Medium Access in Cognitive Radio Networks: from Single Hop to Multiple Hops

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Medium Access in Cognitive Radio Networks: from Single Hop to Multiple Hops

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For where your treasure is, there your heart will be also.

—Matthew 6:21

To my family

Preface

This dissertation is a result of the research work carried out at the Department of Information and Communication Technology (ICT), University of Agder (UiA) in Grimstad, Norway, from August 2008 to May 2012. My main supervisor has been Professor Frank Y. Li, University of Agder, and my co-supervisor has been Associate Professor Vicent Pla, Universitat Politècnica de València. From October 2010 to February 2011, I was a visiting researcher at the University of Minnesota (UMN), USA. My host professor at UMN is Professor Zhi-Quan (Tom) Luo.

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Production note: This dissertation, as well as my papers produced during my PhD study, has been written using LaTeX. The mathematical calculations and simulation results are obtained by using MATLAB and Network Simulator 2.

Acknowledgements

Four years is not long in history, but indeed a long time for a human being. During these precious four years of my PhD study, many people have contributed positively for a fruitful research experience and a happy life to me. I would, therefore, like to take this opportunity to express my sincere gratitude to them.

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The comfortable facilities and friendly environments provided by UiA make my research work enjoyable and efficient. I wish to thank Professor Frank Reichert, Professor Andreas Prinz, and Mr. Tor Erik Christensen for their support. I appreciate especially the assistance provided by the former and the current coordinators of the PhD program at the Department of ICT, UiA, Mrs. Trine Tønnessen and Mrs. Tonje Sti.

I would also like to thank my former and ongoing fellow PhD candidates in our research group, Andreas Häber, Anis Yazidi, Ghislain Maurice Norbert Isabwe, Hongzhi Jiao, Ram Kumar, Xin He, Yohannes Baptista Dafferianto Trinugroho, Ziaul-Haq Abbas. Discussions with them helped me better perceive my research work from different perspectives. Also, I do appreciate the help from Professor Luo's group, Hung-Wei (Andy) Tseng, Maziar Sanjabi, Meisam Razaviyayn, Ruoyu Sun, and Yu Zhang. Their unreserved sharing of knowledge broadened my profession a lot. It is also my pleasure to work with Associate Professor Enbin

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Although far away from my home country, China, where my family live, the love, encouragement, and support from my family members, especially my parents, Yuhe Jiao and Lifang Jia, and parents-in-law, Xinmin Zhang and Shenghong Song, back me up whenever I face difficulties in my life. Their confidence on me is the original source that leads me to every tiny success in my life. I also take great pride in thanking the *primary user* in my little family, my wife, Xuan Zhang, for her help at home and support in my research work. I believe that my grandfather would be proud of me if he knew my work. I devote this thesis to the whole family of mine and to the people who helped me through these years.

Lei Jiao
May 2012
Grimstad, Norway

Abstract

With the growing popularity of wireless communications and the pervasiveness of the Internet in our daily life, wireless devices as well as mobile applications have experienced an explosive growth in the past two decades. On the one hand, as limited natural resource, most spectrum bands that can be utilized for wireless communications have been allocated to different existing systems, leaving little room for emerging wireless systems and services. On the other hand, studies on spectrum utilization have revealed that most of the allocated spectrum is not utilized efficiently. Therefore, how to make an efficient use of the spectrum becomes an important and imperative question for the design of future wireless communication systems. Cognitive radio networks (CRNs), which target at enhancing spectrum utilization by re-utilizing already allocated spectrum without affecting licensed users, have been proposed and regarded as the most promising technology to answer this question.

In the initial stage of the research on CRNs, the main focus has been on the physical layer design. However, physical layer techniques alone do not suffice cognitive radios (CRs) for opportunistic spectrum access and communications among multiple users, neither within single hop nor over multiple hops. Therefore, based on the advanced underlying physical layer technologies developed for CRs, higher layer issues, i.e., medium access control (MAC) and routing, become essential topics for CR networking. In this dissertation, we enhance the state-of-the-art technologies for CRNs considering various single-hop and multiple-hop scenarios.

In the single-hop case, medium access schemes and their corresponding performance evaluation models are derived for different scenarios in multi-channel CRNs. We propose various schemes for channel access in CRNs based on whether channel assembling is supported by the system or not.

When channel assembling is not allowed, a MAC mechanism based on parallel rendezvous points is designed and evaluated. The proposed protocol inherits the advantages that parallel rendezvous MAC protocols have, and it is also able to access heterogeneous channels which have different data rates in a more efficient way.

If channel assembling is enabled, this technique can be utilized for potential performance improvement in CRNs. Two use cases are envisaged for channel assembling. In the first use case, the system can accommodate parallel SU services in multiple channels, while in the second use case, the system allows only one SU service at a time. In the use case where parallel SU services are allowed, various channel assembling strategies are proposed and modeled in order to investigate their performance and to acquire better comprehension of the behavior of CRNs with channel assembling. Moreover, the capacity upper bound for CRNs with channel assembling in the quasistationary regime is derived. In the use case when there is only one SU service that can utilize the vacant channels at a time, we formulate channel access into two optimization problems on power allocation in multi-channel CRNs and propose various algorithms to solve these problems.

While the above research work focuses on the single hop case, the last part of this thesis deals with channel access in the multi-hop case. The first scheme proposed in this thesis is to keep the whole CRN on a common channel, through rendezvous hopping. The second work in this part is to design a routing protocol for multi-hop multi-channel and multi-interface ad hoc networks. In this protocol, we improve the overall network throughput by integrated design of route selection and channel allocation. Although this protocol is not specifically tailored for any CRN, it can be potentially extended to CRNs if more functions, for instance, spectrum sensing, are implemented.

List of Publications

The author of this dissertation is the principal contributor and the first author of all the papers listed below. Papers A-F in the first set of the following list are selected to represent the main research achievements and are reproduced as Part II of this dissertation. Papers 7-12 listed in the second set are complementary to the main focus. They are not included in this dissertation in order to highlight the major contributions of this PhD work.

Papers Included in the Dissertation

Paper A L. Jiao, and F. Y. Li, "A dynamic parallel-rendezvous MAC mechanism in multi-rate cognitive radio networks: Mechanism design and performance evaluation," *Journal of Communications (JCM)*, vol. 4, no. 10, pp. 752-765, Academy Publisher, November 2009.

Paper B L. Jiao, F. Y. Li, and V. Pla, "Modeling and performance analysis of channel assembling in multi-channel cognitive radio networks with spectrum adaptation," *IEEE Transactions on Vehicular Technology*, vol. 61, no. 6, 2012, pp. 2686-2697.

Paper C L. Jiao, E. Song, V. Pla, and F. Y. Li, "Capacity upper bound of channel assembling in cognitive radio networks with quasistationary primary user activities," *IEEE Transactions on Vehicular Technology*, submitted as a correspondence for publication, May 2012.

Paper D L. Jiao, M. Razaviyayn, E. Song, Z.-Q. Luo, and F. Y. Li, "Power allocation in multi-channel cognitive radio networks with channel assembling," in *Proc. the 12th IEEE International Workshop on Signal Processing Advances in Wireless Communications (SPAWC)*, San Francisco, CA, USA, 26-29 June 2011.

Paper E L. Jiao, and F. Y. Li, "MAC strategies for single rendezvous multi-hop cognitive radio networks," in *Proc. the 20th IEEE Personal, Indoor and Mobile Radio Communications Symposium (PIMRC)*, Tokyo, Japan, 14-16 September 2009.

Paper F L. Jiao, K. Yu, and F. Y. Li, "A distributed routing protocol combined with channel assignment in multi-channel multi-hop wireless ad hoc networks," to be submitted to *the IEEE Wireless Communications and Networking Conference (WCNC),* 2013.

Papers Not Included in the Dissertation

Paper 7 L. Jiao, V. Pla, and F. Y. Li, "Dynamic channel aggregation strategies in cognitive radio networks with spectrum adaptation," in *Proc. the IEEE Global Communications Conference (GLOBECOM)*, Houston, TX, USA, 5-9 December 2011.

Paper 8 L. Jiao, V. Pla, and F. Y. Li, "Greedy versus dynamic channel aggregation strategy in CRNs: Markov models and performance evaluation," *Lecture Notes in Computer Science (LNCS)*, vol. 6827, pp. 22-31, Springer, August 2011.

Paper 9 L. Jiao, V. Pla and F. Y. Li, "Analysis on channel bonding/aggregation for multi-channel cognitive radio networks," in *Proc. the 16th European Wireless Conference (EW)*, Lucca, Italy, 12-15 April 2010.

Paper 10 L. Jiao, and F. Y. Li, "A single radio based channel datarate-aware parallel rendezvous MAC protocol for cognitive radio networks," in *Proc. the 34th IEEE Annual Conference on Local Computer Networks (LCN)*, Zürich, Switzerland, 20-23 October 2009 (Full paper).

Paper 11 L. Jiao, J. Xing, and F. Y. Li, "Performance comparison of residual related algorithm for ToA positioning in wireless terrestrial and sensor networks," in *Proc. the 1st International Conference on Wireless VITAE*, Aalborg, Denmark, 17-20 May 2009.

Paper 12 L. Jiao, F. Y. Li, and Z. Xu, "LCRT: A ToA based mobile terminal localization algorithm in NLOS environment," in *Proc. the 69th IEEE Vehicular Technology Conference (VTC)*, Barcelona, Spain, 26-29 April 2009.

Contents

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Abbreviations

ACK	Acknowledgement
AODV	Ad hoc On-demand Distance Vector
ATR	Average Transmission data Rate
BC	Backup Channel
BDP	Birth and Death Process
CCA	Constant Channel Aggregation
CDMA	Code Division Multiple Access
CDS	Connected Dominating Set
CDSS	Connected Dominating Set based Strategy
C-MAC	Cognitive MAC
CR	Cognitive Radio
CRN	Cognitive Radio Network
CTMC	Continuous Time Markov Chain
CTS	Clear To Send
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
DFA	Dynamic Fully Adjustable strategy
DPA	Dynamic Partially Adjustable strategy
DPR-MAC	Dynamic Parallel Rendezvous MAC protocol
DRI-MAC	Data Rate Independent MAC protocol
DTMC	Discrete Time Markov Chain
DS	Dominating Set
FCC	Federal Communications Commission
FDMA	Frequency Division Multiple Access
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific and Medical
ITU	International Telecommunication Union
KNOWS	K(C)ognitive Networks Over White Spaces
LTE-A	Long Term Evolution-Advanced
MAC	Medium Access Control

McMAC	Multi-channel MAC
NA	No Assembling
NACS	Next Available Channel Strategy
NS2	Network Simulator 2
OFDM	Orthogonal Frequency Division Multiplexing
OSA	Opportunistic Spectrum Access
OS-MAC	Opportunistic Spectrum MAC
PU	Primary User
P-VCA	Probability distribution based Variable Channel Aggregation
QSR	Quasistationary Regime
RC	Rendezvous Channels
RERR	Route Error
RREP	Route Reply
RREQ	Route Request
RTS	Request To Send
R-VCA	Residual channel based Variable Channel Aggregation
SDR	Software Defined Radio
SNR	Signal to Noise Ratio
SINR	Signal to Interference plus Noise Ratio
SS	Spectrum Sharing
SSCH	Slotted Seeded Channel Hopping
SU	Secondary User
TDMA	Time Division Multiple Access
TTL	Time To Live
UNII	Unlicensed National Information Infrastructure
WMN	Wireless Mesh Network

Part I

Chapter 1

Introduction

1.1 The Concept of Cognitive Radio Networks and Research Challenges

Spectrum which is suitable for wireless communications, i.e., the electromagnetic frequency between 3 kHz and 300 GHz, is a scarce nature resource. The access to a spectrum band is authorized by the telecommunication authorities in a country or a region based on the recommendations of the international telecommunication union (ITU) [1]. According to the current spectrum allocation schemes, a large portion of the spectrum band has been allocated statically to various wireless communication systems, while a small portion of spectrum is kept as unlicensed.

On the one hand, the explosive growth of wireless communications over the past two decades demands more and more spectrum resource in order to support emerging wireless applications with high data rates. However, the fact that the overall frequency bands have already been exclusively allocated to various existing systems makes the spectrum over-crowded. On the other hand, many real-life measurements show that most of the allocated frequency bands are largely under-utilized [2]. This contradiction indicates that the problem of spectrum scarcity can be solved to a large extent if we can exploit the already allocated spectrum in a more efficient manner.

Cognitive radio [3, 4, 5], coined by Joseph Mitrola III in 1999 [6], is able to reuse the under-utilized spectrum that has already been allocated to licensed users, and it is considered as a promising approach for efficient spectrum utilization. Cognitive radios, which act as unlicensed users, are also referred to as secondary users (SUs). The licensed users, i.e., the owners of a spectrum, are regarded as primary users (PUs). There are two ways of spectrum reuse in cognitive radios: *spectrum* *sharing* (SS) and *opportunistic spectrum access* (OSA). In the SS mode, the PUs and the SUs are allowed to transmit simultaneously in the same band as long as the resultant interference from SU transmitters to PU receivers is below certain threshold [7] [8]. To evaluate the interference level, *interference temperature* was proposed by the federal communications commission (FCC) as a metric for interference analysis [9]. The higher the interference temperature, the more serious the interference. However, FCC abandoned the terminology of interference temperature in 2007 since no parties provided information on specific technical rules that could be adopted to implement it [10]. Although the interference temperature model has been terminated by FCC, the concept of SS is still valid and it is utilized in many research papers. On the other hand, in the OSA mode, the SUs can transmit over a band only if none of the PUs is transmitting over that band. The decision whether SUs can transmit or not is made according to the result of spectrum sensing. If the sensing result indicates that no PU transmitters are active in this band, SUs can transmit. When PU services arrive to a channel that is occupied by SUs, the SUs have to stop transmission and release the channel immediately. Note that in both SS and OSA, SUs are supposed not to interfere with the PUs. In this thesis, we focus only on the OSA mode.

To utilize spectrum opportunities without affecting PUs, spectrum sensing [11, 12] is essential. In the literature, different techniques and methodologies have been proposed to achieve fast and accurate spectrum sensing for PU activities. Fairly extensive research has been done in this field, including both pure physical layer techniques [13]-[17] and cooperative approaches [18]-[26]. Based on these advanced spectrum sensing approaches, opportunistic channel access can be designed. Therefore, medium access mechanisms in order to efficiently utilize spectrum opportunities have appeared as an interesting and active research area in CRNs.

MAC protocol design is an important aspect in order to make CRNs work and it has attracted intense research efforts during the past five years. There exist many MAC protocols proposed for different scenarios in CRNs [27]. In brief, MAC protocols in CRNs can be classified into two categories, i.e., centralized MAC protocols [28, 29] and distributed MAC protocols [30]-[41]. The IEEE 802.22 standard [28] targets at a typical centralized scenario that re-utilizes broadcast TV channels. The base station in this scenario manages all associated SUs covered by its own cell. As a coordinator, the base station can adopt centralized scheduling among various flows and users on different channels. On the contrary, for non-centralized CRNs without a central controller, distributed protocols are preferable and such protocol design deserves more research efforts.

In many scenarios envisaged for CRNs, multiple channels may exist. With the availability of multiple channels, distributed MAC protocols designed for multi-channel ad hoc networks [43] can be used as references for the design of MAC schemes in CRNs. However, the design of distributed MAC protocols for multi-channel CRNs is more challenging than for ad hoc networks because of the new features in CRNs, for example, the requirement of channel sensing, and channel access in the presence of heterogeneous channels etc. Heterogeneous channels mean that either the availability of different channels, i.e., the percentage of time when PUs do not exist, or the bandwidth of each channel, differs from one channel to another. Therefore, the design of a distributed MAC mechanism for heterogeneous multiple channels in CRNs deserves a further exploration.

For MAC design in multi-channel CRNs, a new technique that can assemble several channels together as one channel for SU services, namely, *channel assembling*[1], has been proposed in many schemes [28], [32]-[35], [40, 41]. With this technique, if there is only one SU service which can utilize multiple vacant channels, it is obvious that higher spectrum utility will be achieved for this SU, since spectrum opportunities will be simply wasted if the SU utilizes only one channel at a time. However, if parallel SU services co-exist and can share these vacant channels, whether it is beneficial for one SU service to assemble multiple channels needs to be further investigated, since other services may be degraded if one service occupies too many channels.

Furthermore, in order to better understand the theory behind these protocols and evaluate the performance of different strategies, it is imperative to build analytical models [44]-[49] for CRNs in different scenarios. However, it lacks in-depth studies on channel assembling strategies as well as their analytical models in the state-of-the-art research in this field. This observation indeed triggered our study on channel assembling as an important part of this thesis.

The scenarios discussed above are based on single hop transmission. However, multi-hop communications may also be enabled in CRNs [50]. With opportunistic multiple channels in CRNs, a method which maintains the connectivity of a network with multiple hops needs to be developed. When CRNs work on multiple channels, SUs are not able to communicate with one another if they have no channels in common. Therefore, if all SUs have a single transceiver and their working channels are all opportunistic, how to keep the multi-hop network connected is not trivial. In

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[1] There exist different methods to combine several channels for an SU service, e.g., channel bonding and channel aggregation. More detailed information about this can be found in Chapter 3. In this thesis, we do not distinguish those methods and utilize channel assembling to refer to all this kind of techniques.

multi-channel multi-hop scenarios, another interesting research topic is routing and channel allocation when multiple interfaces exist. Again, the idea in the design of route selection and channel allocation in ad hoc networks can be utilized in CRNs, since wireless ad hoc networks can be considered as a special case of CRNs when PU activities are relatively static. Although many strategies are proposed in the literature, they are mainly focusing on routing strategies and channel allocation optimization in wireless mesh networks (WMNs) [51]-[57]. WMNs usually have one or several gateways through which mesh routers as well as clients are connected to the Internet. Those gateways are normally the source of incoming traffic and the destination of outgoing traffic from the perspective of mesh routers. Therefore, traffic flows are generally regular and have one end-point in common, following a spanning-tree like topology. Furthermore, in order to have optimized channel allocation, they may require network-wide traffic information, which is quite costly in terms of signaling overhead. Those protocols cannot be directly used in multi-hop wireless networks with random traffic where the source and the destination of a traffic flow can be any nodes in the network. Consequently, a more portable routing protocol together with a channel allocation algorithm which is merely based on local information in multi-channel multi-hop ad hoc networks is required. When such a routing protocol is designed, it can be extended for CRNs with proper modifications in order to make it adjustable in dynamic environments. Compared with multi-hop multi-channel ad hoc networks, the freedom of channel selection becomes lower since available channels in CRNs may differ from one hop to the other.

1.2 Research Objectives and Methodology

As stated above, although tremendous research and development efforts have been made in CRNs, especially in spectrum sensing and many other physical layer techniques, there are still many open questions that need to be answered, more urgently, at the upper layers. For instance, efficient MAC protocols and channel access strategies in multi-channel scenarios need to be designed and evaluated, and how connectivity can be maintained for multi-hop networks in opportunistic environment needs to be studied, etc. Keeping these observations in mind, the objective of this dissertation is to propose a set of medium access mechanisms and protocols in multi-channel CRNs, and evaluate the performance of these approaches analytically or by simulations. Based on a detailed literature survey on open research questions and existing solutions, potential research directions and techniques are identified. The research work starts from designing and analyzing channel access schemes in different single-hop scenarios according to whether channel assembling is supported or not. Then, several research topics in multi-hop scenarios are addressed. More specifically, we attempt to answer the following research questions:

- **Question 1:** When channel assembling is not supported by SUs, how to make multiple SUs, each equipped with a single radio, opportunistically access heterogeneous channels in a more efficient way?
- **Question 2:** If channel assembling is enabled and parallel ongoing SU services can be supported, can we achieve improved performance by assembling multiple channels for SU services? What kind of strategy is preferable?
- **Question 3:** With channel assembling and parallel SU services, what is the maximum capacity the secondary network can achieve in the quasistationary regime[2]?
- **Question 4:** If channel assembling is allowed but only one SU service can utilize multiple idle channels, how to select a set of channels and allocate power among them in order to achieve optimized performance?
- **Question 5:** For SUs with a single radio, how to coordinate SUs over multiple hops in order to maintain connectivity in a multi-channel scenario?
- **Question 6:** How to select path and allocate channel properly in a multi-channel multi-hop ad hoc network?

The questions listed above are organized according to the number of hops in a network. The first four questions are targeting at spectrum access and resource allocation within a single hop, while the last two questions aim at improving the performance over multiple hops. By studying those questions, we aim to enhance the state-of-the-art techniques in CRNs from different aspects.

Fig. 1.1 illustrates how those research questions are addressed by the research papers included in this dissertation. As shown in this figure, we explore our research work towards two directions, i.e., the single hop case and the multi-hop case. In the single hop case, to improve network performance from various aspects, different approaches are proposed according to whether channel assembling is supported or not by SUs. In the multi-hop case, both MAC layer and routing layer issues are investigated. In this case, a scheme for connectivity maintenance is developed, and a routing protocol, which can be further extended to CRNs, is designed for

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[2] The quasistationary regime means that the PU activities are considerably stable compared with SU activities. More detailed description about this will be given in Chapter 3.

