

Preface

1 Introduction

Cognitive radio (CR) is an enabling technology to allow unlicensed (secondary) users to exploit the spectrum allocated to licensed (primary) users in an opportunistic manner. CR is widely considered as a promising technology to deal with the spectrum shortage problem caused by the current inflexible spectrum allocation policy. It is capable of sensing its radio environment, and adaptively choosing transmission parameters according to sensing outcomes, which improves cognitive radio system performance and avoids interfering with primary users. CR has been considered in mobile ad hoc networks (MANETs), which enable wireless devices to dynamically establish networks without necessarily using a fixed infrastructure. CR technology will have significant impacts on the performance in wireless networks, especially in MANETs. Certainly, issues in non-cognitive MANETs in general are still of interest in the CR paradigm. However, some distinct characteristics of CRs introduce new non-trivial issues to CR-MANETs.

The changing spectrum environment and the importance of protecting the transmission of the licensed users of the spectrum mainly differentiate classical MANETs from CR-MANETs. The cognitive capability and re-configurability of CR-MANETs have opened up several areas of research which have been explored extensively and continue to attract research and development. The book will describe the concepts, intrinsic properties, and research challenges of CR-MANETs. Dynamic spectrum access, protocol design, multimedia transmission, modeling, and optimization of CR-MANETs are some of the major research issues related to the development of CR-MANETs.

The contributed articles in this book from the leading experts in this field cover different aspects of modeling, analysis, design, management, deployment, and optimization of algorithms, protocols, and architectures of CR-MANETs. In particular, the topics include distributed cooperative spectrum sensing, spectrum handoff, environment–mobility interaction mapping, spectrum sharing, cognitive radio-enabled multichannel medium access control, control channel management, topology control, routing, multimedia transmission, cognitive vehicular networks, cognitive health care networks, interoperability, game theoretic approach, and self-coexistence. A summary of all of the chapters is provided in the following sections.

2 Dynamic Spectrum Access

As the first chapter of this book, *Chapter 1*, authored by *F. R. Yu, H. Tang, M. Huang, and Z. Li*, introduces challenges related to spectrum sensing in CR-MANETs. Then, the authors propose a fully distributed and scalable cooperative spectrum sensing scheme based on recent advances in consensus algorithms. In the proposed scheme, the secondary users can maintain coordination based on only local information exchange without a centralized common receiver. The authors use the consensus of secondary users to make the final decision. The proposed scheme is essentially based on recent advances in consensus algorithms that have taken inspiration from complex natural phenomena including flocking of birds, schooling of fish, swarming of ants, and honeybees. Unlike the existing cooperative spectrum sensing schemes, there is no need for a centralized receiver in the proposed schemes, which make them suitable in distributed MANETs. Simulation results show that the proposed consensus schemes can have significant lower missing detection probabilities and false alarm probabilities in cognitive radio MANETs. It is also demonstrated that the proposed scheme not only has proven sensitivity in detecting the primary user's presence but also has robustness in choosing a desirable decision threshold.

Chapter 2, authored by *Y. Song and J. Xie*, studies the spectrum handoff problem in CR-MANETs. Since unlicensed users are considered as temporary visitors to the licensed spectrum, they are required to vacate the spectrum when a licensed user reclaims it. Due to the randomness of the appearance of licensed users, disruptions to both licensed and unlicensed communications are often difficult to prevent, which may lead to low throughput of both licensed and unlicensed communications. In this chapter, a proactive spectrum handoff framework for CR ad hoc networks is proposed to address these concerns. In the proposed framework, channel switching policies and a proactive spectrum handoff protocol are proposed to let unlicensed users vacate a channel *before* a licensed user utilizes it to avoid unwanted interference. Network coordination schemes for unlicensed users are also incorporated into the spectrum handoff protocol design to realize channel rendezvous. Moreover, a distributed channel selection scheme to eliminate collisions among unlicensed users in a multi-user spectrum handoff scenario is proposed. In the proposed framework, unlicensed users coordinate with each other without using a common control channel, which is highly adaptable in a spectrum-varying environment. The authors compare the proposed proactive spectrum handoff protocol with a reactive spectrum handoff protocol, under which unlicensed users switch channels *after* collisions with licensed transmissions occur under different channel coordination schemes. Simulation results show that the proactive spectrum handoff outperforms the reactive spectrum handoff approach in terms of higher throughput and fewer collisions to licensed users. Furthermore, the distributed channel selection can achieve substantially higher packet delivery rate in a multi-user spectrum handoff scenario, compared with existing channel selection schemes. In addition, the authors propose a novel three-dimensional discrete-time Markov chain to characterize the process of reactive spectrum handoffs and analyze the performance of unlicensed users. They

