Developments in Cognitive Radio Networks

Bodhaswar TJ Maharaj
Babatunde Seun Awoyemi

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Future Directions for Beyond 5G

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Bodhaswar TJ Maharaj
University of Pretoria
Pretoria, South Africa

Babatunde Seun Awoyemi
University of Pretoria
Pretoria, South Africa

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To family

Foreword

The field of cognitive radio networks is an important field in the development and realization of modern and future wireless communication networks. As the technology evolves, it is necessary to have not just an up-to-date account of its current state in the evolution process but also a detailed insight into its prospects and directions, especially in its drive towards being a key player in the nearest future of wireless communications. Thankfully, this book titled, 'Developments in Cognitive Radio Networks: Future Direction for Beyond 5G' meets this need perfectly.

In the book, the authors provide a brief history on cognitive radio networks before delving into the important aspects of spectrum and resource realization and utilization for modern cognitive radio networks. The book exposes the most recent methods and models for resource optimization in cognitive radio networks and presents adequate analysis of these methods and models. It then examines the latest tools and techniques being employed to drive cognitive radio networks in the beyond 5G era, such as the concepts of queuing theory, cooperative diversity, stochastic geometry and deep learning. Ultimately, the book explores the promising prospects and applications of cognitive radio networks to most other emerging technologies such as fifth and sixth generation networks, internet-of-things, advanced wireless sensor networks, smart cities, fourth industrial revolution and many more. The book is thus comprehensive and compelling in its approach and answers and will definitely be worth the while for all open-minded readers, engineers and researchers keen on learning and advancing the field of cognitive radio networks.

The authors are well-known colleagues and seasoned researchers in the field of wireless communications. The authors' contributions to modern wireless communications are well covered in various IEEE conferences and journal article publications. Most of their works have been presented through patents, articles, book chapters and books in the well-established platforms in Electronic and Computer Engineering and Telecommunications.

It is therefore with deep pleasure that I introduce and welcome this book into the body of knowledge in the field of cognitive radio networks and trust that many will find this a useful text.

Johns Hopkins University, Baltimore, MD, USA Ashutosh Dutta, Ph.D.

Fellow of the IEEE
IEEE Future Networks Founding Co-Chair
IEEE Communications Society Distinguished Lecturer
Member-At-Large—IEEE Communications Society
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Preface

For years now, the cognitive radio networks (CRN) has continued to evolve as a leading technology to help drive modern and near-future wireless communication possibilities. With its impressive prospects and intriguing promises, more efforts and means are being dedicated to studying and developing CRN models that can achieve outstanding results and remarkable performances. Notably, there are already a plethora of volumes on the CRN so much that the need for another book on this subject may be rightly questioned. In response, the authors' perspective is that, despite the sizeable number of volumes on the CRN, most volumes seem to have been too narrow or unintentional in their approach of the CRN. Indeed, there are works that have focussed on the sensing of unused or underutilised radio-frequency spectrum for possible CRN application. There are other works that have focussed on making the sensed spectrum available to help drive CRN operations, and so on. However, there is still a need for a concise but comprehensive book on the CRN that covers all the essential aspects, while also presenting the most recent research ideas and developments on the subject matter. This new book is designed to address that opportunity.

The first part of the book provides the necessary background on the CRN and extends to cover the important aspect of spectrum for the CRN. The spectrum is well established as the most important resource for the CRN. Because of the spectrum's importance in the CRN scheme, emphasis is laid on the need to discover and implement the most efficient techniques for sensing unused and/or underutilised spectrum for an effective CRN realisation. Then, important recent developments and new findings from various spectrum sensing efforts for CRN applications are discussed in depth. Also, the most recently advanced techniques for achieving optimal or near-optimal spectrum sensing for the CRN, particularly the aspects of *cooperative sensing* and *predictive sensing*, are generously explored.

The second part of the book presents the CRN as being *beyond just the spectrum*. While the spectrum is indeed very important for the CRN, there are several other resources—bandwidth, timeslots, data rates, transmission power and others—that must be equally considered for an effective CRN realisation. In that case, the spectrum must be jointly considered, alongside these other CRN resources, in order

to achieve and provide optimal and near-optimal solutions to help realise the utmost for the CRN. This is covered under the broad aspect of resource allocation (RA) optimisation for the CRN. In that second part of the book, the most appropriate optimisation tools for RA in the CRN are exposed, new and/or improved RA models and solutions for modern CRN application are examined, and the performance analyses of the new RA models are extensively carried out.

In the final part of the book, the most recent developments in CRN modelling, applications, evaluations and eventual realisation, are explored. In this part, analytical concepts such as *queuing theory* and *stochastic geometry* and technical concepts such as *cooperative diversity* and *machine/deep leaning* are established as important new ideas and approaches that are being introduced into the modern RA models for the CRN. These relatively newly introduced concepts are specifically incorporated to help improve the design, analyses and solutions of the CRN models, to address the aspect of interference management and control, to mitigate the effects of interference and other limiting constraints, and/or to achieve an overall greater resource management and productivity for the CRN. In this part still, as part of the ongoing developments in the CRN, some of the significant areas in which the CRN is impacting and will continue to impact emerging technologies such as the fifth-generation and the internet-of-things, and its impact on the drive towards the realisation of smart cities and a globally interconnected world, are discussed. Important contributions on how to help fast-track these new technologies and possibilities through the CRN are graciously offered.