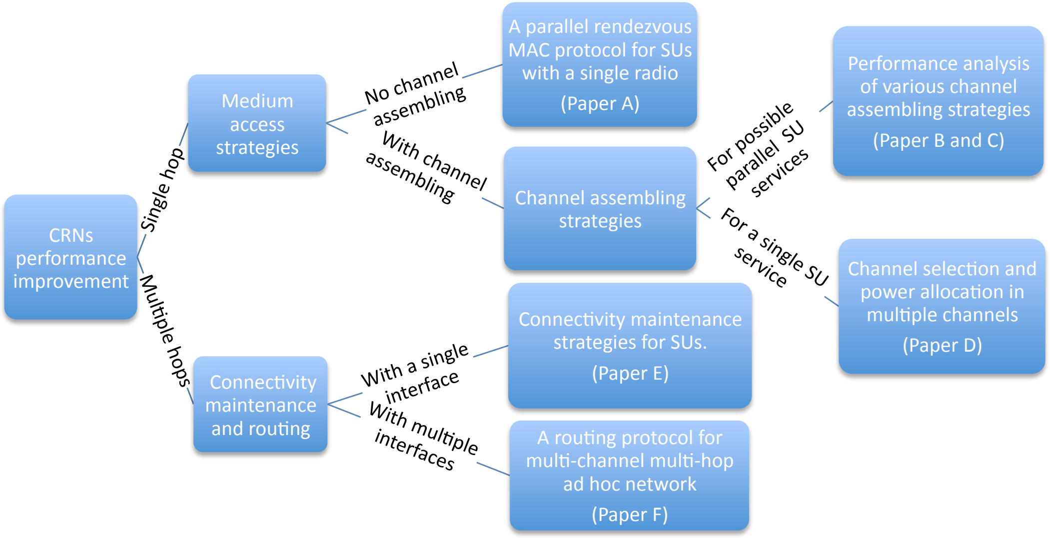

Figure 1.1: The structure of the research work and the connection between the research topics and included papers in this dissertation.

multi-channel multi-hop network. More specifically, to address the above research questions, the following six research goals are identified, and they are achieved through the scientific contributions of the thesis highlighted in Papers A-F.

- **Goal 1:** To explore existing MAC protocols in multi-channel ad hoc networks and CRNs, and to design a novel protocol for SUs with single radio without channel assembling in heterogeneous channels.
- **Goal 2:** To propose channel assembling strategies and evaluate their performance extensively through both mathematical modeling and simulations, in a scenario where parallel SU services are allowed.
- **Goal 3:** To find, through mathematical modeling, the capacity upper bound of channel assembling in the quasistationary regime when parallel SU services are allowed in CRNs .
- **Goal 4:** To develop channel selection and power allocation schemes which optimize different system parameters for SU packet transmissions in multi-channel CRNs.
- **Goal 5:** To develop connection maintenance schemes in multi-channel multi-hop scenarios and evaluate their performance through simulations.
- **Goal 6:** To design a routing protocol for ad hoc networks with multiple interfaces in multi-channel multi-hop scenarios and evaluate its performance through simulations.

The tools to evaluate the proposed schemes include mathematical modeling and computer simulations. Markov chain modeling is the main mathematical method utilized in this thesis work. To facilitate the mathematical analyses, various assumptions are made, as illustrated in each chapter and included papers. Mathematical calculation and simulations are mainly carried out using MATLAB for single hop scenarios. For multi-hop scenarios where the network level simulations are performed, a discrete event simulator, network simulator 2 (NS2) [58] is adopted.

1.3 Organization of the Dissertation

The dissertation is organized into two parts, where Part I consists of Chapters 1-6 and provides an overview of the PhD work. Part II is organized as a collection of six scientific papers, i.e., Papers A-F. Fig. 1.2 illustrates the outline of this dissertation.

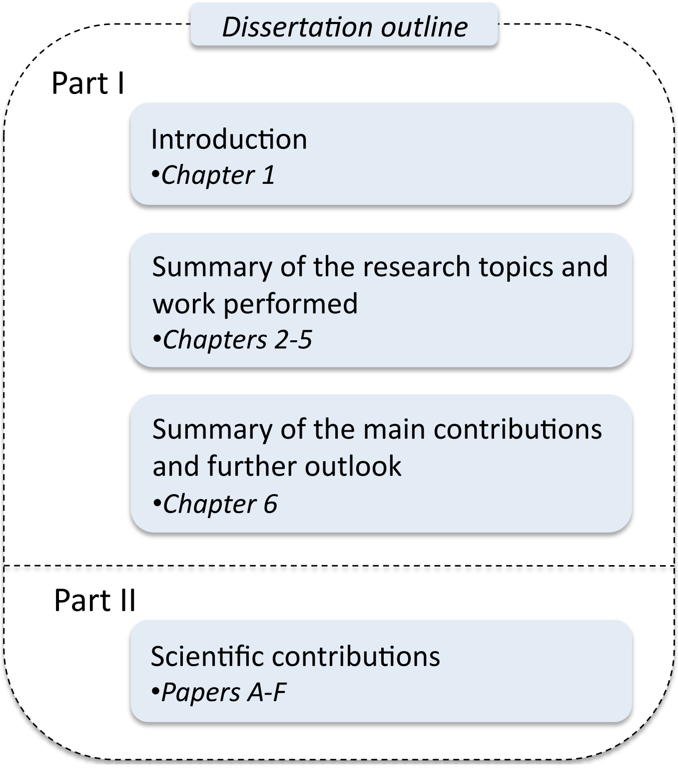

Figure 1.2: Outline of the dissertation.

Chapter 2 focuses on a channel access scenario where only one channel is allowed to use by each SU service at any time. The state-of-the-art MAC protocols in multi-channel ad hoc networks and CRNs are comprehensively overviewed. A new MAC protocol is designed for heterogeneous channels. The first research question is addressed and explored in this chapter. Chapter 3 gives an outline of channel assembling techniques, and summarizes existing channel assembling strategies and their mathematical models. Two channel assembling strategies are proposed and their performance analyses are carried out thoroughly when multiple simultaneous ongoing SU services are allowed. Then the capacity upper bound with channel assembling in the quasistationary regime is also derived in a closed form. The second and the third research questions are addressed in this chapter. Chapter 4 studies various optimization problems on power allocation for packet transmission when only one SU service can utilize multiple idle channels at a time, which corresponds the fourth research question. Different algorithms are proposed for the studied problems in this chapter. Chapter 5 presents two schemes for network connectivity maintenance and further proposes a routing protocol in multi-hop networks, which targets at the fifth and the sixth research goals. The designed schemes for connectivity maintenance work at the MAC layer, while the routing protocol works at layer three. Chapter 6 summarizes the main contributions of this dissertation. Finally, we conclude the whole thesis by pointing out a few directions for future work.

Papers A-F are reproduced as Part II of this thesis.

Chapter 2

Parallel Rendezvous MAC Mechanisms for CRNs

To form a CRN, MAC mechanisms are of great importance, especially for multi-channel CRNs. Chapter 2 presents different MAC mechanisms in multi-channel ad hoc networks and CRNs without channel assembling. Considering the characteristics of CRNs, a novel dynamic parallel rendezvous MAC mechanism is designed, and it can utilize channel resource in a more efficient way in the presence of heterogeneous channels. In this chapter, existing studies on such MAC protocols are summarized first, and then a dynamic parallel rendezvous mechanism is proposed.

2.1 Introduction to MAC Protocols in CRNs

As mentioned earlier, there are two categories of MAC protocols in CRNs , i.e., centralized MAC protocols [28, 29] and distributed MAC protocols [31]-[41]. In this chapter, we focus mainly on the distributed MAC protocols.

For distributed MAC protocols, medium access can also be done in many different ways, like frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA) based *deterministic* access, or carrier sense multiple access with collision avoidance (CSMA/CA) based *random* access. Nowadays, random access, represented by CSMA/CA, has become the dominant MAC mechanism for wireless networks. According to this mechanism, whenever a node has a packet to transmit, it will firstly listen to the channel for a while to determine whether there is any ongoing transmission or not. If the channel is idle, the node can start packet transmission. Otherwise, it will defer its own transmission until the ongoing transmission is finished. CSMA/CA is a very pragmatic approach for distributed medium access in wireless networks.

In many scenarios of CRNs, however, multiple channels may exist, making the design of multi-channel MAC protocols more attractive. In order to make a packet transmission successful when multiple channels co-exist, the following conditions must be satisfied. First, the transmitter must find the working channel of the receiver and at the same time the receiver on that channel is ready for receiving. Second, there is no other transmissions on the same channel in the vicinity at the same time when the intended packet is being transmitted. To meet the first condition, a negotiation process has to be developed to achieve this goal. For the second condition, collision avoidance mechanisms must be employed. When multiple SUs contend for access opportunities on the same channel, the collisions can be efficiently resolved by using a back-off timer similar to the one used in CSMA/CA. However, the negotiation procedure in multiple channels is tedious and needs to be further developed. In what follows, we summarize the negotiation methods in multiple channels and then focus on one of them which is utilized in our design.

2.2 Existing Negotiation Schemes for Channel Access in Multi-channel Networks

In order to negotiate for channel access, SUs must meet with one another. There exist two types of channel access schemes, distinguished by the number of rendezvous points. The first type is single rendezvous MAC protocols [30]-[34], [42], and the other one is parallel rendezvous MAC protocols [39, 43, 59]. As can be inferred by its name, there is only one rendezvous point in the single rendezvous MAC protocols, for example, a control channel, for all devices to negotiate for channel access. Parallel rendezvous MAC protocols, on the other hand, have multiple rendezvous points.

2.2.1 Single Rendezvous Point MAC Protocols

In single rendezvous point MAC protocols, there are three different methods for negotiation, and they require various resources and have distinct performance [43].

The first method of such design is to employ a dedicated control channel [60, 61], where two transceivers are required. Using this method, one transceiver is alway tuned onto this control channel in order to exchange control information and negotiate for channel access. Based on the results of contentions and negotiations in the control channel, data packets can be transferred on various channels simultaneously.

The second method of single rendezvous point MAC protocols employs common hopping sequences [62, 63]. With this idea, only one transceiver is required and a common hopping sequence is utilized to separate packet transmissions among multiple channels. More specifically, all devices hop among different channels according to a common sequence in a synchronous manner. If a packet needs to be transmitted, a request to send (RTS) should be transmitted from the transmitter. When a clear to send (CTS) sent by the intended receiver is received by the transmitter, the communication pair will stay on this channel for data packet transmission, whereas other devices will continue hopping among various channels according to the pre-defined sequence. When the transmission is finished, this communication pair will again hop according to the common sequence.

The third method of single rendezvous point MAC protocols is the split-phase MAC protocols [64, 65]. According to this approach, devices require a single radio and work in a synchronized manner, where time is divided into two phases, i.e., control phase for control message exchange and data phase for data packet transmissions. In the control phase, all devices need to tune onto a pre-defined channel to negotiate for packet transmission. In the second phase, devices will jump onto the agreed channel based on the result of the negotiation in the previous phase and start data transmission.

A common feature of single rendezvous MAC protocols is that a channel or a time period is required and specified as the rendezvous point for all devices to exchange control information and negotiate parameters for data transmission. This single rendezvous point, however, can become a bottleneck under information exchange operations [43] if traffic load becomes heavy. Furthermore, some such MAC protocols, e.g., [41], also need an additional transceiver which is always tuned onto the control channel. More importantly, if each device can utilize only one data channel at a time after negotiation, the channel resources may not be used efficiently. To avoid the above drawbacks of single rendezvous MAC protocols, the type of parallel rendezvous MAC protocols is introduced.

2.2.2 Parallel Rendezvous Point MAC Protocols

The basic idea of parallel rendezvous MAC protocols is that nodes jump among different channels according to their own sequences and the control information can be exchanged at the same time on different channels when nodes meet. In other words, devices can negotiate and make agreements simultaneously on *distinct* channels. It has been demonstrated that parallel rendezvous MAC protocols, like multi-channel MAC (McMAC) [66] and slotted seeded channel hopping (SSCH) [59] in multi-channel wireless networks, generally outperform single rendezvous MAC protocols [43]. These protocols do not have bottleneck like in single rendezvous MAC protocols and they are all based on a single transceiver.

As an example to explain parallel rendezvous protocols, the principle of McMAC is summarized in the following. This MAC protocol requires only one transceiver and works in a time-slotted manner. To operate, each device picks a seed to generate a distinct pseudo-random hopping sequence. In each time slot, those devices hop across different channels according to their sequences when they do not have ongoing communications. This seed can be generated based on, for example, the MAC address of the device and all its neighbors will be aware of its hopping sequence. When a device has packets to transmit to another one, it will deviate from its own hopping sequence and tune onto the channel where its potential receiver is located on. When the transmission finishes, they will hop again according to the pre-defined hopping sequence.

Fig. 2.1 illustrates how McMAC operates. In this figure, A and B are devices and TS1-TS9 denote time slots. A and B with a circle represent their pre-defined hoping pattern. In TS1, A and B are on Channel 1 and Channel 2 respectively and will jump to Channel 2 and Channel 4 at TS2. At TS4, A would jump onto Channel 2 if it has no packets to send. As A has data to send to B, A follows B's sequence and jumps to Channel 3 instead of Channel 2 at TS4. After successful negotiation on transmission, both A and B will stop hopping according to the pre-defined hopping sequence and stay on the current channel for data transmission, as shown in the highlighted part in this figure from TS4-TS7. A and B with dash circle from TS4-TS7 denote their pre-defined hopping sequence. When the data transmission is over (after TS7), A and B will return to the original hopping sequence. In McMAC, since the negotiation is distributed among multiple channels, the bottleneck appeared in

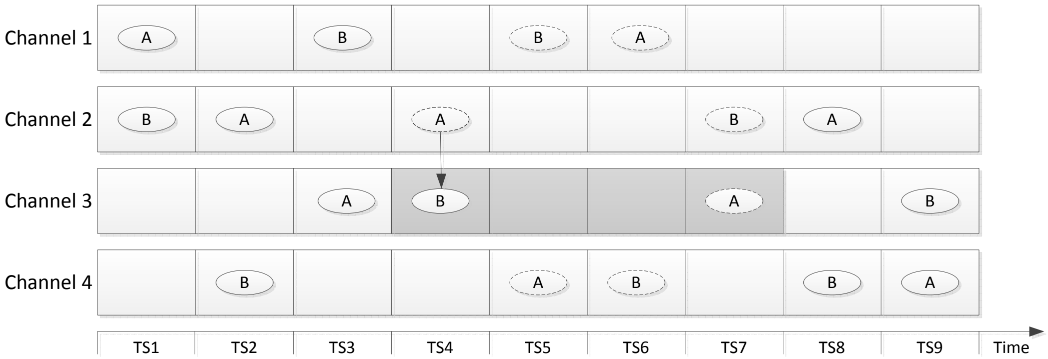

Figure 2.1: Illustration of a parallel rendezvous MAC protocol: McMAC.

the single rendezvous point MAC protocols is avoided, resulting in improved system performance and spectrum efficiency.

However, McMAC is designed for multi-channel ad hoc networks rather than for CRNs. As a further effort, the protocol in [39], which is tailored for CRNs, is proposed. In this protocol, the OSA mode is considered and the PUs are assumed to follow an independent and identically distributed ON/OFF random process, where ON means that the channel is utilized by PUs while OFF means that the channel is vacant for SUs. Each licensed channel is considered to be time-slotted such that the PUs communicate with each other in a synchronized manner. The length of each time slot is equal. SUs, which are also synchronized with the PUs, opportunistically access the licensed channel when it is available.

To model the status of a channel, a simple two-state ON/OFF Markov chain [39] model is often employed, as shown in Fig. 2.2, where α_i is the probability that the ith channel transits from state ON to state OFF and β_i is the probability that the ith channel transits from state OFF to state ON, where $1 \leq i \leq G$ and G is the total number of channels. Then the availability of the ith channel for SUs, denoted by γ_i, which is the state probability of the corresponding Markov chain of being OFF, i.e., the channel is not occupied by PUs, can be expressed as $\gamma_i = \alpha_i/(\beta_i+\alpha_i)$, $1 \leq i \leq G$.

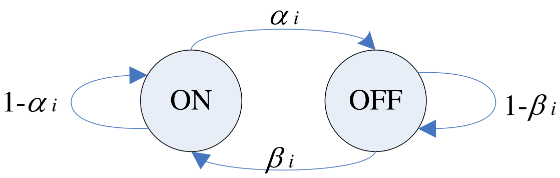

Figure 2.2: ON/OFF channel model.

Indeed, the MAC protocol proposed in [39] is quite similar to McMAC. The difference is that at the beginning of each time slot, devices have to sense the spectrum in order to check whether there are any PU activities before they start negotiation. In the spectrum sensing period, every SU has to keep silence and sense the spectrum. If the sensing result indicates that the channel is idle, it can move further to parameter negotiation and packet transmission. A more detailed description of that protocol can be found in the related work section of Paper A. To avoid overlapping, it is not explicitly presented here.

However, the authors in [39] have only considered the situation that all channels are homogeneous, i.e., with identical channel data rate and channel availability. Therefore, the channel hopping sequences used by SUs are statistically uniformly distributed in their scenario. However, in CRNs, the channels may be heterogeneous. For example, the bandwidth that SUs can utilize may be different from one channel to another. Consequently, each of these channels may have distinct data rates available for SUs [36]. Furthermore, the channel availability, i.e., the percentage of idle time in a channel, might also be quite different from one channel to another. Therefore, it would be advantageous to introduce a method which can adjust communications among heterogeneous channels. This observation indeed triggered our work in Paper A.

2.3 A Dynamic Parallel Rendezvous MAC Mechanism

Motivated by the fact that SUs may use heterogeneous channels, we propose a channel hopping based parallel rendezvous MAC protocol for synchronized CRNs with adaptive hopping sequence in this dissertation. The main idea of the protocol is to adjust the hopping sequence of SUs according to the channel carrier capability for SUs in heterogeneous channels so that better channel utilization can be achieved. The channel carrier capability is defined as the product of the channel availability and the representative data rate (to be explained later) supported in a channel. The detailed design of this protocol is included in Paper A. In what follows, we summarize briefly the idea in this design and the characteristics of this protocol.

2.3.1 Assumptions and Parameters for Channel Sequence Selections

In Paper A, heterogeneous channels are considered, since the channel bandwidth and the channel availability can be highly different from one to another in CRN scenarios. In this case, the ON/OFF channel model assumption is still valid, and we assume further that each SU can sense precisely the signal of PUs that it receives in each particular channel it tunes onto. The envisaged scenario for this investigation is that SUs are located in a limited geographic area while the coverage and distance scale of PUs is far larger than that of SUs', hence the SUs are covered by the same set of PU systems. This assumption implies that the results of channel sensing by each SU node in a particular channel is the same for all SUs. It is further assumed that all the SUs are in close enough proximity so that they can communicate with each other. We do not consider the possible mobility of SUs. With the above assumptions, the percentage that a channel becomes idle can be estimated by the number of idle time slots in that channel over the total number of time slots that a device stays on that channel.

As well known, the supported data rate from different transmitters may not be the same for the same receiver on the same channel, since the channel condition is space and time variant and the channel gain might be quite different among various communication pairs. In order to determine channel carrier capacity for hopping sequence adjustment purpose, a *representative data rate* of a channel for a particular device is required. In our design, we select the representative data rate as the average data rate achieved for receiving packets from various neighbors, when the device acts as a receiver on the channel[1]. The representative data rate of a channel gives an indication on which data rate the device will achieve as a receiver on the channel on average. Without knowing which device is the next transmitter, the channels with higher average data rate values are preferable.

When the channel availability and its representative data rate are acquired, the channel carrier capability can be calculated. Then, each device can make a decision to adjust its hopping sequence in order to achieve better performance according to the calculated channel carrier capability. When a node has a packet to transmit, it tunes onto the channel where the potential receiver is located at. As a consequence, higher overall system performance is expected when the receiver's hopping sequence is adjusted accordingly.

2.3.2 Hopping Sequence Design

The channel hopping sequence determines the channel that a device will jump to at a particular time slot, and this sequence is to be adjusted in order to achieve better system performance in the presence of heterogeneous channels. In this design, the transmitter will follow the receiver's working channel. Therefore, if the receiver has higher probability to visit a channel, it will have higher chance to negotiate for communication in this channel. However, if the channel condition is excellent for most of the devices, e.g., with higher idle probability and wider bandwidth, it will be preferred by most devices since they may enjoy a smoother or faster packet transmission after channel negotiation. As a consequence, when all those devices join this channel, the channel will get over-crowded, resulting in higher collision

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[1] In Paper A, it is assumed that all SUs are in close enough proximity to be able to communicate with each other using the same modulation scheme within a channel. Therefore, the same data rate, named as the maximum data rate in Paper A, applies to all SUs on a particular channel, whereas different channels may have various maximum data rates. The representative data rate defined here is utilized for a more general case where different senders may have distinct data rates for the same receiver on a particular channel. Considering the scenario in Paper A, the representative data rate is, indeed, the maximum data rate of a channel.

probability. At the same time, the channel with slightly lower channel carrier capability but still good enough for packet transmission will become under-utilized. Therefore, it is very important to design a hopping sequence in a more reasonable way in order to make traffic transmission balanced.

The channel sequence generation follows two steps: the first step is to generate a basic hopping sequence, and the second step is to revise the basic hopping sequence according to an algorithm based on the channel carrier capability information. For the basic hopping sequence, we adopt the hopping sequence generation method that is used in McMAC [66]. The generated basic sequences are uniformly distributed. All devices will hop according to its basic sequence initially in order to acquire an estimation of channel carrier capability. After this initial period, channel hopping sequence adaptation can be implemented.