validate the numerical results obtained from the proposed Markov model against simulation and investigate other parameters of interest in the spectrum handoff scenario. The proposed analytical model can be applied to various practical network scenarios.

Chapter 3, authored by *I. Macaluso, T. K. Forde, O. Holland, and K. E. Nolan*, introduces the concept of *environment–mobility* interaction map. CR-MANETs are likely to be complex radio systems. We already know that no single MANET solution can address all environments that may be encountered; such is the rationale of an ad hoc network that it must address the networking demands of unforeseen scenarios. Rather, a CR-MANET should be viewed as a feature-rich radio system, i.e., one which has access to a range of radio and network components, each suited to different demands. Such a reconfigurable system requires cognitive functionality to self-architect the radios when they are deployed in addition to the cognitive functionality required for the various layers to self-organise. However, any cognitive decision-making process requires awareness of the world for which it is trying to optimise the system. This chapter introduces the concept of an *environment–mobility interaction* map, a persistent internal representation of the network which captures the presence of areas in the network’s environment in which particular, sustained, mobility dynamics are observed. Such a self-generated map enables the cognitive MANET to plan a response to challenges brought about by these network dynamics.

Chapter 4, authored by *K. Navaie, H. Yanikomeroglu, M. G. Khoshkholgh, A. R. Sharafat, and H. Nikoofar*, investigates the impact of the primary service communication activity as well as other system parameters on the interference level at the secondary service receiver. The achieved capacity of the secondary service is directly related to the interference level at the secondary service receiver as well as the secondary service adopted sub-channel selection policy. The achievable capacity of the secondary service in such systems are obtained under different sub-channel selection policies in fading environments. Two general sub-channel selection policies are studied in this chapter: *uniform sub-channel selection* and *non-uniform sub-channel selection*. Uniform sub-channel selection fits into the cases where a priori knowledge on sub-channels state information is not available at the secondary transmitter. For cases with available a priori knowledge on sub-channels state information, a variety of non-uniform sub-channel selection policies are studied. The authors then present results on the scaling law of the opportunistic spectrum sharing in DS-CDMA/OFDM systems with multiple users. Numerical results are presented to compare different sub-channel selection policies.

3 Medium Access Control

A major issue in CR-MANETs is the medium access control (MAC). There are many new challenges, such as the multi-channel hidden terminal problem and the fact that the time-varying channel availability differs for different secondary users,

in the MAC layer. To overcome these challenges, *Chapter 5*, authored by *X. Zhang and H. Su*, presents an efficient Cognitive Radio-Enabled Multi-channel MAC (CREAM-MAC) protocol, which integrates the cooperative sequential spectrum sensing at physical layer and the packet scheduling at MAC layer, over the wireless cognitive radio networks. Under the proposed CREAM-MAC protocol, each secondary user is equipped with a cognitive radio-enabled transceiver and multiple channel sensors. The cooperative sequential spectrum sensing scheme improves the accuracy of spectrum sensing and further protects the primary users. The proposed CREAM-MAC enables the secondary users to best utilize the unused frequency spectrum while avoiding the collisions among secondary users and between secondary users and primary users. The authors develop the Markov chain model and $M/G^Y/1$ queueing model to rigorously study the proposed CREAM-MAC protocol for both the saturation networks and the non-saturation networks. Extensive simulations are conducted to validate the developed protocol and analytical models.