In all, the unique feature of this book is that it is able to concisely relate all the important aspects of the CRN—spectrum sensing, spectrum availability, resource optimisation and others—in one simple piece, thereby providing a more holistic perspective about the CRN than most other volumes that are available on the subject. The book stands out from others in that it distinctly integrates the *new and improved ideas on spectrum sensing* with the *recent, most viable solutions on resource optimisation*, as currently achievable for the CRN. The striking contribution of the book is therefore that it successfully *brings together under one title all the important tools needed to get the most from the CRN*. The authors envisage that this book will assist new researchers and graduate students in understanding the field of CRN better and also trigger new opportunities and future research directions in this fast evolving area of modern telecommunications.

University of Pretoria, Pretoria, South Africa — Bodhaswar TJ Maharaj

University of Pretoria, Pretoria, South Africa — Babatunde Seun Awoyemi

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Contents

Acronyms

5G	Fifth generation
AI	Artificial intelligence
AMC	Adaptive modulation and coding
BnB	Branch-and-bound
BPP	Binomial point process
BPSK	Binary phase shift keying
BS	Base station
CR; CRs	Cognitive radio; Cognitive radios
CRN	Cognitive radio network
CSU	Cooperative secondary user
DL	Deep learning
DRL	Deep reinforcement learning
DSA	Dynamic spectrum access
FCC	Federal Communications Commission
HetNet	Heterogeneous networks
IoT	Internet of things
ILP	Integer linear programming
LMI	Linear matrix inequalities
LP	Linear programming
LTE	Long-term evolution
MARA	Margin adaptive resource allocation
MATLAB	Matrix laboratory
MDPs	Markov decision processes
MHCP	Matern hardcore point process
MIMO	Multiple input multiple output
MINLP	Mixed integer non-linear programming
ML	Machine learning
NLP	Non-linear programming
NOMA	Non-orthogonal multiple access
NP	Non-deterministic polynomial-time
NRT	Non-real time

OfCom	Office of communications
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
PCP	Poisson cluster process
PGFL	Probability generating functional
PHP	Poisson hole process
PPP	Poisson point process
PT; PR	Primary transmitter; Primary receiver
PU; PUs	Primary user; Primary users
QAM	Quadrature amplitude modulation
QoS	Quality of service
RA	Resource allocation
RT	Real time
RARA	Rate adaptive resource allocation
SG	Stochastic geometry
SGD	Stochastic gradient descent
SINR	Signal-to-interference plus noise ratio
SIR	Signal-to-inference ratio
SNR	Signal-to-noise ratio
SSU	Source secondary user
ST; SR	Secondary transmitter; Secondary receiver
SU; SUs	Secondary user; Secondary users
SUBS	Secondary user base station
WSN	Wireless sensor network
xG	Next-generation
YALMIP	Yet another LMI parser

Symbols

$K; k$	Total number of heterogeneous secondary users; k is used to identify a particular user
K_1	Number of category one secondary users; number of category two users is $K - K_1$ (or K_2)
$N; n$	Number of available OFDMA subchannels; n is used to identify a particular subchannel
L	Number of primary users
$H^c_{k,n}$	Channel gain between SUBS and SU at the kth SU over the nth subchannel
$H^s_{k,n}$	Channel gain from SSU to CSU at the kth SU over the nth subchannel
$H^r_{k,n}$	Channel gain from CSU to D at the kth SU over the nth subchannel
$P^s_{k,n}$	Transmit power from SSU to CSU at the kth SU over the nth subchannel
$P^r_{k,n}$	Power from CSU to D at the kth SU over the nth subchannel
$c_{k,n}$	Data rate at the kth SU over the nth subchannel
$c^s_{k,n}$	Data rate from SSU to CSU at the kth SU over the nth subchannel
$c^r_{k,n}$	Data rate from CSU to D at the kth SU over the nth subchannel
$c_{k,n,D}$	Data rate at the kth SU over the nth subchannel for direct transmission
$c_{k,n,C}$	Data rate at the kth SU over the nth subchannel when cooperation is employed
$P_{k,n,D}$	Transmit power at the kth SU over the nth subchannel for direct transmission
$P_{k,n,C}$	Transmit power at the kth SU over the nth subchannel when cooperation is employed
$P_{\max}$	Total transmit power at SUBS
$\boldsymbol{x}$	Bit allocation vector
$\boldsymbol{x_I}; \boldsymbol{x_{II}}$	Bit allocation vector for a category one SU; bit allocation vector for a category two SU
$\boldsymbol{b}$	Modulation order vector
$\boldsymbol{b_I}; \boldsymbol{b_{II}}$	Modulation order vector for category one SU; modulation order vector for a category two SU
$\boldsymbol{p}$	Power transmission vector

$\boldsymbol{p_D}$	Power transmission vector for direct communication
$\boldsymbol{p_C}$	Power transmission vector for cooperative communication
R_K	Minimum rate demand of a category one SU
γ_K	Proportional rate constraint for a category two SU