The detailed hopping sequence adjustment algorithm can be found in Subsection III-C-2) of Paper A. The goal of this algorithm is that after sequence adjustment, the visiting probability of a device on various channels must be proportional to their channel carrier capability. The higher the channel carrier capability is, the larger the probability that the device will visit that channel. For those with lower channel carrier capability, devices will still have chance to visit them, although the probability is lower than the ones with larger availability values. It has been proven in the Appendix of Paper A that the adjusted hopping sequence will make the visiting probability proportional to the channel carrier capacity.

When the channel hopping sequence is adjusted, devices must let others know about their new sequences by advertising their new sequences through beacon messages. The detailed design is explained explicitly in Subsection III-C-3) of Paper A.

2.3.3 Performance Evaluation

To evaluate the performance of the proposed MAC protocol, we model mathematically the system through discrete time Markov chain (DTMC) modeling. Furthermore, the performance of the proposed MAC protocol is compared with the one proposed in [39]. If we model the case where different SUs have various average data rate values on a specific channel, the state space of the Markov chain will increase dramatically with a growing number of channels and SUs. Therefore, in order to reduce the state space in DTMC, we consider a special case where all SUs have the same data rate in a specific channel, however the data rate may differ from one channel to another. Consequently, the dimension of the DTMC state reduces to the number of channels and each element in a state has a value equal to one or zero, representing whether the channel is occupied by SUs or not.

To further reduce the dimension of the DTMC, channels that have similar channel carrier capability values can be grouped together. Within each group, the channel carrier capability can be considered as the same for all SUs, whereas the channel carrier capability values are different among various groups. An exemplary case corresponds to a scenario where the representative data rate is the same among all SUs in all channels, while different groups of channels have distinct channel availability values because that the load of PU services is different among those groups. In this case, the state space can be based on the grouped channels. For example, if there are three groups of channels, we can use three elements to represent a state in the Markov chain, with each element indicating the number of ongoing SU services in that group. In this way, the state space of the DTMC becomes much smaller.

When the state space of the DTMC is derived, the transition probabilities must be described. That is, to derive the probability of transferring to a specific state in the next time slot based on the state in the current time slot, given specific traffic distributions and their parameter configurations. A detailed mathematical derivation of such transition probabilities can be found in Section IV of Paper A. When the transitions among different states are derived, the steady state probabilities of the DTMC can be calculated based on the balance equation for each state and the overall normalization equation of state probabilities in the DTMC. Based on the state probabilities, the capacity of the system can be further calculated.

In Section V of Paper A, three cases are examined and the numerical results based on the DTMC models are illustrated. For illustration purpose, we consider two groups of channels which have different values of channel carrier capability. The first case is when the data rates are different among two groups of channels while the channel availability values are the same. In this case, the improvement of the system capacity is obvious compared with the scheme proposed by [39] which adopts the uniformly distributed channel hopping sequences. The second case is with different channel availability values while the data rates are kept as the same. Although improvement is observed, it is not as significant as in the previous case. The last case we considered is when both the data rates and the channel availability values are different in two groups of channels. Numerical results demonstrate that the adaptive channel sequence according to the channel carrier capacity achieves better performance than the protocol with uniformly distributed hopping sequence as well as the mechanism which adjusts the sequence according to a single parameter, i.e., data rates or channel availability.

In addition to system capacity, the overhead of the beacon advertisement scheme is also of interest. The numerical results based on calculations illustrate that the overhead of the beacon advertisement is in the order of a few kbps, while the capacity improvement is in the order of a few Mbps. Therefore, the overhead is negligible as compared with the reward achieved by this scheme. Again, the detailed analysis can be found in Subsection IV-D of Paper A.

2.4 Chapter Summary

MAC protocols in CRNs aim to exploit spectrum utilization in an opportunistic manner. Moreover, when multiple channels exist, an efficient negotiation process for channel access is essential for the operation as well as for the overall performance of the network, especially when only one channel can be utilized by an SU service after successful negotiations. In this case, how to utilize multiple channels efficiently by accommodating parallel services in multiple channels becomes even more challenging.

This chapter begins with an overview of the existing MAC protocols in multichannel ad hoc networks and CRNs. Based on those studies, our work has paid special attention to the development of parallel rendezvous MAC protocols. A novel parallel rendezvous MAC protocol is designed for heterogeneous channels in CRNs, and it is originally reported in Paper A. The main contribution of this work is the MAC mechanism itself in which an adaptive hopping sequence mechanism is proposed in order to make the devices access heterogeneous channels in a more efficient manner. Furthermore, a DTMC based analytical model is also developed to analyze the performance of the proposed mechanism.

Chapter 3

Channel Assembling Strategies and Their Performance Evaluation in Multi-channel CRNs

Chapter 2 focuses the topic of multi-channel MAC mechanisms in CRNs without channel assembling, and proposes a parallel rendezvous MAC protocol in order to have more efficient spectrum utilization. In Chapter 3 we first introduce the concept of channel assembling and then summarize MAC protocols that utilize this technique. Then we give a survey on existing Markov chain models in CRNs and accentuate the modeling and performance analysis of CRNs with channel assembling by proposing and examining two representative channel assembling strategies. The motivation behind our CRN modeling with channel assembling is its popularity in the literature versus the lack of mathematical modeling for this technique. Such models can provide us an insight of this technique with in-depth knowledge and help us better select a strategy in the design and implementation phase.

3.1 The Concept of Channel Assembling

Channel assembling means that multiple idle channels can be combined by SUs for a single SU service, instead of using barely one channel per SU service all the time. With channel assembling techniques, SUs could take the advantages of using several neighboring channels, as well as separated ones in the frequency domain, as one channel at the same time. This technique has been proposed in many CRN MAC protocols and dynamic spectrum access strategies [32, 41, 67, 68, 69]. It has also been proposed for long term evolution-advanced (LTE-A) [70] mobile system for achieving ultra high throughput. A channel occupation snapshot at a particular time instant when two channels can be assembled is illustrated in Fig. 3.1. In this example, SUs combine two idle channels together in two different ways [68]. In the first case, two separated idle channels (Channels 1 and 3) are *aggregated*; and in the second case, two neighboring idle channels (Channels 5 and 6) are *bonded* as one channel. Note that neighboring channels could also be aggregated. The difference is that channel bonding merges adjacent spectrum as one channel in the frequency domain while channel aggregation still keeps the spectrum separated but combines them logically. If the vacant channels are neighboring to each other, the guard band between channels, e.g., Guard Band$_A$ in Fig. 3.1, can be utilized for data transmission when channel bonding is implemented. On the other hand, a larger guard band is required at the band edges, as Guard Band$_B$ in the same figure. In order to keep coherence, we ignore these details and use the term channel assembling to refer to both channel bonding and channel aggregation.

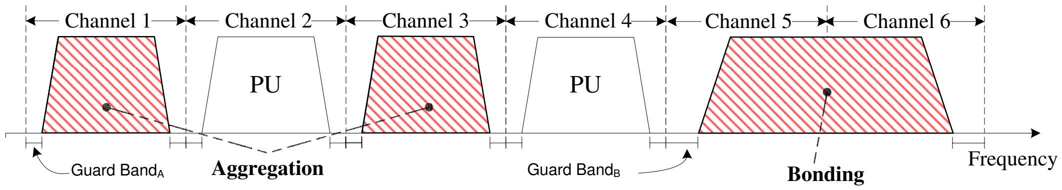

Figure 3.1: Channels used by two types of systems with channel bonding or aggregation.

In this chapter, we investigate various channel access schemes with channel assembling enabled, focusing on two proposed channel assembling strategies. In the mathematical modeling of these two strategies through continuous time Markov chains (CTMCs), we firstly consider the precise models with heterogeneous SU service types, i.e., real-time traffic flows and elastic traffic flows. Then we study the performance of each type of flow in the limiting regimes, including the quasistationary regime and the fluid regime. The capacity upper bound of the elastic traffic type in the quasistationary regime is derived in the end of the chapter.

3.2 Existing Channel Access Schemes and Their Mathematical Models with Channel Assembling

3.2.1 MAC Protocols in CRNs with Channel Assembling

In existing medium access mechanisms for CRNs, the concept of channel assembling has been widely adopted, both in centralized protocols [28] and distributed ones [32]-[35], [40, 41]. In the centralized protocols, there is a central controller which can schedule various channels to different services in the network, whereas in the distributed protocols, there are no coordinated transmissions and SUs usually compete for channel access.

In many contention based MAC protocols for CRNs where SUs compete with each other for channel access, only the winner can utilize available channels after competition [34, 40, 41]. In other words, there exists at most one ongoing SU service in the system at any time instant. In this case, it is beneficial with channel assembling given the existence of multiple channels. For example, in time-slotted channels where [40] and [41] are oriented, if there are no PU activities in the beginning of a slot when SUs sense these channels and PUs will not appear in the rest of the slot, it is beneficial for the winning SU to assemble these channels in that slot since higher data rate will be achieved. In this case, if idle channels are not assembled together by this winner, this opportunity is simply wasted. In [34], a statistical channel allocation MAC protocol which works in un-slotted channels is introduced. In their work, the situation where SU transmissions terminate due to packet collisions with PUs are examined by simulations, and a strategy to avoid such collisions is designed. The benefit of channel assembling in these protocols is in accordance with the intuition that higher resource utilization is achieved. Anyhow, we continue to discuss this topic in Chapter 4.

In this chapter, we consider another case where parallel SU services are allowed in the network [28, 35]. In this case, new arrivals will have limited resource or even be blocked if one SU service occupies too many channels, and the overall performance of CRNs with channel assembling deserves further investigation.

3.2.2 Spectrum Access Strategies with Parallel Services and Their Markov Chain Models

When parallel SU services are allowed, various channel access strategies have been proposed and their performance is evaluated. In this subsection, we summarize the existing channel assess strategies proposed for CRNs, which are analyzed based on CTMCs.

The technique which is opposite to channel assembling, i.e., a PU channel could be split into several channels for SU services, is proposed and modeled through CTMCs in [45], [46] and [47]. The system performance is examined by parameters like throughput, blocking probability and forced termination probability. In [45] and [46], the authors mainly focus on system performance when there are infinite number of users, and both handover and non-handover cases are considered in these studies. Besides, channel reservation which could make a tradeoff between throughput and blocking probability is also investigated. In [47], the performance of the secondary network is investigated in the cases with finite users. Furthermore, the quasistationary regime of the model which could make the computation scalable is also studied in their work.

For channel assembling strategies, we propose two representative strategies as presented in details in Paper B of this thesis. Other research work that has also been done for Markov modeling based performance analyses of channel assembling strategies is summarized as follows in this section. Existing research work distinguishes from each other, depending on whether *spectrum adaptation* is fully supported or not. The meanings of spectrum adaptation are twofolds. On the one hand, it is inherited from spectrum handover, which allows SUs to switch an ongoing SU transmission to a vacant channel that is not occupied by PUs or SUs, if it exists, when a PU activity appears on the current channel. On the other hand, it is meant that an ongoing SU service could adaptively adjust the number of assembled channels according to the availability of channels as well as other SUs' activities. When spectrum adaptation is not fully enabled, i.e., with spectrum handover only or even without spectrum handover, ongoing SU services cannot adjust the number of the assembled channels. Furthermore, how spectrum adaptation is utilized depends on specific channel assembling strategies.

In [48] and [49], channel assembling strategies when spectrum adaptation is not fully supported are investigated mathematically from different angles. In [48], the performance of the secondary network with different channel assembling strategies is studied when spectrum handover is not implemented. Three strategies, i.e., without channel assembling, with fixed number of assembled channels, and assembling all idle channels when SU services access the system, are investigated and compared with each other. In [49], channel assembling strategies denoted by constant channel aggregation (CCA), probability distribution based variable channel aggregation (P-VCA), and residual channel based variable channel aggregation (R-VCA) are studied. CCA is the same as the one in [48], with a fixed number of assembled channels. However, in P-VCA, the number of assembled channels for SUs follows a probability distribution, while in R-VCA, the number of assembled channels is determined based on the number of residual channels that are not occupied by PUs and SUs. The cases for both with and without spectrum handover are examined for these strategies [49]. A common feature of these strategies in [48] and [49] is that ongoing SU services are not able to change the number of the assembled channels. From numerical results of these strategies, the main conclusion from these papers is that the performance gain in the sense of capacity, forced termination probability, and blocking probability can hardly be observed compared with the legacy strategy without channel assembling, no matter whether spectrum handover is allowed or not. The main reason is that the unadjustable ongoing SU services will suffer from high forced termination probability and they will also block newly arrived SU services, resulting in poor overall performance.

To overcome the drawbacks in strategies presented in [48, 49], strategies with full meaning of spectrum adaptation and their mathematical models are proposed in our earlier work [71, 72]. Since the basic idea of the CRNs is to sense the spectrum and adjust the channel occupancy accordingly, strategies with spectrum adaptation fully enabled are essential and more appropriate for CRNs. In [71], two channel aggregation strategies, i.e., a *Greedy* strategy and a *Dynamic* strategy, are proposed. In the *Greedy* strategy, ongoing SU services are given higher priority than the newly arrived ones. More specifically, when an SU service arrives, ongoing SU services will not share their channel occupancy with the new comer if there are not enough idle channels at the moment. However, for the *Dynamic* strategy, ongoing SU services are willing to donate their occupied channels to the new comer. Performance gain compared with the strategy without assembling has been observed from different aspects through the numerical results obtained for the *Dynamic* strategy. For the *Greedy* strategy, capacity gain is still limited because of the high blocking probability of SU services.

Since advantages have been observed in the strategy with dynamic properties, two different dynamic strategies, i.e., dynamic fully adjustable (DFA) strategy and dynamic partially adjustable (DPA) strategy, are modeled and compared in [72], and DPA is actually the same as the *Dynamic* strategy proposed in [71]. The main difference between these two dynamic strategies is how SUs react upon a PU service arrival. More specifically, DPA will simply reduce the number of channels that an ongoing SU service assembles if PUs reappear to one of these channels and no idle channel exists, while DFA will always request the ongoing SU service with the maximum number of channels to donate its channel occupancy. Clearly, DFA has higher flexibility, and better performance has been observed for DFA than for DPA. The models in the quasistationary regime for those dynamic strategies are also developed.

Based on the previous research, two representative strategies and their mathematical modeling are studied in-depth in Paper B of this thesis. In Paper B, a static strategy with only spectrum handover and a dynamic strategy with spectrum adaptation are studied in the scenario in the presence of heterogeneous traffic types, i.e., elastic traffic and real-time traffic. The main difference between elastic traffic and real-time traffic of SUs is that the service time will be reduced if more channels are utilized by elastic traffic, like file downloading, while the service time will remain the same regardless the number of assembled channels for real-time traffic, like a Skype conversation. All the detailed information on these strategies as well as the mathematical models can be found in Paper B. To avoid overlapping, we illustrate in the following the assumptions of the system model which are necessary in order to understand the basic ideas of this network, and give more detailed discussions and examples which are not included in Paper B in the following section.

3.3 Two Representative Channel Assembling Strategies with Spectrum Adaptation

3.3.1 System Models and Assumptions

Consider a frequency band which consists of M channels for PUs, where each PU service utilizes only one channel while SUs can assemble multiple channels for a single service. It is assumed that SUs can precisely sense PU activities. We further assume that the sensing and spectrum adaptation latency is much shorter than the duration of the service events. To keep our analysis simple and consistent for all strategies, the protocol overhead to support different channel assembling strategies is excluded in our modeling.

The modeling is service based, i.e., we do not differentiate a particular user. It is assumed that the services for both PUs and SUs are independent of one another. Denote by $a \in \mathbb{N}^+$ the number of assembled channels for a real-time SU service in the network, where $\mathbb{N}^+$ denotes a set of positive natural numbers. We assume further that with a channels for each SU service of this kind, sufficient service quality can be guaranteed. Parameters W, $V \in \mathbb{N}^+$ represent, the lower bound and the upper bound of the number of assembled channels for an elastic SU service respectively. The values of them are pre-configured for a given strategy and network configuration. Let $N \in \mathbb{N}^+$, $W \leq N \leq V$, be the number of channels that an elastic SU service assembles. The value of N can be different from one service to another, and may even vary along time for a specific SU service if spectrum adaptation is fully enabled.

3.3.2 Channel Assembling Strategies and Precise CTMC Models

In Paper B, two channel assembling strategies are proposed and evaluated comprehensively. One of them is a static strategy where only spectrum handover is enabled. In this strategy, the number of assembled channels for different ongoing SU services can be different. However, for a specific ongoing SU service, the number of its assembled channels cannot be changed along time. Newly arrived SU services are simply blocked if there are not enough idle channels available. When a PU service arrives and there is no idle channel available at the moment, the ongoing SU service which is interrupted by this PU reappearance will be forced to terminate. The other strategy proposed in Paper B is a dynamic strategy in which the whole meaning of the spectrum adaption is supported. In this strategy, the number of assembled channels among various ongoing SU services can be different. Moreover, the number of assembled channels for an ongoing SU service can also be changed along time according to different events. For example, upon an SU service arrival, ongoing SU services are willing to share their occupied channels if the number of idle channels is not enough. The dynamic strategy in Paper B is the same as the *Dynamic* strategy presented in [71] if the real-time service type does not exist.

To avoid overlapping, we do not elaborate the proposed strategies here and the detailed definition and descriptions of those two strategies can be found in Section IV in Paper B. The mathematical modeling processes of these strategies are illustrated in Section V of Paper B and the parameters for performance evaluation, i.e., the blocking probability, the forced termination probability, the capacity, and the average service rate per ongoing SU service, are derived in the same section. Briefly, the blocking probability represents the probability that a newly arrived SU service request is blocked before it enters the system, while the forced termination probability indicates the probability of an ongoing SU service being forced to terminate before the service is finished. Note that the capacity here is different from Shannon capacity [73] and the capacity of a type of SU services is defined by the average service rate of SUs in that type, i.e., the average number of SU service completions per time unit. The average service rate per ongoing SU service represents the rate that an ongoing service will be processed on average.

In Paper B, no CTMC examples are illustrated due to space limit. In this subsection, instead of repeating the general mathematical derivations and equations which are included in Paper B, we demonstrate our models through two exemplary CTMCs given concrete values of M, V, W. For illustration convenience, we consider pure elastic traffic, i.e., assuming that the real-time traffic does not exist in the network. To model different strategies with CTMCs, we assume that the arrivals of SU elastic services and PU services are both Poisson processes with arrival rates λ_S and λ_P respectively. Correspondingly, the service times are exponentially distributed with service rates μ_S and μ_P in one channel. For an elastic SU service with N assembled channels, the service rate for that service becomes $N\mu_S$.

Fig. 3.2 illustrates the CTMC model with $M = 6$ and $N = V = W = 2$, which means that each SU service assembles exactly two channels. The same as in Section V of Paper B, the states in this model can be expressed by an integer pair (i, j), where i is the number of PU services and j is the number of SU services.

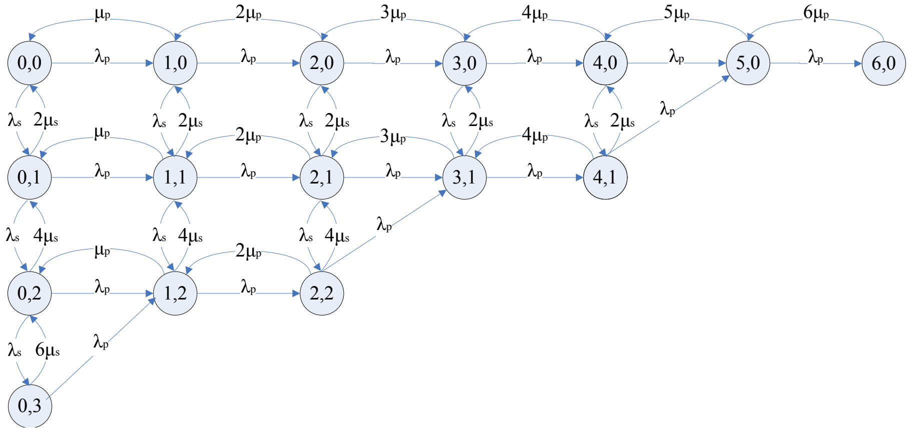

Figure 3.2: An example CTMC when $M = 6$ and SU services always assemble two channels, i.e., $N = V = W = 2$.

