of cognitive networks including chapters on concepts and fundamentals for beginners to get started, advanced topics and research-oriented chapters.

This book offers an unfolding perspective on current trends in cognitive networks. The lessons learned and issues raised in this book pave the way toward the exciting developments of next-generation networks.

Audience

This book is aimed at students, researchers and practitioners. It may be used in senior undergraduate and graduate courses on cognitive networks, adaptive networks, wireless networks and future-generation networks. Students and instructors will find the book useful as it provides an introduction to cognitive networks, their applications and research challenges. It provides researchers with a state-of-the-art guide to cognitive networks, as well as pointers to who else is doing what in the field. Practitioners will find the book useful as general reading and as a means of updating their knowledge on particular topics such as adaptive networks, self-managing networks, autonomic networking, cross-layer-design, cognitive radio technology, machine learning and security issues in cognitive networks.

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My family has provided me so much throughout this project – and many others. Your patience and love sustain me and keep me going.

Qusay H. Mahmoud
Toronto, Canada

Introduction

Motivation

As the Internet moves well beyond the classical services of email, file transfer and remote login, and as the explosion of Internet portable devices continues, the applications and services needed to support mobility will have different network requirements. This has motivated research on active and programmable networks, on a large scale in the 1990s, which represents a novel approach to network architecture in which the switches perform customized computation on the messages flowing through them [11]. The objective was to make the network adaptive and programmable, but despite the many research projects, networks still have to be managed by human administrators. This is simply because the network is still not aware of its state or needs, and doesn't have knowledge of its goals and how to achieve them, and it is not able to reason for its actions [10]. Such properties would render the network adaptive and self-governed. Current data networking technology perform reactive adaptation by responding to changes in the environment after a problem has occurred [12]. Instead, adaptation should be proactive by actively affecting the network when the environment changes.

Mobile computing is becoming pervasive but in order to reach its full potential, significant improvements are needed in usability of end users and manageability of administrators [8], which can be realized by incorporating intelligence into the network environment, and autonomic networking is the key into this area. Autonomic networking connotes the self-regulating capability of the human nervous system. An autonomic computing system needs to know and understand itself. The system will need detailed knowledge of its components, operating environments and connections to other systems. To function properly, it will need to know the resources it owns, the ones it can borrow, lend, buy or simply share with others.

Networks need to be self-aware in order to provide resilient applications and services. Such networks should exhibit cognitive properties where actions are based on reasoning, autonomic operations, adaptive functionality and self-manageability. However, it is important to note that the concept of cognitive networks is different from intelligent networks that have been considered by the telecommunications community in the past, in the sense that in a cognitive network actions are taken with respect to the end-to-end goals of a data flow. In such a network, the collection of elements that make up the network observes network conditions and based on prior knowledge gained from previous interactions, it plans, decides and acts on this information [12]. However, as discussed in this book, there is a performance issue with cognitive techniques since such systems would not reach their performance level instantly; there is an adaptation step. Such systems, however, have a higher resilience towards critical errors.