Chapter 6, authored by *V. B. Mišić and J. Mišić*, investigates the performance of a cognitive personal area network (CPAN) in which spectrum sensing is linked to packet transmissions. Efficient CPAN operation may be achieved if each data transmission is taxed by requiring the transmitting node to participate in cooperative sensing for a prescribed time period. In this approach, each node is allowed to transmit a single packet in one transmission cycle, but must then ‘pay’ for it by spectrum sensing, which ensures fairness with respect to transmission but also distributes the sensing burden to all nodes. The authors describe a probabilistic model of the integrated system and evaluate its performance with respect to packet transmissions and spectrum sensing. The authors discuss two modifications that involve centralized and distributed selection of the channels to be sensed. They also propose an adaptive algorithm to determine the tax coefficient and show that it offers superior data transmission performance while not affecting the sensing accuracy.

Chapter 7, authored by *T. Chen, H. Zhang, and Z. Zhao*, introduces the concept of the control channel cloud to solve the control channel problem in dynamic spectrum access (DSA)-based ad hoc networks. A DSA-based ad hoc network is an infrastructure-less wireless network based on DSA and featured by self-organization, self-configuration, and self-healing. One of the challenges in such a network is the common control channel problem, which is caused by the opportunistic spectrum sharing nature of secondary users in the network. Without a common control channel, it is a challenge to coordinate the behaviors of SU nodes in a DSA-based ad hoc network. The control channel cloud approach, which relies only on the local information exchange to function, aligns the control channel of SU nodes to the same channel in a distributed way if a common control channel exists. It provides a simple but scalable way to synchronize the control channel in a dynamically changed radio environment. The convergence of the proposed approach is proved. The performance of proposed algorithms is studied by simulation.

4 Topology Control and Routing

Chapter 8, authored by *Q. Guan, F. R. Yu, and S. Jiang*, studies topology control and routing in CR-MANETs. CR technology will have significant impacts on upper layer performance such as topology control and routing in wireless networks, especially in MANETs. The dynamic spectrum availability issue imposes more challenges on routing in CR-MANETs. Since the spectrum availability is affected by primary user activities and the mobility of cognitive users, cognitive routing is required to be forward-looking rather than reactive. To this end, a topology control and routing framework is presented in this chapter, where cognitive routing is enabled by topology control. In the framework, topology control serves as a middle-ware and a cross-layer module residing between routing and CR module. Prediction techniques can be used to construct a smart network topology, which provisions cognition capability to routing. Particularly, the author present a distributed prediction-based Cognitive topology control (PCTC) scheme to demonstrate the framework and verify its feasibility.

Chapter 9, authored by *J. Li, Y. Zhou, and L. Lamont*, presents a survey of existing routing schemes for CR-MANETs. The authors describe a CR-MANET model and present a novel adaptive routing design for the CR-MANET, referred to as ARDC, algorithmically and through examples. ARDC is based on the graph modeling approach, and its most significant contribution is that ARDC adapts to dynamic changes in the network topology much more computationally efficient than other CR-MANET routing schemes. At last, some further research directions on CR-MANET routing are identified.

Chapter 10, authored by *Y. Yang, C. Han, and B. Gao*, presents analysis for delays for both multihop cognitive radio networks and single-hop cognitive radio networks. For multihop cognitive radio networks, we analyze the amount of time that a packet spends to travel over the intermittent relaying links over multiple relaying hops and characterize it with the metric called *information propagation speed*. Optimal relaying node placement strategies are derived to maximize information propagation speed. For single-hop cognitive radio networks, we will analyze how delay is affected by multiple cognitive radio design options, including the number of channels to be aggregated, the duration of transmission, the channel separation constraint on channel aggregation, and the time needed for spectrum sensing and protocol handshake. How these different options may affect the delay under different secondary and primary user traffic loads is revealed. Methods for computing optimal cognitive radio design and operation strategy are derived.