The state space is expressed as $\mathscr{S} = \{(i, j) \mid i, j \geq 0;\ i + 2j \leq 6\}$ in this case. Based on the feasible states and the transition rates summarized in Table I in Paper B, balance equations can be built. Denote by $\pi_{i,j}$ the steady-state probability of $(i,\ j)$. Let $\psi_{i,j}$ be a variable that indicates if the state (i, j) is within $\mathscr{S}$, i.e., $\psi_{i,j} = 1$ if $(i, j) \in \mathscr{S}$, and 0 otherwise. For each state, the balance equation can be written as

$$\begin{aligned}
&[2j\mu_S + i\mu_P + \lambda_S\psi_{i,j+1} + \lambda_P(\psi_{i+1,j} + \psi_{i+1,j-1} - \psi_{i+1,j}\psi_{i+1,j-1})]\pi_{i,j}\psi_{i,j}\\
&= (i+1)\mu_P\pi_{i+1,j}\psi_{i+1,j} + 2(j+1)\mu_S\pi_{i,j+1}\psi_{i,j+1}\\
&+ \lambda_P\pi_{i-1,j}\psi_{i-1,j} + \lambda_S\pi_{i,j-1}\psi_{i,j-1},\\
&\text{when } (i-1) + 2(j+1) < 6, \qquad (3.1)\\
&[2j\mu_S + i\mu_P + \lambda_S\psi_{i,j+1} + \lambda_P(\psi_{i+1,j} + \psi_{i+1,j-1} - \psi_{i+1,j}\psi_{i+1,j-1})]\pi_{i,j}\psi_{i,j}\\
&= (i+1)\mu_P\pi_{i+1,j}\psi_{i+1,j} + 2(j+1)\mu_S\pi_{i,j+1}\psi_{i,j+1}\\
&+ \lambda_P\pi_{i-1,j+1}\psi_{i-1,j+1} + \lambda_P\pi_{i-1,j}\psi_{i-1,j} + \lambda_S\pi_{i,j-1}\psi_{i,j-1},\\
&\text{when } (i-1) + 2(j+1) \geq 6, \qquad (3.2)
\end{aligned}$$

where $i = 0, 1, \ldots, 6$ and $j = 0, 1, \ldots, 3$. Additionally, the sum of the probabilities for all feasible states should be one,

$$\sum_{i=0}^{6} \sum_{j=0}^{\lfloor (6-i)/2 \rfloor} \pi_{i,j} = 1. \tag{3.3}$$

Once the state probability of the Markov chain is obtained, the forced termination probability, the blocking probability, the capacity, and the average service rate for commenced SU services can be calculated.

Fig. 3.3 illustrates another CTMC model for the dynamic strategy given $W = 2$, $V = 3$, and $M = 6$. Similarly, the states in this model can be expressed by (i, j_2, j_3), where i is the number of PU services while j_2 and j_3 are the number of SU services that assemble two and three channels respectively. Similar approach can be adopted as in the previous example for performance parameter calculation, so we do not explain the procedure explicitly here.

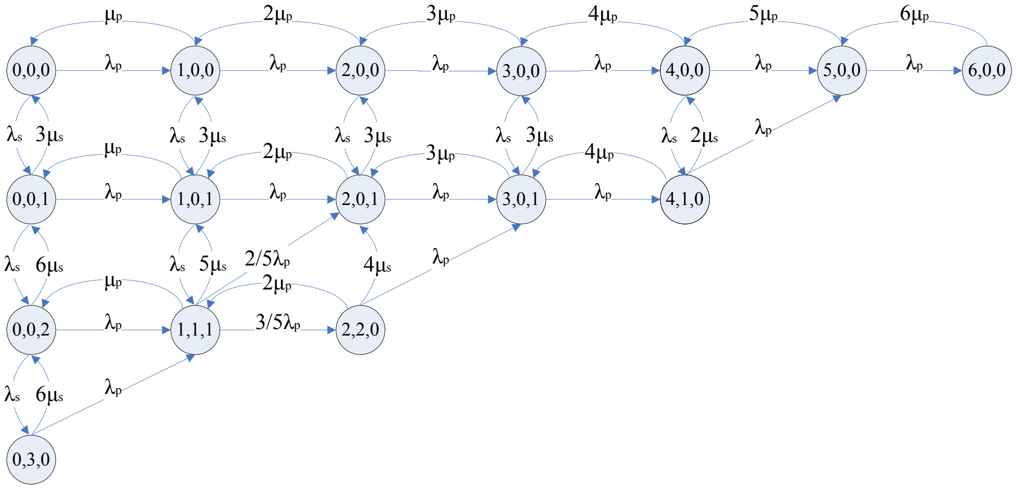

Figure 3.3: An example CTMC for the dynamic strategy given $W = 2$, $V = 3$, and $M = 6$.

3.3.3 CTMC Models in Limiting Regimes

In this subsection, the models in the limiting regimes for these strategies, i.e., the quasistationary regime and the fluid regime, are analyzed. The limiting regimes refer to the scenario when PU activities are relatively static or extremely dynamic, compared with SU activities. When PU activities are relatively static, the system approaches the quasistationary regime. On the other hand, when PU activities are extremely dynamic, the system is close to the fluid regime.

In the quasistationary regime, since it is assumed that PU activities are relatively static compared with SU activities, the distribution of SU services in the system reaches equilibrium between consecutive PU events. In this case, although forced terminations may still occur, there will be, at most, one upon each arrival of PU service. Since between two consecutive arrivals of PUs an infinitely large number of SU arrivals occur, the probability of forced termination approaches zero. The quasistationary regime is studied extensively in Paper B for two reasons. The first reason is that it is an interesting case that can be applied in many real-life scenarios. In many existing MAC protocols where channel assembling is utilized, the authors focus on the scenarios when the time scale for PU activities largely exceeds that of the SUs' [28, 32, 33]. This assumption is similar to the ones made in the quasistationary regime from mathematical modeling's point of view, where PU activities are comparatively static. Another important reason is that the scalability of CTMC can be improved with this assumption because the PU activities and the SU activities can be separately modeled in CTMCs. An inspection of Section IV in Paper B reveals the detailed mathematical process in modeling on those strategies in the quasistationary regime.

In the fluid regime, the PU activities change so fast that all SU services commenced in the network will be preempted almost immediately. From its definition, it could be inferred that almost all commenced SU services are forced to terminate in this regime. Consequently, we can conclude that the forced termination probability is close to one hundred percent and the capacity of SUs trends to zero under this regime. In this case, the blocking probability and the average service rate per ongoing SU service become meaningless, even though their values may be positive.

In order to observe the performance of different strategies in the limiting regimes and to describe the dynamic of PU activities, we introduce a scaler f to reflect PU activities while keeping the offered load constant for both PUs and SUs, as $\lambda_P = 1 \times f$, $\mu_P = 0.5 \times f$, $\lambda_S = 1.5$, and $\mu_S = 0.82$. The capacity as a function of f has been plotted in Fig. 6 in Paper B and discussed in Section VII-C in the same paper. To provide more information, we plot here another result which is not included in Paper B, the forced termination probability, as a function of f with the same system configuration.

In Fig. 3.4, $\mathrm{S}(a,1,3)$ denotes the static strategy without real-time traffic when $W = 1$ and $V = 3$, whereas $\mathrm{D}(a,1,3)$ corresponds to the dynamic strategy with the same parameter configuration, and NA denotes the strategy without channel assembling. From this figure, we can observe that when $f \ll 1$, which means that the service time of PUs is quite long while the arrival rate is low, the forced termination

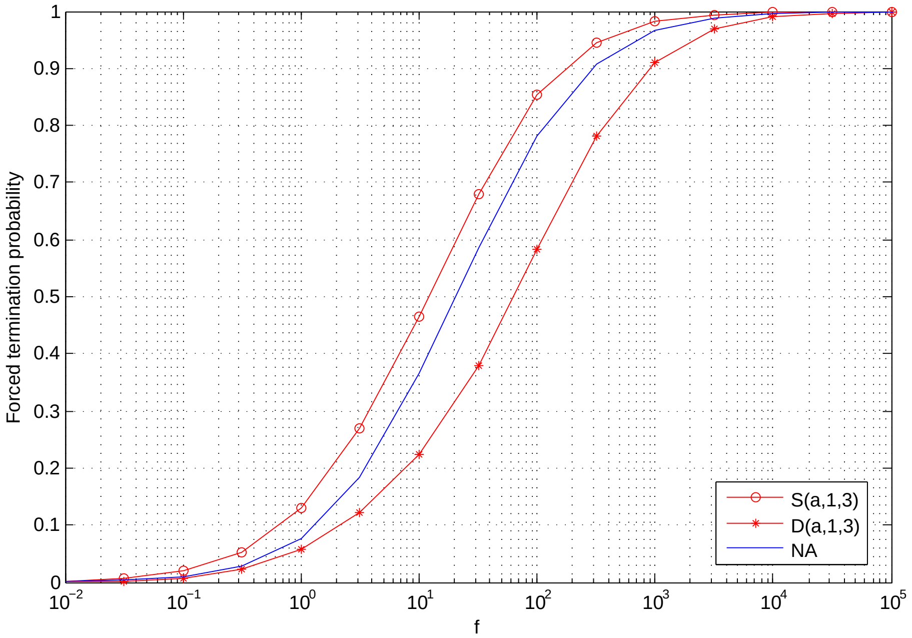

Figure 3.4: Forced termination probability as a function of f.

is close to zero. This result corresponds to the assumptions in the quasistationary regime well for all examined strategies. When f become larger than 10^3, meaning that PU services arrive frequently and the service time is very short, the forced termination probability of SU services is close to one hundred percent. These observations confirm our pervious analysis.

As mentioned earlier, Poisson arrival and exponentially distributed service time are assumed in order to utilize CTMC analyses. In real-life, however, the traffic patterns [74, 75, 76] might be quite different from those ones. In order to further investigate the applicability and the preciseness of our Markov chain based analytical models, we run simulations extensively with diverse PU and SU traffic types and further investigate our proposed strategies. The simulation results obtained based on different distributions demonstrate that the mathematical analysis presented in Paper B can be adopted as a robust reference model for analyzing the performance of channel assembling strategies in CRNs.

From the CTMC models and the numerical results of the channel assembling strategies, we draw the following main conclusions. The dynamic strategy can achieve better performance than the NA strategy does in the investigated cases. For the static strategy, however, its overall performance is poorer than the no channel assembling case except one aspect, i.e., a higher average service rate for ongoing services. More detailed numerical results and discussions can be found in Section VII of Paper B.

3.4 Capacity Upper Bound of Channel Assembling in the Quasistationary Regime

Based on the results presented in the previous sections, the capacity of CRNs can indeed be improved by adopting channel assembling with spectrum adaptation. A further question of interest is thus — does there exist maximum capacity for CRNs when channel assembling is enabled? And if yes, what is the maximum possible capacity?

As discussed previously, the achieved higher capacity with channel assembling is meant for elastic traffic. To examine the maximum capacity with channel assembling, we focus on the elastic traffic only. With more channels for an elastic service, the service can be processed faster. Therefore, more services can be processed if a proper strategy is utilized with appropriate parameter configurations for this kind of traffic. For a specific injected SU traffic load, given the arrival and the service rates for PUs, the capacity of SU services with channel assembling must be upper bounded given a limited number of channels and the SU service rate in each channel.

Paper C deduces the capacity upper bound of CRNs with channel assembling in the quasistationary regime. We adopt the following logic to find the upper bound. First of all, we propose a dynamic strategy with full spectrum adaptation and sharing, referred to as FAFS, and its SU service behavior is modeled by a birth and death process in the quasistationary regime for any given number of PU services in the system. Note that FAFS is different from the two representative strategies presented in Paper B. Then, we prove that this birth and death process has the maximum capacity when $V = M$ and W equals to the minimum possible number that a service can be supported. In the end, we confirm that no other strategies can achieve higher capacity than FAFS does, given the same system configuration. Therefore, it is concluded in Paper C that the maximum capacity in the quasistationary regime is achieved when the dynamic strategy is utilized with parameters $V = M$, i.e., V equals to the maximum number of channels, and W configured as the minimum possible number that a service can use. More specifically, for $W,\ V \in \mathbb{N}^+$, the maximum capacity is achieved when the dynamic strategy is adopted and configured as $W = 1$ and $V = M$.

3.5 Chapter Summary

In this chapter, channel assembling technique is presented firstly and then various channel access strategies are summarized when parallel SU services are allowed in the network. The performance of channel assembling strategies, represented by the static strategy and the dynamic strategy, is thoroughly examined through both mathematical modeling and simulations. More detailed information which is not included in Paper B is elaborated in this chapter. The numerical results demonstrate that channel assembling can achieve benefits from different aspects over the strategy without channel assembling if an appropriate strategy is selected and the parameters are configured properly. The closed-form capacity upper bound of CRNs with channel assembling in the quasistationary regime is also derived based on mathematical modeling. The derivation of this capacity upper bound is originally reported in Paper C.

Chapter 4

Power Allocation in Multi-channel CRNs with Channel Assembling

In the previous chapter, various channel assembling strategies are proposed and examined extensively in multi-channel CRNs when parallel SU services are allowed. In this chapter, however, we consider a case where SUs compete with each other for channel access but there is *only one* SU service as a winner that can utilize multiple idle channels after each competition [34], [40], [41]. Instead of designing a signaling process which has been proposed in many MAC protocols, another important aspect, i.e., channel selection and power allocation, is studied in this chapter.

4.1 Introduction to Power Allocation in CRNs

In distributed CRNs in the OSA mode, MAC protocols usually operate in a competing manner whereby the SUs compete for access opportunities, and the winning SU utilizes the available channels but other SUs have to wait for the next round of competition [34] [40] [41]. When multiple channels are available for the winner, channel assembling techniques can be utilized by the winner in order to support higher data rate and further improve spectrum utilization. On the one hand, different channels may have different channel conditions and various PU arrival rates. On the other hand, SUs have a limited transmission power budget. Therefore, how to select channels and allocate power among them in order to achieve a pre-defined goal deserves an exploration. Note that *channel selection can be integrated with power allocation* from the perspective of algorithm design *since a channel is not selected if no power is allocated on that channel*. Therefore, we focus only the on power allocation schemes in this chapter. Traditionally, to maximize data rate, waterfilling is adopted for power allocation among multiple channels [77]. However, in CRNs, collisions in an SU transmission because of the re-appearance of PU activities need to be considered as well. If such collision happens, i.e., PU activities appear during an SU packet transmission, SUs must release the channel immediately in order to leave room for PUs, resulting in possible cost or even unsuccessful packet transmission for SUs [4, 34].

In CRNs, with diverse resource constraints, SUs may achieve optimized performance from different aspects. For example, SUs require to maximize transmission data rate with a given power budget while keeping collision probability low. Those requirements can be formulated to various optimization problems, and based on the analyses of those problems, different algorithms can be proposed. In this chapter, power allocation is studied in order to optimize system performance considering various channel conditions and PU arrival rates among multiple idle channels. Specifically, two optimization problems in power allocation are formulated and studied considering that SUs access the channels through competition and only the winner can utilize the vacant channels for packet transmission. The first problem is to minimize the collision probability of an SU transmission with PU activities. The other one is to maximize the data rate given the upper bound of collision probability. In each of those problems, two kinds of power constraints, i.e., per-channel power constraint and total channel power constraint are further imposed. Based on the analyses of these problems, different power allocation algorithms are proposed in order to solve those problems under various conditions. Numerical experiments are utilized to validate these proposed solutions.

In what follows, related work on power allocation is summarized first. Then the power allocation optimization problems are presented and analyzed in-depth. Different algorithms are proposed for each of the examined problems based on these analyses.

4.2 Existing Power Allocation Algorithms in CRNs

In this section, the related work is summarized from two perspectives. The first subsection gives a brief overview of power allocation in the SS case, and the second subsection discusses power allocation schemes in channel access based on the OSA mode as well as their limitations.

4.2.1 Power Allocation in the Spectrum Sharing Mode

In SS based CRNs, simultaneous transmissions for both PUs and SUs, if not generating intolerable interference among one another, will make spectrum more efficiently used. To keep the interference generated by SU transmitters below a threshold at PU receivers, it is important to impose an interference spectrum mask constraint [78] or an SINR/noise constraint at the PU receiver side [7, 79, 80]. In [35], instead of utilizing an SU-to-PU power mask, a limit on the fraction of time duration which the PUs' reception is affected by SU transmissions is introduced. Based on this idea, a distributed cognitive radio MAC protocol that enables SUs to dynamically utilize the spectrum while limiting the interference to PUs is developed. A Rayleigh fading channel model is utilized to analyze the interference between PUs and SUs. In [81], two optimal power allocation algorithms to maximize the ergodic capacity of SUs are proposed under the PU outage probability constraint and under the average or peak transmission power constraint. However, that work is not targeting at multiple channels and applied only for the SS case. In [8], optimization problems for dynamic resource allocation in CRNs from convex optimization's perspective are summarized and analyzed. In brief, although a great amount of valuable work has been done for optimal power allocation and transmission based on the SS mode, these approaches developed for the SS mode do not apply to the OSA mode.

4.2.2 Power Allocation in the Opportunistic Spectrum Access Mode

In most existing MAC protocols and channel access schemes in OSA, it is usually assumed that channels are time-slotted [40, 41, 82], or that the time scale for PU activities largely exceeds the time scale of SUs [28, 32, 33]. Therefore, the collision of ongoing SU packet transmissions by PU activities can be ignored and the idle channels can be utilized by SU packet transmissions without considering the reappearance of PUs. In these scenarios, the traditional waterfilling algorithm can be applied if multiple channels are found as idle. In [34], a statistical channel selection scheme is introduced in their proposed MAC protocol. In their work, channels for packet transmissions are selected based on statistic characteristics of PU events on different channels, however, how power is allocated on those channels is not analyzed nor optimized.

Recently, the authors of [83] introduce a power allocation algorithm for CRNs based on a risk-return model in which the cost of the reappearance of PUs in a given band is modeled as a rate loss depending on the power level that SUs allocate to this band. Under this model, the optimal power allocation scheme turns out to be similar to the traditional waterfilling. However, this algorithm does not apply to the OSA mode, since a few important aspects in OSA are not considered. More specifically, the impact of PU reappearance is much more than just wasted transmission power or associated rate loss. It includes other important ramifications, such as SU packet loss, delay and overhead in the handshake process. Hence, modeling this collision just as a rate loss is insufficient.

In this chapter, we propose to minimize or constrain the collision probability[1] of the transmitting SU packet by allocating power among multiple channels in the presence of different channel conditions and PU reappearances in the OSA mode. The detailed information on the analyses of these optimization problems and their corresponding algorithms can be found in Paper D. To avoid overlapping, only the main idea of Paper D is summarized in the following paragraphs without explaining the detailed mathematical derivations, and more research results which are not included in Paper D are provided in this chapter.

4.3 System Models

Assume that there are two types of radios, PUs and SUs, operating in the same frequency band. Each PU service requires only one channel but SUs may assemble multiple channels for a service. All of these channels have the same bandwidth B. In order to protect PU services, SUs must release their channel occupancy immediately whenever PU services appear. It is assumed that SUs can sense the PU activities precisely.

Consider that there are M idle channels[2] that can be utilized by the current winner after SU competition. Since SUs may have constrained hardware[3], it is assumed that an SU can assemble up to N channels for a packet transmission. Therefore, for a given number of idle channels and hardware constraint, SUs may assemble up to $\min\{M,N\}$ channels for one packet transmission. Those channels can be either neighboring to each other or separated in the spectrum domain.

Assume further that each channel contains S sub-channels corresponding to S sub-carriers in orthogonal frequency-division multiplexing (OFDM), and each sub-

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[1] It is worth mentioning that we consider the case that SUs compete for transmission opportunities and there is no collision between SUs after competition. So possible collision is between an ongoing SU packet and a PU reappearance.

[2] Note that M in this chapter has a different meaning from M in Chapter 3, where in Chapter 3 M denotes the total number of channels in the system.

[3] As pointed out in [33], the number of channels that an SU can assemble is up to a limit.

carrier has equal bandwidth b. Therefore, we have $Sb = B$. Denote respectively $h_{i,j}$, $n_{i,j}$, and $p_{i,j}$ the channel state, the noise density, and the SU's allocated power for the jth sub-channel on channel i, where $i \in I$, $I = \{1, \cdots, M\}$ and $j \in J$, $J = \{1, \cdots, S\}$. If a transmission scheme other than OFDM is utilized where no sub-channels exist, $h_{i,j}$, $n_{i,j}$, and $p_{i,j}$ become h_i, n_i, and p_i correspondingly.

The same as many other studies, the PU service arrival process is usually modeled as a Poisson process. This is not only due to its mathematical convenience, but also because it indeed captures the nature of the arrival processes in different communication systems. It is shown by many real-life measurements [74, 76] that the call arrivals in cellular systems are well modeled by a Poisson process. Similarly, in the scenario where IEEE 802.11 equipments (as PUs) share spectrum with IEEE 802.15.4 equipments (as SUs), the channel idle time of PUs, i.e., the duration that there is no 802.11 packet transmission, is shown to be geometrically distributed from real-life measurements [84]. Note that geometric distribution is memoryless, which corresponds to the exponential distribution in the continuous time domain. This is mainly due to the widely used exponential back-off timer in CSMA/CA. Consequently, in our work, the arrival of PUs is also modeled as a Poisson process with rate λ_i in channel i, $i \in I$.

With the Poisson arrival assumption, within a period τ, the probability that there is no PU arrival in channel i is expressed as $\mathscr{P}_i(\tau) = e^{-\lambda_i \tau}$. Assuming that PU activities are independent among different channels, then the probability that none of these channels are occupied by PUs in a given channel set C_s during period τ, denoted by $\mathscr{P}_{C_s}(\tau)$, is expressed as $\mathscr{P}_{C_s}(\tau) = \prod_{i \in C_s} \mathscr{P}_i(\tau) = e^{-\sum_{i \in C_s} \lambda_i \tau}$.

Let us define a channel utilization indicator ξ_i, $i \in I$ as

$$\xi_i = \begin{cases} 1, & \sum_j p_{i,j} > 0, \\ 0, & \text{otherwise}, \end{cases} \tag{4.1}$$

where $\sum_i \xi_i \leq \min\{M, N\}$. ξ_i indicates whether channel i is utilized by an SU packet transmission or not.

