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Cognitive Radio Networks

From Theory to Practice

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To my great parents, Ahmed Khattab
To my beloved family, Dmitri Perkins
To my dear students, Magdy Bayoumi

Preface

Cognitive Radio Networks (CRNs) are the key enabling technology for realizing Opportunistic Spectrum Access (OSA) to alleviate the severe spectrum underutilization and provide a solution to the wireless spectrum scarcity. OSA refers to the communications paradigm in which the communicating parties dynamically exploit the spectrum bands that are not utilized by the primary wireless services licensed to operate over such bands. CRNs are foreseen as the future of wireless communication technologies that provide wireless connectivity for emerging services. The main component of CRNs, and hence OSA, is the cognitive radio transceiver. A cognitive radio is a wireless device that senses the surrounding radio environment and opportunistically accesses the unutilized spectrum band(s) based on its assessment of the activities of the surrounding primary licensed networks. OSA in distributed ad-hoc CRNs is the focus of significant research interest, especially from a theoretical perspective. The resulting theoretical OSA approaches are challenged by the practical limitations of existing cognitive radios. The focus of this book is on the less well-studied issue of implementing distributed Opportunistic Spectrum Access given practical radio transceiver technologies.

This book distinguishes itself from the existing affluent literature of CRNs and OSA. Existing literature can be classified into two categories: One that presents a self-contained introduction of the emerging Cognitive Radio Networking paradigm outlining the theoretical fundamentals and requirements for enabling such a technology. The emphasis of such books is on the theoretical design, optimization, and performance evaluation of Opportunistic Spectrum Access in CRNs. The second—and more related—category is mainly concerned with the implementation of CRNs using software-defined radios (SDR). While SDR provided seamless flexibility in the design and implementation of CRNs due to the fact that the design is carried out in software, SDR-based CRN implementations lag orders of magnitude behind realistic communication speeds. In contrast, this book:

- Incorporates the practical implementation constraints and issues in the theoretical formulation of the Opportunistic Spectrum Access problem in distributed CRNs

and presents a first-of-its-kind analytically optimized framework for designing distributed ad-hoc CRNs based on contemporary radio transceiver technologies.
- Provides an in-depth illustration of the implementation of such a framework that shows that Opportunistic Spectrum Access and CRNs can indeed be implemented using traditional hardware rather than only being restricted to the SDR implementations presented in the related literature that cannot achieve the high communication speeds of today's world.
- Quantifies the gains that existing theoretical approaches can attain by adopting the individual components of the proposed practical OSA framework that were designed in lieu of the common practices of contemporary radio technologies.

This book is the first to combine CRN theory with practice and target real-life technologies. It serves as a guide in the transition from conventional communications to cognitive radio communications without assuming currently unavailable transceiver technologies as the case with existing theoretical approaches which are only implementable using SDR platforms.

The main challenge of existing distributed opportunistic spectrum management schemes is that they do not consider the unavoidable practical limitations of today's Cognitive Radio Networks such as the inability to measure the interference at the primary receivers. Consequently, optimizing the constrained Cognitive Radio Network performance based only on the local interference measurements at the cognitive radio senders does not lead to truely optimal performance due to the existence of hidden or exposed primary senders. More specifically, existing schemes have a cognitive radio sender decide its transmission strategy based on its local interference measurement—while such decisions should have been made based on the interference measurement at the nearby primary receivers to be interfered with its transmission. However, there does not exist a practical mechanism that enables a cognitive radio to determine the interference at nearby primary receivers. Furthermore, existing transceiver technologies and spectrum measurement techniques are incapable of accurately assessing the spectrum usage over a wide frequency range due to the limitations imposed by the transceiver hardware.

Cognitive Radio Networks: From Theory to Practice presents a probabilistic framework for opportunistic spectrum management that optimizes the constrained cognitive user goodput while taking the unavoidable sources of spectrum sensing inaccuracy into account. This book introduces the Rate-Adaptive Probabilistic (RAP) spectrum management approach that (1) probabilistically explores individual spectrum bands as local interference measurements lead to inaccurate spectrum access decisions and (2) adopts a non-greedy probabilistic spectrum access policy that prevents a single cognitive transmission from monopolizing an available spectral opportunity, and hence allows multiple cognitive flows to fairly share the available bandwidth without explicit coordination. In contrast, existing opportunistic spectrum management techniques greedily use the highest possible power/rate only over the best frequency band thought to be available. Furthermore, such techniques require explicit coordination between different cognitive flows to ensure fairness in opportunity sharing.

The book presents the analytical formulation of the CRN performance optimization problem of the proposed RAP approach as a mixed integer non-linear program to derive its optimal probabilities and powers/rates. Packet-level simulations are used to evaluate the RAP performance and demonstrate its gains in arbitrary large-scale ad-hoc networks. The large-scale simulation results show that such a probabilistic approach achieves up to 138% higher goodput compared to greedy and hypothetically optimal approaches with significantly better fairness at the expense of slightly higher primary network outages within their permissible limits.

Finally, the proposed Opportunistic Spectrum Access approach is implemented using the Wireless open Access Research Platform (WARP) to demonstrate its superior performance in a real system. Our empirical results show that the proposed RAP approach indeed achieves multiple folds increase in the achieved goodput (up to 673% gain) compared to existing Opportunistic Spectrum Access approaches especially with highly active primary networks. We conclude that despite relying on simple cognitive radio hardware, this book presents a practical distributed opportunistic spectrum management approach which outperforms existing theoretical approaches that assume fully capable cognitive radios.

This book is an extension of the Ph.D. dissertation of Dr. Ahmed Khattab submitted to the University of Louisiana at Lafayette under the supervision of Dr. Dmitri Perkins and Dr. Magdy Bayoumi. We started this work at the Center of Advanced Computer Studies (CACS) at the University of Louisiana at Lafayette in 2009 using the facilities of the Wireless Systems and Performance Engineering Research (WiSPER) and the Very Large-Scale Integration (VLSI) research laboratories.

Cognitive Radio Networks: From Theory to Practice targets a wide range of readers including but not limited to researchers, industry experts, and graduate students. On the one hand, readers with theoretical interests will experience an unprecedented treatment of the conventional CRN performance optimization problem that takes into account the practical limitations of today's technologies. On the other hand, readers interested in real-life distributed CRN realization will be exposed to a first-of-its-kind clean-slate implementation approach that demonstrates the significant multi-faced performance improvement achieved by practical OSA.

This book offers the reader a range of interesting topics portraying the current state-of-the-art in cognitive radio technologies. In simple terms, while several existing Opportunistic Spectrum Access approaches have been developed and theoretically optimized, they are challenged by the inherent constraints of practical implementation technologies. Analyzing these constraints and proposing an attractive and practical solution to counter these limitations are the basic aims of this book. This book presents the set of practical OSA system components that the interested reader will be able to glean information not only to incorporate into his/her own particular OSA design problem, but also most of all to experience an enjoyable and relatively effortless reading, providing the reader with intellectual stimulation.

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