5 Multimedia Transmissions

Chapter 11, authored by *H. Luo, S. Ci, D. Wu, Z. Feng, and H. Tang*, studies the multimedia transmissions problem in CR-MANETs. Most current research only considers spectrum utilization and effectiveness at MAC and PHY layers, ignoring

the system performance of upper layers. Therefore, in this chapter, the authors aim to improve the user experience of secondary users for wireless video services over cognitive radio networks. They propose a quality-driven cross-layer optimized system to maximize the expected user-perceived video quality at the receiver end, under the constraint of packet delay bound. By formulating network functions such as encoder behavior, cognitive MAC scheduling, transmission, as well as modulation and coding into a distortion-delay optimization framework, important system parameters residing in different network layers are jointly optimized in a systematic way to achieve the best user-perceived video quality for secondary users in cognitive radio networks. Furthermore, the proposed problem is formulated into a MIN-MAX problem and solved by using dynamic programming. The performance enhancement of the proposed system is evaluated through extensive experiments based on H.264/AVC.

6 Applications of Cognitive Radio Mobile Ad Hoc Networks

Chapter 12, authored by *D. Niyato, E. Hossain, and Teerawat Issariyakul*, considers an adaptive networking platform using WiFi/WiMAX technologies for cognitive vehicle-to-roadside communications, which can be used to transfer safety messages and provide Internet access for mobile users inside vehicles. The proposed platform is based on a heterogeneous multihop cluster-based vehicular network, where a vehicular node can choose to play the role of a gateway or a client. Gateway nodes communicate directly with a roadside base station through a WiMAX link. Client nodes connect to the gateways through WiFi links. Traffic from client nodes are relayed by the gateways to a roadside base station. The vehicular nodes are the self-interest (i.e., rational) and have capability to learn and adapt decision to achieve their objectives independently. A decision-making framework is proposed for this WiFi/WiMAX platform. This distributed decision-making framework, which enables the vehicular nodes with cognitive capability, is modeled and analyzed using game theory. Also, a Q-learning algorithm is used in vehicular nodes to provide the cognitive capability to learn and adapt their decision. Dynamics of Q-learning algorithm can be modeled as an evolutionary game.

Chapter 13, authored by *Z. Dong, S. Sengupta, S. Anand, K. Hong, R. Chandramouli, and K. P. Subbalakshmi*, studies to use CR-MANETs in health care. Low-cost automated health monitoring system sees a high demand with the President's proposal on health care reform. Legacy health care monitoring systems demand a great amount of resources such as health care personnel and medical equipments. This increases the cost of health care making it unaffordable to the majority of our society. This chapter introduces an architecture and design of a health care automation network. The health care automation network uses a cognitive radio-based infrastructure to monitor real time patients' vital signs, collect and document medical information. The health care automation network can be implemented in hospitals or in senior communities. This network can leverage the existing infrastructure

and reduce the cost of implementation. Research challenges in development of cognitive radio health care automation network are also discussed.