During one SU packet transmission, the set of assembled channels for this packet is fixed. Then, the probability that the packet is transmitted without collision with a PU activity is given by

$$\mathscr{P}_r = \exp\left(- \frac{\sum_{i=1}^{M} \lambda_i \xi_i L_p}{\sum_{i=1}^{M} \sum_{j=1}^{S} b \log(1 + h'_{i,j} p_{i,j})} \right), \tag{4.2}$$

where L_p is the packet length and $h'_{i,j} = |h_{i,j}|^2 / (n_{i,j} b)$.

4.4 Problem Formulations

Two optimization problems for power allocations are identified as follows. The first problem is to directly minimize the collision probability, whereas the second problem is to maximize the data rate while keeping the collision probability below a limit.

4.4.1 Minimizing Collision Probability

Since $\exp(-x)$ decreases monotonically with an increasing $x > 0$, in Eq. (4.2), $\mathscr{P}_r$ is maximized if $\frac{\sum_{i=1}^{M}\lambda_i\xi_i L_p}{\sum_{i=1}^{M}\sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j})}$ is minimized. Then, the optimization problem of minimizing the probability that the SU packet will collide with PUs, i.e., minimizing $1-\mathscr{P}_r$, can be formulated as

$$\min_{\{p_{i,j}\}_{i\in I, j\in J}} \frac{\sum_{i=1}^{M}\lambda_i\xi_i L_p}{\sum_{i=1}^{M}\sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j})}, \tag{4.3}$$

$$\text{s.t.} \quad \xi_i = \begin{cases} 1, & \sum_j p_{i,j} > 0, \\ 0, & \text{otherwise}, \end{cases}$$

$$1 \le \sum_i \xi_i \le \min\{M,N\}, \; p_{i,j} \ge 0,$$

$$\sum_i\sum_j p_{i,j} \le p_t; \text{or} \sum_j p_{i,j} \le p_t, \forall i \in I, \tag{4.4}$$

where p_t is the total power budget.

In this optimization problem formulation, there are two kinds of power constraints as shown in Eq. (4.4), i.e., either a total power budget is given for all channels or there exists a power constraint for each channel. The condition $\sum_i \xi_i \ge 1$ is introduced so that at least one channel is utilized by the winning SU to send its packet.

However, the solution for problem (4.3) is not obvious. First of all, the problem is neither convex nor continuous. Secondly, there is a conflicting effect if we increase the number of utilized channels. On the one hand, utilizing more channels can increase the data rate therefore reduce the transmission time for a packet, which will reduce collision probability. On the other hand, a larger number of utilized channels will involve more PU activities, which will potentially increase collision probability.

The main conclusion to solve this optimization problem is that the optimal solution is to allocate all power to only one channel, i, which gives the minimum value of $\lambda_i L_p / \sum_{j=1}^{S} b\log(1+h'_{i,j}p^*_{i,j})$, where $p^*_{i,j}$ is the allocated power for each sub-channel based on the waterfilling algorithm in channel i with p_t. The detailed mathematical proof of this conclusion can be found in Paper D.

4.4.2 Maximizing Data Rate with Constrained Collision Probability

More generally, the network would like to maximize its data rate while keeping the collision probability below a threshold value. In other words, SUs could choose a group of channels which have better channel conditions, while keeping the collision probability requirement satisfied. Then the optimization problem can be formulated as follows,

$$\begin{aligned}
\max_{\{p_{i,j}\}_{i\in I, j\in J}} \quad & \sum_{i=1}^{M}\sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j}), && (4.5)\\
\text{s.t.} \quad & \frac{\sum_{i=1}^{M}\lambda_i\xi_i}{\sum_{i=1}^{M}\sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j})} \le \gamma_0, && (4.6)\\
& \xi_i = \begin{cases} 1, & \sum_j p_{i,j} > 0,\\ 0, & \text{otherwise}, \end{cases}\\
& \sum_i \xi_i \le \min\{M,N\}, && (4.7)\\
& p_{i,j} \ge 0,\\
& \sum_i\sum_j p_{i,j} \le p_t; \text{or} \sum_j p_{i,j} \le p_t, \forall i \in I,
\end{aligned}$$

where $\gamma_0 = -\log(1-\mathscr{P}_{rc0})/L_p$ and $\mathscr{P}_{rc0}$ is the maximum tolerable level of the collision probability.

Again, this problem is neither convex nor continuous. Actually, it is proven in Paper D that the problem with per-channel power constraint is NP-hard.

4.5 Algorithms for Power Allocation

In Paper D, for the data rate maximization problem, a dynamic programming based pseudo-polynomial time algorithm which can find the global optimal solution is developed for the per-channel power constraint case, and a heuristic method based sub-optimal algorithm is proposed for the total channel power constraint case. In this section, we illustrate more our research results on this topic which are not included in Paper D. We firstly discuss the feasibility of the data rate maximization problem, and then propose a sub-optimal algorithm for the data rate maximization problem with per-channel power constraint based on a similar heuristic method utilized in the total channel power constraint case.

4.5.1 Feasibility Study

Before starting to solve the problem, the feasibility of the problem for the given system parameters, i.e., whether there exists a feasible solution according to the current system configuration, needs to be investigated. Based on the solution for the collision probability minimization problem, the feasibility check for the data rate maximization problem is straightforward. Since the collision probability is minimized when all power is allocated onto the best channel, we can put all power onto a single channel one by one, and then check if the collision probability requirement is satisfied. If there exists a channel that satisfies the collision probability requirement, the problem is feasible and we can further search for the optimal solution. Otherwise, the problem is infeasible and the searching procedure for the optimal solution is stopped.

4.5.2 A Heuristic Algorithm for Data Rate Maximization Problem with Per-channel Power Constraint

Even though the pseudo-polynomial time algorithm suggested in Paper D can find the optimal solution, the procedure is still quite time consuming, especially for packet level transmissions. Therefore, a heuristic method based sub-optimal algorithm which is not included in Paper D is suggested here. This algorithm is designed based on two facts. The first one is that a channel with a smaller λ_i/R_i, $\forall i \in I$, may better satisfy the probability constraint, where R_i is the resulted capacity in channel i based on the waterfilling algorithm with power budget p_t. The second one is that the more spectrum (the greater number of channels in this case) utilized, the higher capacity. The algorithm is illustrated as Algorithm 1 in this section. In this algorithm, $[R_i, \mathbf{p}_i] := wf(i, p_t)$ is a function which will return the power allocation result based on the waterfilling algorithm in the ith channels, $\forall i \in I$, with power budget p_t. In this function, $\mathbf{p}_i$ is the resulted power allocation vector with elements $p^*_{i,j}$, $j \in [1, S]$, in channel i, where $p^*_{i,j}$ represents the allocated power in each subchannel and $\sum_j p^*_{i,j} = p_t$.

In the beginning of the algorithm, waterfilling is done for each channel individually. In this way, the feasibility of the problem can be checked. If $N \geq M$, i.e., without hardware constraint, we firstly find out all the channels with $w_i \leq 0$, which

Algorithm 1 : A sub-optimal algorithm for the per-channel power constraint case

```
for $i := 1$ to $M$ do
    $[R_i, \mathbf{p}_i] := wf(i, p_t)$.
end for
if $\forall\, w_i > 0, i \in I$ then
    Problem infeasible.
else
    if $N \geq M$ then
        $Cs_n := \{\text{channel } i |\ \forall i \in I, w_i \leq 0\}$; $Cs_p := \{\text{channel } i |\ \forall i \in I, w_i > 0\}$,
        Let the number of channels in $Cs_p$ be $M'$; $R := \sum_{i \in Cs_n} R_i$; $W := \sum_{i \in Cs_n} w_i$,
        if $M' \geq 1$ then
            Rank channels in $Cs_p$ according to $\lambda_i / R_i$, $i \in [1, M']$ from low to high, and denote the ranked channel set as $Cs_o$.
            for $j := 1$ to $M'$, channel $j \in Cs_o$ do
                if $W + w_j \leq 0$ then
                    $R := R + R_j$, $W := W + w_j$.
                    Add channel $j$ to $Cs_n$.
                end if
            end for
        end if
    else
        Rank all channels according to $\lambda_i / R_i$ from low to high.
        Let the ranked channel set be $Cs_o$; $W := 0$; $R := 0$; $Cs_n := \emptyset$.
        for $j := 1$ to $M$, channel $j \in Cs_o$ do
            if $j \leq N$ then
                if $W + w_j \leq 0$ then
                    $W := W + w_j$, $R := R + R_j$,
                    Add channel $j$ to $Cs_n$.
                end if
            else
                $R_T := 0$, $W_T := 0$, $Cs_{nT} := \emptyset$
                for $i := j - N + 1$ to $j$, channel $i \in Cs_o$ do
                    $R_T := R_T + R_i$, $W_T := W_T + w_i$,
                    Add channel $j$ to $Cs_{nT}$.
                    if $W_T \leq 0$ and $R_T > R$ then
                        $R := R_T$, $Cs_n := Cs_{nT}$.
                    end if
                end for
            end if
        end for
    end if
    Let the waterfilling solution for channels in $Cs_n$ be $\mathbf{p}$,
    Return $[R, \mathbf{p}]$.
end if
```

will make the probability constraint satisfied, where $w_i = \lambda_i - \gamma_0 R_i$. Denote this channel set as Cs_n. For the remaining channels, we rank them according to λ_i / R_i, and then put the channels one by one into the channel set Cs_n, until the probability constraint is not satisfied.

Similarly, if $N < M$, i.e., with hardware constraint, we firstly rank all channels according to λ_i / R_i, $\forall i \in I$. Then we keep a sliding window with the size of N on those newly ranked channel set. In each window, we calculate the aggregated data rate and the collision probability constraint from the first element to the current one in the window. If the current data rate is higher than the previous one and the probability constraint is still satisfied, we update the data rate and corresponding Cs_n.

4.6 Numerical Results and Discussions

In this section, the performance of the proposed algorithms is evaluated via numerical experiments. Since most of the numerical results have already been included in Paper D, we plot only the results in the per-channel power budget constraint case based on Algorithm 1, which is not included in Paper D, and compare them with the results from the pseudo-polynomial time algorithm and from the exhaustive search. The default system parameters are configured the same as in Table 1 of Paper D. The proposed algorithms are compared with the exhaustive search from two aspects: the resulted capacity and computational complexity. The computational complexity is compared in terms of machine running time.

For the data rate maximization problem with collision probability constraint, it is observed that the pseudo-polynomial time algorithm, which is based on the dynamic programming, can always find the optimal solutions. Therefore, we plot only the result from the exhaustive search algorithm. Fig. 4.1 shows the achieved capacity as a function of M. As shown from this figure, the achieved capacity grows almost linearly with the increasing number of channels when $N \geq M$, i.e., when there is no hardware constraint. However, when N becomes smaller, the achieved capacity becomes lower since fewer number of channels can be utilized. The sub-optimal algorithm achieves lower but very close capacity to the global optimal, which means that our heuristic algorithm is very efficient.

Furthermore, the time consumption curves with respect to the number of channels M for the sub-optimal algorithm, the pseudo-polynomial time algorithm, and the exhaustive search algorithm are plotted in Fig. 4.2 and Fig. 4.3 when $N \geq M$, i.e., with sufficient hardware on SUs. To illustrate the curves more clearly, the re-

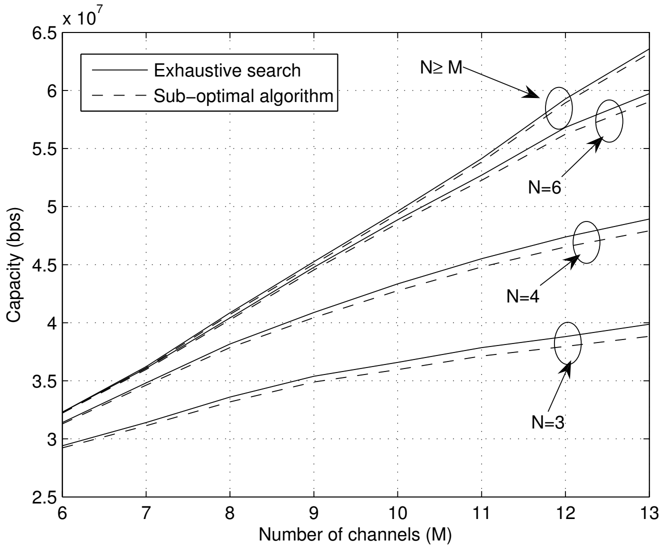

Figure 4.1: Capacity as a function of M.

sults when $M \in [3,10]$ are shown in Fig. 4.2 while the results for $M \in [10,14]$ are plotted in Fig. 4.3.

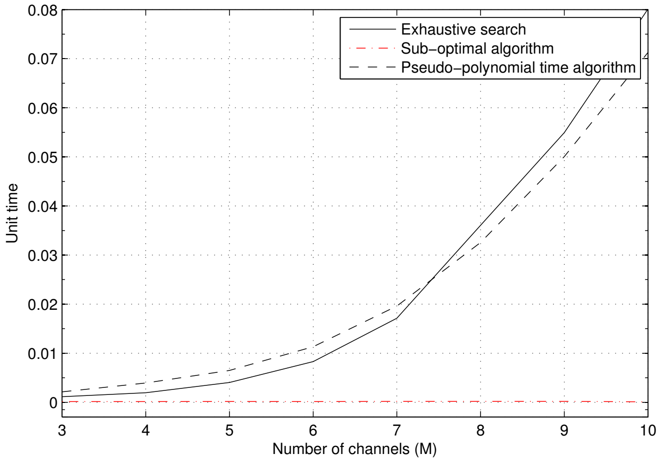

Figure 4.2: Time consumption as a function of $M \in [3,10]$ when $N \geq M$.

As observed from Fig. 4.2 and Fig. 4.3, as the number of total channels grows, the time used by both of the pseudo-polynomial time algorithm and the exhaustive search algorithm increases sharply. However, the proposed sub-optimal algorithm consumes much shorter time. From Fig. 4.2, one can observe that when M is small, i.e., $M \in [3,7]$, the pseudo-polynomial time algorithm consumes slightly more time than the exhaustive search does. However, when the number of total channels grows, the time used by exhaustive search increases dramatically, which

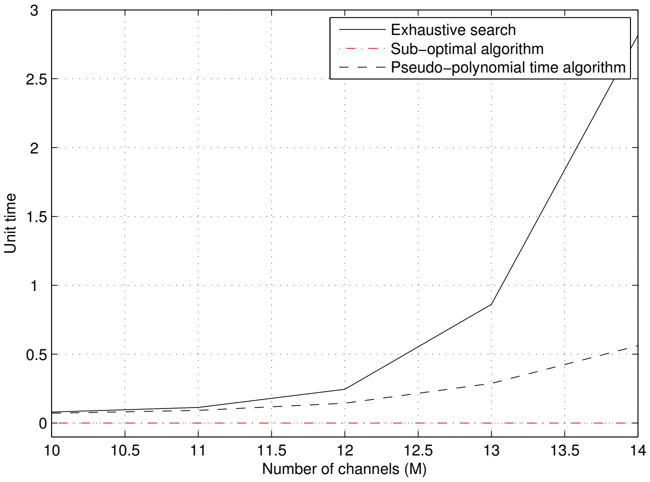

Figure 4.3: Time consumption as a function of $M \in [11,15]$ when $N \geq M$.

can be observed clearly in Fig. 4.3. This is mainly because that the searching space of the exhaustive search algorithm will grow exponentially with an increasing M. However, in the pseudo-polynomial time algorithm which is based on dynamic programming, the final optimal solution can be calculated based on the optimal solution of sub-problems[4]. Furthermore, when the solution of a sub-problem is to be utilized, it can check from a looking-up table and read the solution of the sub-problem directly if it has already been calculated. For each sub-problem, no matter how many times it is utilized in the recursion, it is calculated only once. Therefore, the time required for the dynamic programming algorithm is largely reduced even though M increases. This result tells us that, to get the optimal solution, the exhaustive search method is a workable option, given that the number of available channels is few. However for a large M, the pseudo-polynomial time algorithm through dynamic programming is recommended. The time consumed by the sub-optimal algorithm, which is in the order of 10^{-4} unit time, is much shorter than the time consumption of these two global optimal solutions, although the curve is hardly visible in the current plot. Also, the increasing trend of the curve in the sub-optimal algorithm with a growing M is not obvious. Considering the significant saving in terms of computation time, the sub-optimal algorithm is preferable if the global optimization is not mandatory.

In order to further compare the complexity of the algorithms when $N < M$, i.e.,

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[4] Dynamic programming is a scheme to solve a problem by breaking it down into simpler sub-problems. By combining the solutions to the sub-problems, the overall solution can be reached. The problem studied in this work with per-channel power constraint can be solved by dynamic programming. More information detailed can be found in [85] and Paper D.

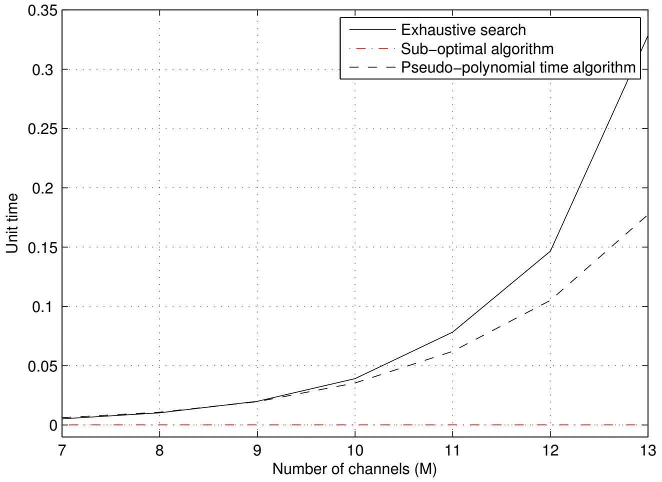

Figure 4.4: Time consumption as a function of $M \in [7, 15]$ when $N = 6$.

with hardware constraint, Fig. 4.4 illustrates the time used to compute the optimal solution when $N = 6$ as a function of M. In this case, the searching spaces for both algorithms are reduced therefore the time consumed is shorter than the case with $N = M$. Similar to what we have been observed earlier, the time utilized by the pseudo-polynomial time algorithm is shorter than that of the exhaustive search algorithm as M increases, while the sub-optimal algorithm consumes the shortest time among all these three algorithms.

4.7 Chapter Summary

In this chapter, the scenario where SUs contend for channel access and the only winning SU can assemble multiple idle channels is considered in CRNs. Two power allocation problems, i.e., minimizing the collision probability with PUs and maximizing the data rate with constrained collision probability, are further formulated, and various optimization algorithms are proposed accordingly. These algorithms apply to power allocation in CRNs for contention based multi-channel MAC protocols with channel assembling.

To the best of our knowledge, the study on this topic is originally carried out in Paper D. The optimal solution of the collision probability minimization problem is provably to put full power on the single best channel while the data rate maximization problem with constrained collision probability is proven to be NP-hard in the per-channel power-constraint case in Paper D. Therefore a dynamic programming method is proposed for power allocation with a per-channel power constraint.

Moreover, two highly efficient heuristic algorithms are proposed in both the per-channel power constraint and the total power constrained cases. As expected, the numerical results demonstrate that the dynamic programming achieves the optimized result, and that the heuristic algorithms are capable of achieving a data rate close to the global optimal value however with very low computational complexity.

Chapter 5

MAC and Routing Protocol Design in Multi-hop Multi-channel CRNs

In the previous chapters, extensive studies are carried out in single-hop multi-channel CRNs. To support a network with larger coverage, CRNs over multiple hops are also of essential interest. In this chapter, we continue our studies on MAC and routing layer issues respectively by considering various scenarios in multi-hop networks. The proposed MAC layer mechanisms target at making the network connected on a common channel over multiple hops based on a single interface which can tune in among multiple opportunistic channels. For routing protocol design, path selection and channel allocation are integrated to improve system performance in multi-channel multi-hop wireless networks with multiple interfaces equipped on each node.

5.1 Introduction to Protocol Design in Multi-hop Wireless Network

Different from traditional multi-hop wireless networks where all nodes are provided with certain dedicated channels, the frequency spectrum that can be utilized by SUs in CRNs may vary from time to time, and even from node to node along the path of a flow over multiple hops. These dynamic access opportunities bring many new challenges to the design of multi-hop CRNs. If nodes have no dedicated common channel or have no interface tuned onto a common channel among the neighborhood, the connectivity of the network over multiple hops cannot be maintained. Although having a dedicated control channel in a network makes connectivity not an issue, designing a routing protocol integrated with channel allocation is not trivial due to distinct spectrum availability among channels and nodes over multiple hops. In the rest of this section, we summarize the network connectivity maintenance schemes designed for CRNs. Existing routing algorithms and protocols for multi-channel multi-hop networks are also briefly surveyed.

5.1.1 Existing Network Connectivity Maintenance Schemes

When a dedicated control channel exists and there is an interface that is always tuned onto such a channel, it is easy to keep nodes in the network connected and further coordinate spectrum allocation through this common channel. However, in many scenarios where these two conditions do not meet, a mechanism is required to maintain the connectivity of multi-hop CRNs in the presence of multiple channels. In [86], a distributed group coordination scheme is proposed considering spectrum heterogeneity among multiple hops. In their scheme, only a local control channel is required for a group of neighboring nodes which have channels in common, since spatial spectrum heterogeneity reduces the feasibility of utilizing a global common control channel. Furthermore, the network connectivity is maintained at group boundaries by nodes that are associated with multiple common channels.

To solve a similar connectivity problem with spatial spectrum heterogeneity, the authors in [87] propose a cluster-based approach. They demonstrate that if neighbor discovery is perfect and the network is fully connected in the physical topology graph, full connectivity of the network at the link layer is achieved. In a similar study [88], a distributed swarm intelligence-based control channel assignment mechanism is presented, considering that common channels may temporarily exist among a local group of SUs. In all the above strategies, a single half-duplexed transceiver is assumed.

In a scenario envisaged by [89], a common control channel is required and there is an 802.11a based radio which is dedicated to the control channel. This mechanism maintains a global channel set including channels that are common to all nodes. If the common control channel that is currently utilized by the network becomes unavailable, another channel from the global channel set can be selected as the new control channel.

The above mentioned schemes focus on the cases where the multi-hop network is covered by different sets of PUs, resulting in spatial varieties of available channels. However, if we consider the case where CRNs are covered by the same set of PUs, e.g., TV broadcast (as the PUs) collocated with an ad hoc network (as the SUs) within a building, simpler schemes can be expected.

5.1.2 Existing Routing Algorithms and Protocols for Multi-channel Multi-hop Networks

To study routing algorithms and protocols in CRNs, we start from the ones originally designed for multi-channel ad hoc networks or multi-channel WMNs since the ideas in those schemes can be borrowed by CRNs. There are three categories of existing work on multi-channel multi-hop wireless networks. The first category targets at WMNs [51]-[57] where traffic pattern is relatively regulated in the network since most traffic flows are carried between gateway(s) and mesh routers. The second category focuses on multi-channel multi-hop networks with a single transceiver [90, 91, 92], while the third category mainly deals with scheduling [93, 94]. In addition to the above mentioned protocols, a 2.5 layer solution which handles channel selection and interface assignment is proposed in [95], and a source routing protocol is proposed in [96]. More detailed discussions on these protocols can be found in Section I of Paper F.

For routing schemes in CRNs, the challenges and solutions are overviewed and discussed in [50]. According to this reference paper, existing CRN routing protocols distinguish from each other based on the spectrum knowledge required by the schemes, i.e., the approaches based on full spectrum knowledge [97]-[103] or only on local knowledge [104]-[120]. The first type of such protocols usually requires full knowledge about the network, e.g., network topology, available spectrum band etc. Therefore, a network-wide signaling procedure needs to be designed in order to collect and share enough information for path selection and channel allocation. However, these protocols may not scale well as the network size increases, and the PU dynamic needs to be low enough so that the resulted channel allocation and path selection will not become stale for route and channel selection. On the other hand, since spectrum conditions may change frequently over both time and space, routing schemes based on local knowledge provide good options to reflect this dynamic nature. In this type of protocols, routing and channel allocation can be adopted based on various parameters, for instance, transmission power and interference, throughput etc, and various routing parameters are also designed in the literature for performance improvement. In this dissertation, the design of our routing protocol is based on local information considering its scalability and practicality.

5.1.3 Two Multi-hop Scenarios Considered in this Dissertation

In this dissertation, two cases in multi-hop multi-channel networks are studied and their solutions are proposed. The first case is about network connectivity maintenance and common channel selection. Two MAC mechanisms are proposed to maintain network connectivity in a common channel for communication purpose. These MAC mechanisms can also be utilized for common control channel selection in multi-channel multi-hop and multi-interface scenarios, and be applied to the dedicated interface which is responsible for control message exchange.

The other case considered in this dissertation is routing in multi-channel multi-interface ad hoc networks, which is a preliminary study on routing protocol design for CRNs. There are two reasons for considering routing in multi-channel ad hoc networks as a first-phase study of CRNs. Firstly, mature routing protocols can be used as references in this design and it is relatively easier to handle path selection and channel allocation in ad hoc networks than in CRN scenarios where channels are dynamic in the latter case. Secondly, the scenario in ad hoc networks can be considered as a special case in CRNs in which channels are relatively static, like in the quasistationary regime from mathematical modeling point of view. In this design, further extension to CRNs is also considered. Instead of only designing a path selection and channel allocation algorithm, the signaling messages are also elaborated, and the whole routing protocol is implemented and simulated using NS2. In what follows, the proposed mechanisms for the two cases are summarized in two separate sections.

5.2 MAC Mechanisms for Common Channel Selection in Multi-hop Multi-channel CRNs

As discussed in the previous section, common channel selection and connectivity maintenance in multi-hop CRNs are an important aspect in CRN protocol design. In this section, two MAC mechanisms originally proposed in Paper E for common channel selection purpose are outlined.

5.2.1 System Model and Assumptions

In Paper E, it is assumed that all the nodes in the multi-hop CRNs are covered by the same set of PUs, as shown in Fig. 5.1. With this assumption, space heterogeneity, which means that the available channels are different among multiple hops due to various coverages of PUs in the network, does not exist. In other words, if a channel is available to one SU in the network, it is also available to other SUs in the same network. Consider that the topology of a network guarantees the network connectivity if all nodes tune onto a common channel, i.e., all nodes can communicate with one another through single or multi-hop communications if they operate all on a common channel. It is further assumed that each node has one 802.11 based transceiver which works on one channel at a time but can jump among different channels if necessary. The goal of our design is to keep all nodes always on a single common channel. When PU activities appear in the current common channel, the nodes over multiple hops must tune onto another channel at the same time. Furthermore, if the channels have different bandwidth with various supported data rates, it is preferable for the network to select a channel which can support a higher data rate among multiple idle channels.

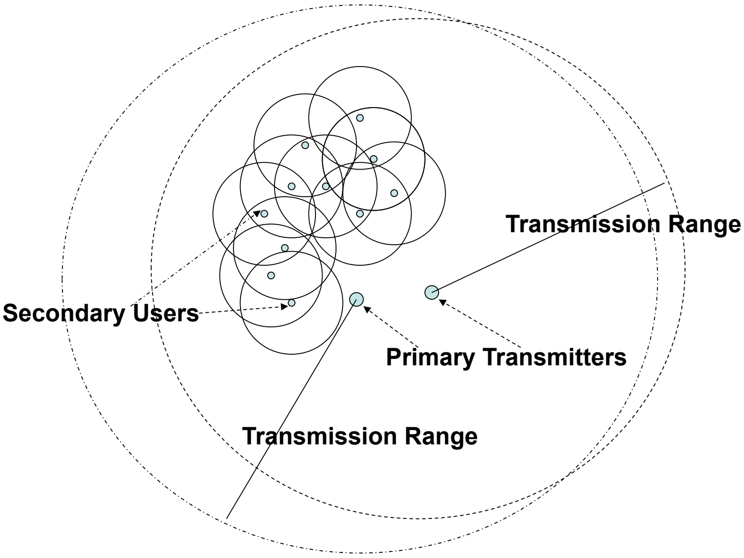

Figure 5.1: Scenario for the considered system.

5.2.2 Strategy Descriptions and Simulations

Based on the assumptions and the designing goal, two MAC mechanisms are proposed for the common channel selection. The first mechanism is straightforward such that SUs will always switch to the next idle channel if any PU activity appears in the current channel. Since we have assumed that the sensing result is precise enough and the network is covered by the same set of PUs, this mechanism can make the network connected in the next available channel among multiple channels. Clearly, although network connectivity is achieved, this mechanism cannot support the idea of tuning onto an idle channel with a higher data rate even if it exists.

The second mechanism utilizes the idea of connected dominating set (CDS) in the network in order to achieve network connectivity and perform channel selection among channels with different supported data rates. Consider that a multi-hop network forms a graph where the SUs are vertices in the graph, and an edge between two vertices means that the SUs can communicate with each other directly if they are on the same channel. Then the CDS of this graph means a group of nodes which have the following properties. First, they are all connected through a single hop or multiple hops. Second, any node in the graph is either within the CDS or one hop away from a node in the CDS. In this mechanism, there are two events that can trigger channel switching in the network. One event is a PU reappearance in the current channel. The other event is upon the discovery of an idle channel with higher data rate, which the network will switch to. The CDS nodes can be used to maintain and recover network connectivity when these events happen. If we can keep the CDS nodes always connected, other non-CDS nodes can easily find and join this network because they are only one hop away from this set. Therefore, the task becomes how to make the CDS nodes connected in another channel in the presence of a PU activity reappearance or the discovery of an idle channel with a higher data rate. In other words, the CDS nodes should be able to jump onto the same channel when PU activities appear in the current channel or when an idle channel with a higher data rate is discovered. Upon the first event, a channel is selected based on a database of the idle channels, which requires information of channels rather than the current one. Furthermore, in order to make the CDS nodes switch altogether onto the same channel with a higher data rate, information about channels other than the current common channel should also be gathered and shared.

The information collection on other channels is done by idle non-CDS nodes. When non-CDS nodes have no traffic to transmit, they will scan other channels periodically in order to find vacant channels. When the channel information is gathered, it will jump back to the current common channel and broadcast the acquired information. This information will be utilized further by the CDS nodes for channel selection and switching. If a channel with higher data rate is discovered, the nodes in multiple hops will switch to that channel at approximately the same time according to the validation time field carried by the broadcast message about the updated channel condition. If an idle channel is found however not with higher data rate, the working channel of the network remains unchanged. Nevertheless, the information about the idle channels will still be distributed among the network, and this information will be added to the database of idle channels in each CDS node. More detailed information about the idle channel discovery and channel switching procedure can be found in Paper E.

The proposed MAC mechanisms are evaluated through NS2. The simulation results, as shown in Paper E, demonstrate that the first mechanism has better performance in channels with identical data rate since it generates less overhead on channel information shared over multiple hops. However, for channels with heterogeneous data rates, the latter mechanism is more efficient since higher throughput is achieved when a channel with higher data rate is preferably selected.

5.3 A Distributed Routing Protocol with Channel Assignment in Multi-channel Multi-hop Wireless Ad Hoc Networks

5.3.1 The Applicability of the Proposed Protocol to CRNs

As a preliminary study for CRNs, a distributed routing protocol in multi-channel multi-hop wireless ad hoc network is proposed in Paper F. As stated earlier, the scenario in multi-channel multi-hop ad hoc networks can be considered as a special case in a CRN where the PU activities are relatively static, like in TV broadcast channels. In this case, multiple channels are in a sense dedicated to SUs and the proposed protocol can be enhanced to fit this scenario with minor revision, for instance, by adding channel sensing schemes for PUs.

In our design, we have left room for further extensions to CRNs with opportunistic channels. One consideration is to introduce a common control channel in this protocol as many CRN routing protocols do [98, 109, 112, 113, 118, 119]. In CRNs, signaling is even more important but also more difficult than in ad hoc networks because of opportunistic channel availability. Since the available channels may be quite different from one SU to another in both the time and space domains, it is necessary to have a common control channel to connect different nodes together for information exchange. This common control channel must be used for signaling message transmissions and should always be available [4]. If a dedicated control channel does not exist, however, the mechanisms presented in the previous section and many other mechanisms [86]-[89] can be applied to select a control channel.

Another consideration for potential extension to CRNs is that only partial network information is required by the routing protocol, instead of the network-wide information. Although global information is obtainable in many ad hoc network scenarios, in CRNs, however, always requiring global information on real-time traffic flows and available channels is quite costly and even impossible for large-scale networks with dynamic channels. Therefore, designing a routing scheme based on local information is more pragmatic from the perspective of information sharing. More importantly, even if the network-wide information is gathered, the joint path and channel allocation problem is in general NP-hard in both ad hoc networks [57] and CRNs [50]. Therefore, considering practicality, we do not expect to design a routing protocol which targets at achieving global optimization with signaling process and channel allocation implemented based on network-wide information. In our design, we employ, instead, separate procedures for path selection and channel allocation, and then integrate them together. The aim is to design a plug-and-play distributed routing protocol together with channel allocation without global information acquisition and sharing. The end-to-end route is established in an on-demand fashion while channel allocation is made along the path based on collected local information. In what follows, the proposed routing protocol is summarized.

5.3.2 Description of the Proposed Routing Protocol

The distributed routing protocol with channel assignment in multi-channel multi-hop wireless ad hoc networks is proposed originally in Paper F and it works as follows.

5.3.2.1 System Configuration and Channel State Estimation

In the proposed protocol, each node is equipped with three half-duplex interfaces. One interface is always turned onto a common control channel which is responsible for control and broadcast message exchange, and the other two perform as transmitter and receiver respectively, operating on different data channels for data transmission. To allow an interface access multiple channels, the interface needs to switch among different channels at a cost of switching delay. More specifically, if a node will transmit a packet to a particular neighbor, the interface which is responsible for transmission will switch to the channel on which the neighbor's receiver is tuned and then communicate.

In order to acquire channel information among the neighborhood, the receiving interface of a particular node will jump among various channels according to a predefined hopping sequence when there is no traffic load at the node. The hopping sequence of a particular node is broadcast on the common control channel to its one-hop neighbors using a BEACON message with time to live (TTL) as one. In this way, the neighbors can obtain information about its hopping sequence. At the same time, HELLO messages with TTL =1 will be broadcast by the transmitting interface on different channels periodically. These HELLO messages are utilized as probing messages for traffic load and channel condition estimation purpose between a communication pair. When a neighbor node receives the HELLO messages, a channel condition parameter between this communication pair, namely average transmission data rate (ATR) can be estimated and this value will be utilized in the channel allocation process later on in this protocol. The detailed channel probing scheme and ATR calculation can be found in Subsection III-A of Paper F.

5.3.2.2 Route Discovery and Establishment Process

The proposed routing protocol follows the on-demand principle and it operates somewhat similar to the ad hoc on demand distance vector (AODV) routing protocol [121]. Our routing protocol is however different from AODV in two aspects: one is path selection, i.e., route discovery, and the other is channel allocation, which is not included in legacy AODV. Briefly, the route discovery process works as follows. When a routing request is triggered by the upper layer, a path from source to destination needs to be discovered by sending a route request (RREQ) on the common control channel. Nodes with lighter traffic load is preferred in the path discovery process and a back-off scheme of RREQ forwarding is designed for this purpose. The back-off timer is proportional to a combined value integrating the queue length and the number of destinations in the queue at the transmitter. More specifically, if a node that has no packets buffered in the transmission queue receives a RREQ, it will forward it immediately. Otherwise, it will wait for a time period which is proportional to the product of the number of destinations in the queue and the total queue length at the node before the RREQ is forwarded.

For RREQ forwarding, at each hop, the working channel of the receiver in a node should be attached in this RREQ if its receiver has already been fixed on a channel for ongoing flows. Otherwise, the ATR values from the upstream node to the downstream node at each channel should be attached. When the RREQ arrives at the destination or an intermediate node which has fresh enough route information to the destination, the destination node or the intermediate node will allocate channel according to a channel allocation algorithm all the way back to the source. According to our protocol, the RREQ which arrives first will be processed and the later RREQs, even if exist, will be discarded. The results about the allocated channel for each hop are attached in a routing reply (RREP). When a node receives a RREP, it will establish a routing entry for this destination and the receiver of this node will tune onto the allocated channels for the lifetime of the flow instead of hopping among multiple channels. The detailed route discovery and establish process can be found in Subsection III-B and III-D of Paper F.

5.3.2.3 Channel Allocation along the Selected Path

Given the existence of parallel flows in a network, we try to reduce both the inter-path and the intra-path interference in the network for a specific path of a flow to achieve better performance. The intra-path interference means the co-channel interference caused from the same traffic flow which is transmitted on another hop along the path or from other flows which have a common path over several hops. The inter-path interference, on the other hand, is the co-channel interference caused by other traffic flows being transmitted in the neighborhood, excluding intra-path interference. Although the path has already been selected, it is still difficult to select a proper channel among a given number of channels for each hop. Indeed, channel allocation in such case can be related to a graph coloring problem which is NP-hard. Therefore, with limited information carried with RREQ along a single path, we design a heuristic algorithm targeting at a sub-optimal channel allocation.

The heuristic algorithm follows two principles. The first one is to separate the to-be-allocated channels along the path as much as possible in order to reduce the intra-path interference. The other one is to reduce the inter-path interference by selecting the channels with higher ATR values, since the higher the ATR value, the better the channel condition. The algorithm works in a recursive manner, as shown in Alg. 1 of Paper F. In each round of iteration, it will firstly check whether there exists a channel which is not utilized by its one hop neighbor(s) along the path. If there is no idle channel left, we select the already allocated channel with the maximum ATR value. If there is only one idle channel, just use that channel. Otherwise, it is meant that at least two idle channel are not utilized by its one hop neighbors and we have more freedom to select. Then, we start to eliminate the channels with small ATR values for each node. Thirdly, the nodes which have the minimum number of channels will get channels assigned first because they have less freedom for channel selection.

More detailed descriptions about the aforementioned principles and other aspects of this design, like route maintenance, are given in Paper F. For illustration purpose, an example on how route discovery and channel allocation are performed in this protocol is depicted in Fig. 5.2. In this figure, the dashed lines between two nodes mean that the connected nodes are neighboring to each other. For example, when Node 0 has packets to send to Node 8 and there is no route available at Node 0, it will broadcast a RREQ message first. The RREQ will be forwarded by the intermediate nodes according to the aforementioned RREQ forwarding method. When the RREQ message arrives at the destination, i.e., Node 8, this node will calculate the channel allocation based on the information carried by the RREQ message.

As mentioned earlier, only the first-arrived RREQ message will be utilized and the RREQ messages which arrived later on will be simply discarded by Node 8. The calculated channel allocation information will be inserted into the RREP message and then the RREP message will be sent back along the reverse path that the RREQ was forwarded, i.e., through Nodes 6, 5, 3, 0[1] by unicasting on the control channel. When an intermediate node receives the RREQ, it will tune its receiver onto the allocated channel. For instance, Node 5 will tune its receiver onto channel 3. When the RREP is received by Node 0, the end-to-end communication is established, as the solid line with arrow illustrated in Fig. 5.2.

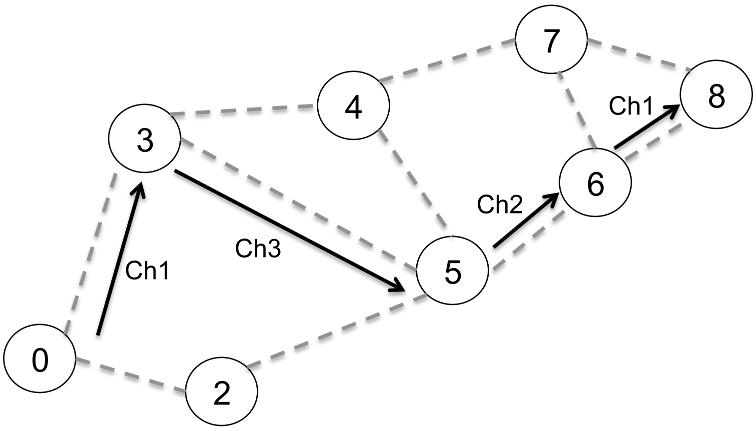

Figure 5.2: Example for the routing protocol.

To evaluate the efficiency of the proposed protocol, we implemented it in NS2 and performed extensive simulations. The simulation results illustrate that the proposed routing protocol can efficiently improve the system performance in terms of throughput and end-to-end delay by taking the advantage of multiple channels.

5.4 Chapter Summary

Communications over multiple hops are important in wireless networks. It can make the network cover a larger distance, or similarly, reduce transmission power to reach the same distance by adding multiple relays in between. This chapter begins with a summary of existing work in multi-hop multi-channel wireless ad hoc networks and CRNs. Triggered by those earlier studies, two MAC mechanisms targeting at common channel selection and network connectivity maintenance are proposed for CRNs with a single transceiver on each node. Then, a routing protocol

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[1] In this example, we assume the RREQ that traverses Nodes 3, 5 and 6 is the first-arrived RREQ at Node 8.

integrated with channel allocation for nodes with multiple interfaces is designed for multi-channel multi-hop ad hoc networks. Instead of using mathematical modeling for performance evaluation as in the approaches carried out in the previous chapters, the schemes designed in this chapter are implemented and evaluated through NS2 simulations.

Chapter 6

Summary of Contributions and Further Outlook

6.1 Main Contributions

This dissertation explores various research facets in MAC and routing design aspects of CRNs, and it covers a range of topics for medium access in single hop and multi-hop CRNs. In the single hop scenarios, a MAC protocol without channel assembling and various strategies with channel assembling are designed and modeled, and optimal power allocation schemes are also investigated. In the multi-hop case, common channel selection schemes are developed and a routing protocol integrated with channel allocation is proposed. In the following, the main contributions of this dissertation are summarized.

- A dynamic parallel rendezvous MAC protocol is proposed for single-radio multi-channel CRNs when only one channel can be utilized for an SU service. This novel protocol requires only one transceiver and can utilize channel opportunities more efficiently in networks with heterogeneous channels.

- When channel assembling is supported by SUs, two representative channel assembling strategies are proposed and examined thoroughly through CTMC models considering both elastic and real-time traffic types when spectrum adaptation is enabled and parallel SU services are allowed. The results from mathematical modeling are validated by extensive simulations and the preciseness as well as the robustness of the mathematical models are checked by simulations using diverse traffic distributions. The advantages of employing channel assembling are achieved by selecting a proper strategy with appropriate parameter configuration.