Chapter 14, authored by *O. Cabral, J. M. Ferro, and F. J. Velez*, proposes an application of CR technology for interoperability between High-Speed Downlink Packet Access (HSDPA) and Wi-Fi. This scenario involves the end-user traveling in public transportation system and requesting multimedia services to the operator. The inter-operability between HSDPA and Wi-Fi (IEEE 802.11e standard) Radio Access Technologies (RAT) is first addressed, a topology in which the user has access to both RATs was considered, together with a Common Radio Resource Management (CRRM) to manage the connections. The authors reached the conclusion that the CRRM enables to increase the system throughput when the load thresholds are set to 0.6 for HSDPA and 0.53 for Wi-Fi. Then, spectrum aggregation is implemented in HSDPA. A Resource Allocation (RA) algorithm allocates user packets to the available radio resources (in this case Node Bs operating at 2 and a 5 GHz are available) in order to satisfy user requirements. Simulation results show that gains up to 22% may be achieved. The authors have also sought the most efficient way to manage routing packets inside the Wi-Fi network. The proposal which uses links with higher throughputs enables to reach the best results, with gains up to 300% in the packet delivery ratio. Finally, the authors discuss the challenges that need to be addressed in order to materialise the envisaged cognitive radio scenario in public transportation.

Chapter 15, authored by *B. R. Tamma, B. S. Manoj, and R. Rao*, presents an application of the Cognitive Networking paradigm to the design and development of autonomous Cognitive Access Point (CogAP) for Wi-Fi hotspots and home wireless networks. In these environments, the authors typically use only one AP per service provider/residence for providing wireless connectivity to the users. Here it can reduce the cost of autonomic network control by equipping the same AP with a cognitive functionality. The authors first present the architecture of autonomous CogAP which consists of two main modules: Traffic sensing module and Cognitive controller module. The traffic sensing module uses an efficient packet sampling scheme to characterize traffic from all Wi-Fi channels with single wireless interface. The cognitive controller module consists of two sub-modules: traffic predictor and cognitive decision engine. The Neural Network-based traffic predictor module makes use of the historical traffic traces for traffic prediction on all channels. The cognitive decision engine makes use of traffic forecasts to dynamically decide which channel is best for CogAP to operate on. They have built a prototype CogAP device using off-the-shelf hardware components and obtained better performance with respect to state-of-the-art channel selection strategies.

7 Game Theoretic Approach for Modeling and Optimization

Chapter 16, authored by *S. Maharjan, Y. Zhang, and S. Gjessing*, presents an extensive summary of the related work that uses economic approaches such as game theory and/or price theory/market theory in CR networks. Efficient resource allocation

is one of the key concerns of implementing cognitive radio networks. Game theory has been extensively used to study the strategic interactions between primary and secondary users for effective resource allocation. The concept of spectrum trading has introduced a new direction for the coexistence of primary and secondary users through economic benefits to primary users. The use of price theory and market theory from economics has played a vital role to facilitate economic models for spectrum trading. So, it is important to understand the feasibility of using economic approaches as well as to realize the technical challenges associated with them for implementation of cognitive radio networks. With this motivation, The authors present an extensive summary of the related work that uses economic approaches to model the behavior of primary and secondary users for spectrum sharing and discuss the associated issues. The authors also propose some open directions for future research on economic aspects of spectrum sharing in cognitive radio networks.

Chapter 17, authored by *S. K. Das, V. Gardellin, and L. Lenzini*, studies the self-coexistence problem. One of the major challenges for implementing cognitive radio networks is to guarantee self-coexistence among devices, which means address interference issues among devices operating under the same set of rules and sharing the same resources. Among the several mathematical tools used to address the self-coexistence problem, the authors recognize the game theoretic approach as the most powerful. In this chapter, first the authors present an overview of cognitive radio technology focusing on the importance of guaranteed self-coexistence among cognitive devices. Then, they analyze the pros and cons of several game theoretic approaches proposed in the literature in order to model the self-coexistence problem. This chapter is concluded by describing non-cooperative and cooperative game paradigms to model the self-coexistence problem in cognitive radio networks.

8 Conclusion

A summary of the contributed chapters has been provided that will be helpful to follow the rest of this book. These chapters essentially feature some of the major advances in the research on cognitive radio mobile ad hoc networks for the next generation wireless communications systems. Therefore, the book will be useful to both researchers and practitioners in this area. The readers will find the rich set of references in each chapters particularly valuable.

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