- When channel assembling is enabled and parallel SU services are allowed, the capacity upper bound of the secondary network in the quasistationary regime is derived based on a proposed dynamic strategy. The upper bound is documented in a closed-form expression based on mathematical modeling, and this upper bound is achievable if a dynamic strategy is utilized and configured with appropriate parameters.
- In the case where channel assembling techniques are adopted but there is only one winning SU that can utilize multiple idle channels after a round of SU competition, various algorithms for optimized power allocation are proposed based on our formulated problems. Numerical results demonstrate that the algorithms can provide solutions to these problems efficiently.
- In multi-hop CRNs, it is important to have a common channel in order to exchange control messages and maintain network connectivity. Two MAC schemes are proposed for common channel selection in multi-hop CRNs. These schemes apply to a CRN with a single radio, and can also be adopted as common control channel selection schemes in multi-interface CRNs.
- In order to explore and utilize multiple channels more efficiently in ad hoc networks, a routing protocol which is integrated with channel allocation for multi-channel multi-hop and multi-interface wireless ad hoc networks is proposed. Instead of targeting at a global optimal channel allocation and path selection solution which is costly in terms of both signaling and computation, our protocol is pragmatic and expedient since it has a workable signaling process and a channel allocation algorithm with low complexity. Furthermore, this routing protocol can also be extended to CRNs.

6.2 Further Outlook

This dissertation makes an effort into the issues related to the design, modeling, optimization, and performance analyses of the medium access mechanisms and routing schemes in CRNs, by considering different layer two and layer three technologies and application scenarios. Various approaches have been proposed and their performance is analyzed. However, the research in CRNs is a vast area and therefore there are still many open questions that remain to be answered. Some of them are summarized in the following.

- In the dynamic parallel rendezvous protocol, the revised channel hopping sequence in the our proposed scheme does give higher overall system capacity as illustrated in Paper A. However, the algorithm on channel hopping sequence adjustment is still a heuristic method, and an optimal way of adjusting the sequence needs to be further investigated.

- Similar to many other studies within the field of teletraffic theory, in our mathematical modeling of channel assembling strategies, we assume that SU services are able to enjoy stable services with the help of the underlying physical layer techniques. However, more realistic assumptions regarding the system model, for example, spectrum sensing inaccuracy and time-varying fading channel, could make the results closer to reality. More realistic and sophisticated models should be designed in order to evaluate system performance before those detailed physical layer effects can be addressed sufficiently.
- Although we manage to provide a simple and closed-form capacity expression of CRNs with channel assembling in the quasistationary regime, more efforts are required to extend our studies on this topic to a more general case, i.e., when PU activities become comparatively dynamic.
- The benefit from channel assembling when parallel services are supported relies on the principle of adaptability. However, to support this adaptability, more signaling and scheduling procedures are required, making the strategies more complicated. Furthermore, various channel assembling strategies may have different levels of complexity. Therefore, the evaluation on the complexity of various channel assembling strategies becomes an interesting topic.
- Regarding to the optimized power allocation schemes, we have considered the case that a single winner can utilize the available channels. The situation when multiple SU services can utilize the idle channels deserves a further exploration, since different services may have diverse spatial diversity and channel availability, making the problems even more complicated.
- The number of nodes in our simulations is generally small. Therefore, simulations for large-scale networks are encouraged in order to evaluate the performance and scalabilities of the proposed mechanisms.
- Besides mathematical modeling and computer simulations, prototype implementations are anticipated in order to further evaluate the proposed protocols.

REFERENCES

[1] ITU, “ITU training on spectrum management principle and spectrum management system for developing countries,” available online at: http://www.itu.int/ITU-D/asp/CMS/Events/2010/SMS4DC/, accessed on 20 May 2012.

[2] M. H. Islam, C. L. Koh, S. W. Oh, X. Qing, Y. Y. Lai, C. Wang, Y. C. Liang, B. E. Toh, F. Chin, G. L. Tan, and W. Toh, “Spectrum survey in Singapore: Occupancy measurements and analyses,” in *Proc. IEEE CROWNCOM*, Singapore, Jul. 2008.

[3] S. Haykin, “Cognitive radio: Brain-empowered wireless communications,” *IEEE J. Select. Areas Commun.*, vol. 23, no. 2, pp. 201–220, Feb. 2005.

[4] I. F. Akyildiz, W. Y. Lee, and K. Chowdhury, “CRAHNs: Cognitive radio ad hoc networks,” *Ad Hoc Networks*, vol. 7, no. 5, pp. 810–836, Elservier, Jul. 2009.

[5] Y. C. Liang, K. C. Chen, Y. (G.) Li, and P. Mähönen, “Cognitive radio networking and communications: An overview,” *IEEE Trans. Veh. Technol.*, vol. 60, no. 7, pp. 3386–3407, Sept. 2011.

[6] J. Mitra III and G. Q. Maguire, “Cognitive radio: Making software radios more personal,” *IEEE Personal Communications*, vol. 6, no. 4, pp. 13–18, Aug. 1999.

[7] M. Shaat and F. Bader, “Computationally efficient power allocation algorithm in multicarrier based cognitive radio networks: OFDM and FBMC systems,” *EURASIP Journal on Advances in Signal Processing*, doi:10.1155/2010/528378, Jan. 2010.

[8] R. Zhang, Y. C. Liang, and S. Cui, “Dynamic resource allocation in cognitive radio networks: A convex optimization perspective,” *IEEE Signal Processing Magazine*, vol. 27, no. 3, pp. 102–114, May 2010.

[9] FCC, “Notice of inquiry and notice of proposed rulemaking: In the matter of establishment of an interference temperature metric to quantify and manage interference and to expand available unlicensed operation in certain fixed, mobile and satellite frequency bands,” *ET Docket No. 03-237, FCC-03-289*, Nov. 2003.

[10] FCC, "Order: In the matter of establishment of an interference temperature metric to quantify and manage interference and to expand available unlicensed operation in certain fixed, mobile and satellite frequency bands," *ET Docket No. 03-237, FCC 07-78*, May 2007.

[11] T. Yucek and H. Arslan, "A survey of spectrum sensing algorithms for cognitive radio applications," *IEEE Commun. Surveys Tuts.*, vol. 11, no. 1, pp. 116–130, First Quarter 2009.

[12] Y. Zeng, Y. C. Liang, A. T. Hoang, and R. Zhang, "A review on spectrum sensing techniques for cognitive radio: Challenges and solutions," *EURASIP Journal on Advances in Signal Processing*, doi:10.1155/2010/381465, Jan. 2010.

[13] H. S. Chen, W. Gao, and D. G. Dautn, "Spectrum sensing using cyclostationary properties and application to IEEE 802.22 WRAN," in *Proc. IEEE GLOBECOM*, Washington DC, USA, Nov. 2007.

[14] Y. Zeng and Y. C. Liang, "Spectrum sensing algorithms for cognitive radio based on statistical covariance," *IEEE Trans. Veh. Technol.*, vol. 58, no. 4, pp. 1804–1815, May 2009.

[15] ——, "Eigenvalue-based spectrum sensing algorithms for cognitive radio," *IEEE Trans. Commun.*, vol. 57, no. 6, pp. 1784–1793, Jun. 2009.

[16] R. Zhang, T. J. Lim, Y. C. Liang, and Y. Zeng, "Multiantenna-based spectrum sensing for cognitive radios: A GLRT approach," *IEEE Trans. Commun.*, vol. 58, no. 1, pp. 84–88, Jan. 2010.

[17] Y. Zeng, Y. C. Liang, and R. Zhang, "Blindly combined energy detection for spectrum sensing in cognitive radio," *IEEE Signal Process. Lett.*, vol. 15, pp. 649–652, Oct. 2008.

[18] M. Wellens, J. Riihijarvi, M. Gordziel, and P. Mähönen, "Evaluation of cooperative spectrum sensing based on large-scale measurements," in *Proc. IEEE DySPAN*, Glasgow UK, Oct. 2008.

[19] A. K. Kattepur, A. T. Hoang, Y. C. Liang, and M. J. Er, "Data and decision fusion for distributed spectrum sensing in cognitive radio networks," in *Proc. IEEE ICICS*, Singapore, Oct. 2007.

[20] E. Peh, Y. C. Liang, Y. L. Guan, and Y. Zeng, "Optimization of cooperative sensing in cognitive radio networks: A sensing-throughput tradeoff view," *IEEE Trans. Veh. Technol.*, vol. 58, no. 9, pp. 5294–5299, Nov. 2009.

[21] G. Ganesan and Y. (G.) Li, "Cooperative spectrum sensing in cognitive radio—Part I: Two user networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 6, pp. 2204–2213, Jun. 2007.

[22] ——, "Cooperative spectrum sensing in cognitive radio—Part II: Multiuser networks," *IEEE Trans. Wireless Commun.*, vol. 6, no. 6, pp. 2214–2222, Jun. 2007.

[23] J. Ma, G. D. Zhao, and Y. (G.) Li, "Soft combination and detection for cooperative spectrum sensing in cognitive radio networks," *IEEE Trans. Wireless Commun.*, vol. 7, no. 11, pp. 4502–4507, Nov. 2008.

[24] Z. Quan, S. Cui, and A. H. Sayed, "Optimal linear cooperation for spectrum sensing in cognitive radio networks," *IEEE J. Sel. Topics Signal Process.*, vol. 2, no. 1, pp. 28–40, Feb. 2008.

[25] W. Zhang, R. K. Mallik, and K. B. Letaief, "Cooperative spectrum sensing optimization in cognitive radio networks," in *Proc. IEEE ICC*, Beijing, China, May 2008.

[26] X. Zhou, J. Ma, G. Y. Li, Y. H. Kwon, and A. C. K. Soong, "Probability based combination for cooperative spectrum sensing in cognitive radio networks," in *Proc. IEEE ICC*, Dresden, Germany, May 2009.

[27] C. Cormio and K. R. Chowdhury, "A survey on MAC protocols for cognitive radio networks," *Ad Hoc Networks*, vol. 7, no. 7, pp. 1315–1329, Elservier, Sept. 2009.

[28] IEEE 802.22 WG, "IEEE standard for wireless regional area networks—Part 22: Cognitive wireless RAN medium access control (MAC) and physical layer (PHY) specifications: Policies and procedures for operation in the TV bands," IEEE Std., Jul. 2011.

[29] C. Zou and C. Chigan, "A game-theoretic DSA-driven MAC framework for cognitive radio networks," in *Proc. IEEE ICC*, Dresden, Germany, May 2009.

[30] L. Long and E. Hossain, “OSA-MAC: A MAC protocol for opportunistic spectrum access in cognitive radio networks,” in *Proc. IEEE WCNC*, Las Vegas, NV, USA, Mar. 2008.

[31] C. Cordeiro and K. Challapali, “C-MAC: A cognitive MAC protocol for multichannel wireless networks,” in *Proc. IEEE DySPAN*, Baltimore, MD, USA, Nov. 2005.

[32] Y. Yuan, P. Bahl, R. Chandra, P. A. Chou, J. I. Ferrell, T. Moscibroda, S. Narlanka, and Y. Wu, “KNOWS: Cognitive radio networks over white spaces,” in *Proc. IEEE DySPAN*, Dublin, Ireland, Apr. 2007.

[33] J. Jia, Q. Zhang, and X. Shen, “HC-MAC: A hardware-constrained cognitive MAC for efficient spectrum management,” *IEEE J. Select. Areas Commun.*, vol. 26, no. 1, pp. 106–117, Jan. 2008.

[34] A. C. Hsu, D. S. L. Wei, and C. -C. J. Kuo, “A cognitive MAC protocol using statistical channel allocation for wireless ad-hoc networks,” in *Proc. IEEE WCNC*, Hong Kong, China, Mar. 2007.

[35] H. A. B. Salameh, M. M. Krunz, and O. Younis, “MAC protocol for opportunistic cognitive radio networks with soft guarantees,” *IEEE Trans. Mobile Comput.*, vol. 8, no. 10, pp. 1339–1352, Oct. 2009.

[36] P. N. Anggraeni, N. H. Mahmood, J. Berthod, N. Chaussonniere, L. My, and H. Yomo, “Dynamic channel selection for cognitive radios with heterogeneous primary bands,” *Wireless Pers. Commun.*, vol. 45, no. 3, pp. 369–384, Springer, May 2008.

[37] S. Huang, X. Liu, and Z. Ding, “Optimal transmission strategies for dynamic spectrum access in cognitive radio networks,” *IEEE Trans. Mobile Comput.*, vol. 8, no. 12, pp. 1636–1684, Nov. 2009.

[38] Y. Song, Y. Fang, and Y. Zhang, “Stochastic channel selection in cognitive radio networks,” in *Proc. IEEE GLOBECOM*, Washington DC, USA, Nov. 2007.

[39] H. Su and X. Zhang, “Channel-hopping based single transceiver MAC for cognitive radio networks,” in *Proc. IEEE CISS*, Princeton, NJ, USA, Mar. 2008.

[40] ——, “The cognitive radio based multi-channel MAC protocols for wireless ad hoc networks,” in *Proc. IEEE GLOBECOM*, Washington DC, USA, Nov. 2007.

[41] ——, “Cross-layer based opportunistic MAC protocols for QoS provisionings over cognitive radio mobile wireless networks,” *IEEE J. Select. Areas Commun.*, vol. 26, no. 1, pp. 118–129, Jan. 2008.

[42] Q. Zhao, L. Tong, A. Swami and Y. X. Chen,“Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework,” *IEEE JSAC*, vol. 25, no. 3, pp. 589 - 600, Apr. 2007.

[43] J. Mo, H. S. W. So, and J. Walrand, “Comparison of multichannel MAC protocols,” *IEEE Trans. Mobile Comput.*, vol. 7, no. 1, pp. 50–65, Jan. 2008.

[44] P. K. Tang and Y. H. Chew, “On the modeling and performance of three opportunistic spectrum access schemes,” *IEEE Trans. Veh. Technol.*, vol. 59, no. 8, pp. 4070–4078, Oct. 2010.

[45] X. R. Zhu, L. F. Shen, and T. S. P. Yum, “Analysis of cognitive radio spectrum access with optimal channel reservation,” *IEEE Commun. Lett.*, vol. 11, no. 4, pp. 304–306, Apr. 2007.

[46] J. Martinez-Bauset, V. Pla, and D. Pacheco-Paramo, “Comments on ‘analysis of cognitive radio spectrum access with optimal channel reservation’,” *IEEE Commun. Lett.*, vol. 13, no. 10, pp. 739, Oct. 2009.

[47] E. W. M. Wong and C. H. Foh, “Analysis of cognitive radio spectrum access with finite user population,” *IEEE Commun. Lett.*, vol. 13, no. 5, pp. 294–296, May 2009.

[48] L. Jiao, V. Pla, and F. Y. Li, “Analysis on channel bonding/aggregation for multi-channel cognitive radio network,” in *Proc. European Wireless*, Lucca, Italy, Apr. 2010.

[49] J. Lee and J. So, “Analysis of cognitive radio networks with channel aggregation,” in *Proc. IEEE WCNC*, Sydney, Australia, Apr. 2010.

[50] M. Cesana, F. Cuomo, and E. Ekici, “Routing in cognitive radio networks: Challenges and solutions,” *Ad Hoc Networks*, vol. 9, no. 3, pp. 228–248, Elservier, Jul. 2010.

[51] A. Raniwala, K. Gopalan, and T. C. Chiueh, “Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks,” *ACM Mobile Computing and Communications Review*, vol. 8, no. 2, pp. 50–65, 2004.

[52] A. K. Das, R. Vijayakumar, and S. Roy, “Static channel assignment in multi-radio multi-channel 802.11 wireless mesh networks: Issues, metrics and algorithms,” in *Proc. IEEE GLOBECOM*, San Francisco, CA, USA, Nov. 2006.

[53] A. H. Mohsenian-Rad and V. W. S. Wong, “Joint logical topology design, interface assignment, channel allocation, and routing for multi-channel wireless mesh networks,” *IEEE Trans. Wireless Commun.*, vol. 6, no. 12, pp. 4432–4440, Dec. 2007.

[54] ——, “Partially overlapped channel assignment for multi-channel wireless mesh networks,” in *Proc. IEEE ICC*, Glasgow, UK, Jun. 2007.

[55] A. Raniwala and T. Chiueh, “Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network,” in *Proc. IEEE INFOCOM*, Miami, FL, USA, Mar. 2005.

[56] H. S. Chiu, B. Wu, K. L. Yeung, and K. S. Lui, “Widest spanning tree for multi-channel multi-interface wireless mesh networks,” in *Proc. IEEE WCNC*, Las Vegas, NV, USA, Mar. 2008.

[57] M. Alicherry, R. Bhatia, and L. Li, “Joint channel assignment and routing for throughput optimization in multiradio wireless mesh networks,” *IEEE J. Select. Areas Commun.*, vol. 24, no. 11, pp. 1960–1971, Nov. 2006.

[58] The network simulator 2 (NS2), http://www.isi.edu/nsnam/ns/.

[59] V. Bahl, R. Chandra, and J. Dunagan, “SSCH: Slotted seeded channel hopping for capacity improvement in ad hoc networks,” in *Proc. ACM MOBICOM*, Philadelphia, PA, USA, Sept. 2004.

[60] N. Jain, S. R. Das, and A. Nasipuri, “A multichannel CSMA MAC protocol with receiver-based channel selection for multihop wireless networks,” in *Proc. IEEE ICCCN*, Scottsdale, AZ, USA, Oct. 2001.

[61] S. L. Wu, Y. Lin, Y. C. Tseng, and J. P. Sheu, “A new multi-channel MAC protocol with on-demand channel assignment for mobile ad hoc networks,”

in *Proc. Int'l Symp. Parallel Architecture, Algorithms and Networks*, Dallas/Richardson, TX, USA, Dec. 2000.

[62] A. Tzamaloukas and J. J. Garcia-Luna-Aceves, "Channel-hopping multiple access," in *Proc. IEEE ICC*, New Orleans, LA, USA, Jun. 2000.

[63] ——, "Channel-hopping multiple access with packet trains for ad hoc networks," in *Proc. IEEE Device Multimedia Communications*, Tokyo, Japan, Oct. 2000.

[64] J. So and N. H. Vaidya, "A routing protocol for utilizing multiple channels in multi-hop wireless networks with a single transceiver," *Technical Report*, University of Illinois at Urbana-Champaign, Oct. 2004, available online at: http://www.crhc.illinois.edu/wireless/papers/multichannel_routing.pdf, access on 25 May 2012.

[65] J. Chen, S. Sheu, and C. Yang, "A new multichannel access protocol for IEEE 802.11 ad hoc wireless LANs," in *Proc. IEEE PIMRC*, Beijing, China, Oct. 2003.

[66] H. S. W. So, J. Walrand, and J. Mo, "McMAC: A parallel rendezvous multi-channel MAC protocol," in *Proc. IEEE WCNC*, Hong Kong, China, Mar. 2007.

[67] R. Khalona and K. Stanwood, "Channel aggregation summary," *IEEE P802.22 WG*, available online at: https://mentor.ieee.org/802.22/dcn/06/22-06-0204-00-0000-channel-aggregation-summary.ppt, Oct. 2006, accessed on 20 May 2012.

[68] C. Cordeiro and M. Ghosh, "Channel bonding vs. channel aggregation: Facts and faction," *IEEE P802.22 WG*, available online at: https://mentor.ieee.org/802.22/dcn/06/22-06-0108-00-0000-bonding-vs-aggregation.ppt, Jul. 2006, accessed on 20 May 2012

[69] L. Cao, L. Yang, and H. Zheng, "The impact of frequency-agility on dynamic spectrum sharing," in *Proc. IEEE DySPAN*, Singapore, Apr. 2010.

[70] S. Parkvall, A. Furuskär, and E. Dahlman, "Evolution of LTE toward IMT-Advanced," *IEEE Communications Magazine*, vol. 49, no. 2, pp. 84–91, Feb. 2011.

[71] L. Jiao, F. Y. Li, and V. Pla, "Greedy versus dynamic channel aggregation strategy in CRNs: Markov models and performance evaluation," *LNCS*, vol. 6827, pp. 22–31, Springer, Aug. 2011.

[72] ——, "Dynamic channel aggregation strategies in cognitive radio networks with spectrum adaptation," in *Proc. IEEE GLOBECOM*, Houston, TX, USA, Dec. 2011.

[73] X. Ge, K. Huang, C. X. Wang, X. Hong, and X. Yang, "Capacity analysis of a multi-cell multi-antenna cooperative cellular network with co-channel interference," *IEEE Trans. Wireless Commun.*, vol. 10, no. 10, pp. 3298–3309, Oct. 2011.

[74] D. Willkomm, S. Machiraju, J. Bolot, and A. Wolisz, "Primary users in cellular networks: A large-scale measurement study," in *Proc. IEEE DySPAN*, Glasgow, UK, Oct. 2008.

[75] P. Barford and M. Crovella, "Generating representative Web workloads for network and server performance evaluation," in *Proc. ACM SIGMETRICS*, Madison, WI, USA, Jul. 1998.

[76] D. Willkomm, S. Machiraju, J. Bolot, and A. Wolisz, "Primary users behavior in cellular networks and implications for dynamic spectrum access," *IEEE Communications Magazine*, vol. 47, no. 3, pp. 88–95, Mar. 2009.

[77] W. Yu, W. Rhee, S. Boyd, and J. Cioff, "Iterative water-filling for Gaussian vector multiple access channels," *IEEE Trans. on Inf. Theo.*, vol. 50, no. 1, pp. 145–151, Jan. 2004.

[78] T. Shu, S. Cui, and M. Krunz, "Medium access control for multi-channel parallel transmission in cognitive radio networks," in *Proc. IEEE GLOBECOM*, San Francisco, CA, USA, Nov. 2006.

[79] E. Del Re, F. Argenti, L. S. Ronga, T. Bianchi, and R. Suffritti, "Power allocation strategy for cognitive radio terminals," in *Proc. CogART*, Aalborg, Denmark, Feb. 2008.

[80] M. Haddad, A. M. Hayar, and M. Debbah, "Optimal power allocation for cognitive radio based on a virtual noise threshold," in *Proc. ACM CWNETS*, Vancouver, Canada, Aug. 2007.

[81] X. Kang, R. Zhang, Y. C. Liang, and H. K. Garg, "Optimal power allocation strategies for fading cognitive radio channels with primary user outage constraint," *IEEE J. Select. Areas Commun.*, vol. 29, no. 2, pp. 374–383, Feb. 2011.

[82] R. Urgaonkar and M. J. Neely, "Opportunistic scheduling with reliability guarantees in cognitive radio networks," *IEEE Trans. Mobile Computing*, vol. 8, no. 6, pp. 766–777, Jun. 2009.

[83] Z. Hasan, E. Hossain, C. Despins, and V. K. Bhargava, "Power allocation for cognitive radios based on primary user activity in an OFDM system," in *Proc. IEEE GLOBECOM*, New Orleans, LA, USA, Nov. 2008.

[84] A. Motamedi and A. Bahai, "MAC protocol design for spectrum-agile wireless networks: Stochastic control approach," in *Proc. IEEE DySPAN*, Dublin, Ireland, Apr. 2007.

[85] S. Dasgupta, C. H. Papadimitriou, and U. V. Vazirani, *Algorithms*, Chapter 6, available online at: http://www.cs.berkeley.edu/ vazirani/algorithms.html, accessed on 20 May 2012.

[86] J. Zhao, H. Zheng, and G. Yang, "Distributed coordination in dynamic spectrum allocation networks," in *Proc. IEEE DySPAN*, Baltimore, MD, USA, Nov. 2005.

[87] T. Chen, H. Zhang, G. Maggio, and I. Chlamtac, "Topology management in CogMesh: A cluster-based cognitive radio mesh network," in *Proc. IEEE ICC*, Glasgow, UK, Jul. 2007.

[88] T. Chen, H. Zhang, M. Katz, and Z. Zhou, "Swarm intelligence based dynamic control channel assignment in CogMesh," in *Proc. IEEE ICC*, Beijing, China, Jun. 2008.

[89] S. Krishnamurthy, M. Thoppian, S. Venkatesan, and R. Prakash, "Control channel based MAC-layer configuration, routing and situation awareness for cognitive radio networks," in *Proc. IEEE MILCOM*, Atlantic City, NJ, USA, Oct. 2005.

[90] C. A. Jackson and H. B. Russell, "Channel-access and routing protocols to utilize multiple heterogeneous channels for ad hoc networks," in *Proc. IEEE MILCOM*, San Jose, CA, USA, Oct. 2010.

[91] A. Zubow, M. Kurth, and J. Redlich, "Multi-channel opportunistic routing in multi-hop wireless networks," in *Technical Report*, Humboldt University Berlin, 2006, available online at: http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.87.8202, accessed on 20 May 2012.

[92] J. So and N. Vaidya, "Multi-channel MAC for ad hoc networks: Handling multi-channel hidden terminals using a single transceiver," in *Proc. ACM MOBIHOC*, Tokyo, Japan, May 2004.

[93] K. Jain, J. Padhye, V. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," in *Proc. ACM MOBICOM*, San Diego, CA, USA, Sept. 2003.

[94] X. Meng, K. Tan, and Q. Zhang, "Joint routing and channel assignment in multi-radio wireless mesh networks," in *Proc. IEEE ICC*, Istanbul, Turkey, Jun. 2006.

[95] H. Wu, F. Yang, K. Tan, J. Chen, Q. Zhang, and Z. Zhang, "Distributed channel assignment and routing in multiradio multichannel multihop wireless networks," *IEEE J. Select. Areas Commun.*, vol. 24, no. 11, pp. 1972–1983, Nov. 2006.

[96] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *Proc. ACM MOBICOM*, Philadelphia, PA, USA, Sept. 2004.

[97] C. Xin, B. Xie, and C. -C. Shen, "A novel layered graph model for topology formation and routing in dynamic spectrum access networks," in *Proc. IEEE DySPAN*, Baltimore, MD, USA, Nov. 2005.

[98] ——, "A path-centric channel assignment framework for cognitive radio wireless networks," *Mobile Networks and Applications*, vol. 13, no. 5, pp. 463–476, Kluwer Academic Publishers, Oct. 2008.

[99] X. Zhou, L. Lin, J. Wang, and X. Zhang, "Cross-layer routing design in cognitive radio networks by colored multigraph model," *Wireless Pers. Commun.*, vol. 49, no. 1, pp. 123–131, Springer, Apr. 2009.

[100] Q. Wang and H. Zheng, "Route and spectrum selection in dynamic spectrum networks," in *Proc. IEEE CCNC*, Las Vegas, NV, USA, Jan. 2006.

[101] Y. Hou, Y. Shi, and H. Sherali, "Optimal spectrum sharing for multi-hop software defined radio networks," in *Proc. IEEE INFOCOM*, Anchorage, AK, USA, May 2007.

[102] ——, "Spectrum sharing for multi-hop networking with cognitive radios," *IEEE J. Select. Areas Commun.*, vol. 26, no. 1, pp. 146–155, Jan. 2008.

[103] M. Ma and D. Tsang, "Joint spectrum sharing and fair routing in cognitive radio networks," in *Proc. IEEE CCNC*, Las Vegas, NV, USA, Jan. 2008.

[104] M. Xie, W. Zhang, and K. K. Wong, "A geometric approach to improve spectrum efficiency for cognitive relay networks," *IEEE Trans. Wireless Commun.*, vol. 9, no. 1, pp. 268–281, Jan. 2010.

[105] H. Ma, L. Zheng, X. Ma, and Y. Luo, "Spectrum aware routing for multi-hop cognitive radio networks with a single transceiver," in *Proc. IEEE CrownCom*, Singapore, May 2008.

[106] G. Cheng, W. Liu, Y. Li, and W. Cheng, "Spectrum aware on-demand routing in cognitive radio networks," in *Proc. IEEE DySPAN*, Dublin, Ireland, Apr. 2007.

[107] G. Cheng, W. Liu, Y. Li, and W. Cheng, "Joint on-demand routing and spectrum assignment in cognitive radio networks," in *Proc. IEEE ICC*, Glasgow, UK, Jun. 2007.

[108] Z. Yang, G. Cheng, W. Liu, W. Yuan, and W. Cheng, "Local coordination based routing and spectrum assignment in multi-hop cognitive radio networks," *Mobile Networks and Applications*, vol. 13, no. 1-2, pp. 67–81, Kluwer Academic Publishers, Apr. 2008.

[109] H.-P. Shiang and M. van der Schaar, "Distributed resource management in multihop cognitive radio networks for delay-sensitive transmission," *IEEE Trans. Veh. Technol.*, vol. 58, no. 2, pp. 941–953, May 2009.

[110] I. Pefkianakis, S. H. Y. Wong, and S. Lu, "SAMER: Spectrum-aware mesh routing in cognitive radio networks," in *Proc. IEEE DySPAN*, Glasgow, UK, Oct. 2008.

[111] L. Ding, T. Melodia, S. Batalama, and M. J. Medley, "ROSA: Distributed joint routing and dynamic spectrum allocation in cognitive radio ad hoc networks," in *Proc. ACM MSWiM*, Tenerife, Canary Islands, Spain, Oct. 2009.

[112] A. Sampath, L. Yang, L. Cao, H. Zheng, and B. Y. Zhao, "High-throughput spectrum aware routing for cognitive-radio-based ad hoc networks," in *Proc. IEEE CROWNCOM*, Singapore, May 2008.

[113] G. M. Zhu, I. Akyildiz, and G. S. Kuo, "STOD-RP: A spectrum-tree based on demand routing protocol for multi-hop cognitive radio networks," in *Proc. IEEE GLOBECOM*, New Orleans, LA, USA, Nov. 2008.

[114] W. Feng, J. Cao, C. Zhang, and C. Liu, "Joint optimization of spectrum handoff scheduling and routing in multi-hop multi-radio cognitive networks," in *Proc. IEEE ICDCS*, Montreal, Quebec, Canada, Jun. 2009.

[115] A. Abbagnale and F. Cuomo, "Gymkhana: A connectivity-based routing scheme for cognitive radio ad hoc networks," in *Proc. IEEE INFOCOM*, Orlando, FL, USA, May 2010.

[116] I. Filippini, E. Ekici, and M. Cesana, "Minimum maintenance cost routing in cognitive radio networks," in *Proc. IEEE MASS*, Macau, China, Oct. 2009.

[117] K. Chowdhury and M. Felice, "Search: A routing protocol for mobile cognitive radio ad-hoc networks," *Computer Communications*, vol. 32, no. 18, pp. 1983–1997, Elservier, Dec. 2009.

[118] H. Khalife, S. Ahuja, N. Malouch, and M. Krunz, "Probabilistic path selection in opportunistic cognitive radio networks," in *Proc. IEEE GLOBECOM*, New Orleans, LA, USA, Dec. 2008.

[119] C. W. Pyo and M. Hasegawa, "Minimum weight routing based on a common link control radio for cognitive wireless ad hoc networks," in *Proc. ACM IWCMC*, Honolulu, HI, USA, Aug. 2007.

[120] Y. Shi and Y. Hou, "A distributed optimization algorithm for multi-hop cognitive radio networks," in *Proc. IEEE INFOCOM*, Phoenix, AZ, USA, May 2008.

[121] C. Perkins, E. Belding-Royer, and S. Das, "Ad hoc on-demand distance vector (AODV) Routing," *IETF RFC 3561*, Jul. 2003.

Part II

Paper A

Title: A Dynamic Parallel-rendezvous MAC Mechanism in Multi-rate Cognitive Radio Networks: Mechanism Design and Performance Evaluation

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A Dynamic Parallel-rendezvous MAC Mechanism in Multi-rate Cognitive Radio Networks: Mechanism Design and Performance Evaluation

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Abstract — **Parallel rendezvous multi-channel MAC mechanisms are regarded as an efficient method for media access control in cognitive radio networks since they do not need a control channel and use only one transceiver. However, existing parallel rendezvous MAC mechanisms assume that all channels have the same maximum capacity and channel availability for secondary users. In this paper, we propose a dynamic parallel rendezvous multi-channel MAC mechanism for synchronized multi-rate cognitive radio networks in which secondary users jump among different channels according to their own distinct hopping sequences and a node can adjust its hopping sequence according to channel conditions, in order to achieve higher system capacity. A Markov chain based model is designed to analyze the system capacity of the proposed mechanism. Numerical results show that the new mechanism can significantly improve system capacity of cognitive radio networks, compared with the traditional channel hopping MAC mechanisms.**

Keywords—Cognitive radio networks, MAC mechanism, Dynamic parallel-rendezvous, Markov chain, Performance evaluation.

I. INTRODUCTION

Electromagnetic radio spectrum is one of the most valuable resources in wireless communications. With rapid increase of the wireless applications and products, unlicensed bands such as Industrial, Scientific and Medical (ISM) and Unlicensed National Information Infrastructure (UNII) have become over-crowded. On the other hand, a large portion of the assigned spectrum is used sporadically and a significant amount of the allocated spectrum remains under-utilized. Cognitive Radio (CR) [1], as a promising solution to efficiently utilize the unused spectrum, has become

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a hot research topic these days. However, the functions of cognitive radio devices become very limited if they do not form a network. Together with existing legacy infrastructure and/or ad hoc networking devices, CRs can form a Cognitive Radio Network (CRN). This new type of network is built based on CR terminals and wireless networking technologies, and can transport packets to facilitate emerging services and applications.

To form a CRN, Media Access Control (MAC) mechanisms are of great importance, especially for multi-channel CRNs. The MAC mechanisms for CRN can be grouped into two categories: centralized or distributed MAC mechanisms. The most eminent approach for centralized CRN MAC is IEEE 802.22 [2]. In this study, we focus on the distributed mechanisms. Existing distributed multi-channel CRN MAC mechanisms can be further categorized into two classes: single- or parallel-rendezvous MAC mechanisms [12].

For single-rendezvous MAC, it has a control channel as the rendezvous channel and Secondary Users (SUs) can exchange control information and negotiate parameter configurations for data transmission on this channel [4] -[11]. Furthermore, data channel combining technology can be used in control channel based mechanisms. With channel combining technology which can bind data channels that are not used by Primary Users (PUs) together, the MAC mechanisms can use the free spectrum more efficiently [7][8][11]. But these mechanisms usually need more complicated hardware which have two radios [7] or one radio and several spectrum sensors [11]. For other single-rendezvous multi-channel mechanisms without using data channel combining technology [5][6][9][10], the control channel, however, can become a bottleneck under operations [3], or they need more transceivers on data channels, e.g., in [9].

Parallel rendezvous MAC mechanisms, on the other hand, do not need a common control channel. The basic idea behind parallel rendezvous mechanisms is that nodes jump among different channels according to their own sequences and the control information is exchanged at different channels when nodes meet. It has been demonstrated that parallel-rendezvous MAC mechanisms, like Multi-channel MAC (McMAC) [12] and Slotted Seeded Channel Hopping (SSCH) [13], generally outperform control channel MAC mechanisms in multi-channel cases [3]. Furthermore, parallel-rendezvous MAC mechanisms do not have a bottleneck like in the single rendezvous case and they are all based on a single transceiver. Parallel-rendezvous MAC mechanisms are originally used in multi-channel ad hoc networks, but have recently been extended to CRN by the authors of [14].

However, existing multi-channel parallel-rendezvous MAC mechanisms in multi-channel ad hoc networks and CRNs do not consider heterogeneous channel conditions. If the channels are unbalanced, for example, when different parameters, like diverse bandwidth and maximum transmission power available for SUs and distinct transmission probabilities of PUs exist in different channels, a method needs to be adopted to adjust the communication according to these parameters. In this paper, we propose a dynamic channel hopping based parallel-rendezvous single transceiver MAC mechanism for synchronized CRNs. The main idea behind this work is to adjust the hopping sequence of SUs according to the transmission datarate and channel availability of the idle channels. For comparison convenience, we refer to this method as Dynamic Parallel-rendezvous MAC protocol (DPR-MAC) while the method proposed in [14] is referred to as Datarate Independent MAC protocol (DRI-MAC).

The rest of this paper is organized as follows. Section II summarizes related work. Section III presents the proposed MAC mechanism. The system capacity of the proposed MAC mechanism is analyzed in Section IV using a Markov chain model. In Section V, numerical results and comparison with DRI-MAC are given. Finally, the paper is concluded in Section VI.

II. RELATED WORK

In this section, we give more detailed descriptions on a few related MAC mechanisms mentioned in Section I, categorized as distributed multi-channel MAC mechanisms: single-rendezvous or parallel-rendezvous.

A. Single-Rendezvous MAC Mechanisms

In single-rendezvous MAC mechanisms, channels are classified as either control channel or data channels.

1) C-MAC:

Cognitive MAC (C-MAC) [10] is a time-slotted CR MAC based on one transceiver. Time slotted here means that it splits a time period into different sub-periods for different usages. In this design, super-frames are defined for each channel which is further divided into a data transfer period, beacon period and quiet period. In different periods, nodes have different functions.

In this MAC, there are three type of channels: Rendezvous Channels (RC), Backup Channels (BCs) and data channels. This mechanism needs a control channel but not a dedicated one. To operate this mechanism, the RC is used as a control channel, and BC is the backup for RC. The mechanism chooses the best channel as the RC based on the traffic information obtained from the beacon. Data transmission may occur over different data channels. As a control channel is used, there exists a bottleneck. The selection and rendezvous pattern of RC in multi-hop cases is still a challenging task in C-MAC.

2) OS-MAC:

Opportunistic Spectrum MAC (OS-MAC) [6] is a single transceiver based CR MAC mechanism. It needs a common control channel and uses SUs' group formation. The SUs exchange control information in the common control channel and communicate on different data channels. Fixed durations are used to form groups of SUs, to determine their channel occupancy status, and to exchange channel traffic load. In this MAC, there is a channel traffic balancing algorithm that can balance the load among different channels. For new data packets, the mechanism can choose a channel with less load and establish communication on it. However, the complexity of this mechanism is relatively high and the group formation introduces certain amount of overhead for the network.

3) KNOWS:

KNOWS [11] is another CR MAC that uses channel combination technology and targets for TV bands. It also needs a dedicated control channel for control information exchange. It demands one transceiver and several spectrum sensors. The transceiver is in charge of control and data packet communications, and the spectrum sensors are responsible for gathering channel information. For data transmission, it combines channels that are not occupied by PUs as one data channel. The advantage of this channel combination is that it can avoid common control channel bottleneck, but the requirement for hardware is much higher, compared with the OS-MAC case.

From the above discussions, we can conclude that the MAC mechanisms that based on single-rendezvous channel (control channel) usually have problems like transmission bottleneck or high demand for hardware complexity.

B. Parallel-Rendezvous MAC Mechanisms

Different from single-rendezvous MAC mechanisms, parallel-rendezvous MAC mechanisms do not need a control channel and nodes establish communication simultaneously in different channels. The main motivation of parallel-rendezvous is to overcome the single control channel bottleneck problem [3].

1) SSCH:

In SSCH [13], nodes jump among channels according to their hopping sequences. The sequences used are uniquely determined by the seed of a pseudo-random generator [3]. Each device picks multiple sequences and follows them in a time-multiplexed manner. For example, when node A has data to B, A waits until it is on the same channel as B. If A frequently wants to send data to B, A adopts one or more of B's sequences, thus increasing the time spend on the same channel. To let this mechanism work, the sender learns the receiver's current sequences via a seed broadcast mechanism.

This MAC is based on multiple sequences and the complexity of the MAC control is relatively high.

2) McMAC:

McMAC is also proposed for multi-channel cases initially and it works properly in the 802.15.4 based equipments [12]. The main idea of McMAC is similar to that of SSCH, but the hopping sequence generating strategy of McMAC is simpler. In McMAC, each node has its own unique sequence and the sequence is generated by a pseudo-random generator. The seed of the sequence is the node's own MAC address. The pseudo-random generator that is used in McMAC is the Park-Miller random number generator: X(t)=16807· X(t-1)mod(2^{31}-1), where $X(t)$ means the current number and $X(t-1)$ means the previous number.

Nodes in the McMAC network switch across the channels following their hopping sequences. The sequence of a node is broadcast and if other nodes want to communicate with a particular node, it should follow to the node's sequence and tune to the same channel to establish communication. Since the communication procedure in McMAC is quite similar to the MAC mechanism discussed in the next paragraph, we will describe it in more details there.

3) DRI-MAC:

DRI-MAC is quite similar to McMAC but the difference is that it has a quiet period in the beginning of each time slot in order to check the presence of PUs.

In DRI-MAC [14], each SU has its own pseudo-random hopping sequence and switches across the channels following the hopping sequence. SUs decide their own hopping sequence based on their unique ID and share the same hopping sequence generating algorithm. For a given SU, the hopping sequence is fixed. Each SU periodically broadcasts beacons with its own hopping sequences over an unused channel. Once a sender receives the hopping pattern information of the receiver, it can follow the receiver's hopping sequence to meet it if the sender has packets to the intended receiver. A quiet period is introduced in the beginning of each slot. During this period, every SU in difference channels keeps silence and listens to the channel to check whether there is a PU. If PUs are not there, the SUs deem it is proper to use the channel.

Fig. A.1 illustrates the principle of this parallel-rendezvous MAC mechanism. As illustrated in the figure, the two SUs, A and B, are on Channel 1 and Channel 4 respectively in Time Slot 1 (TS1) and will jump to Channel 3 and Channel 2 in

TS2. In TS3, A would jump to Channel 2 if it has no packets to send. As A has data to send to B, A follows B's sequence and jumps to Channel 4 in TS3, instead of jumping to Channel 2. They will stay on the same channel till the transmission finished (as in TS3-TS6). During the transmission period, if PU appears (as in TS5), they will wait until the next slot and transmit if then the channel is idle again (as in TS6).

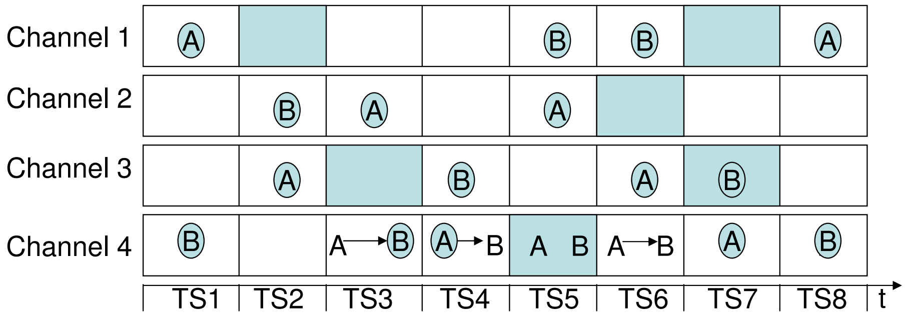

Figure A.1: Illustrations of DRI-MAC. The highlighted slots mean that the time slots are used by PUs. A, B are SUs. TS1-8 mean time slots respectively. A, B with a circle denote their pre-defined hoping pattern.

A common feature of the existing parallel-rendezvous MAC mechanisms is that the sequences used are based on a pseudo-random sequence generator and they are statistically uniform distributed [17], regardless of channel conditions. In the following sections, we will present the DPR-MAC which can adjust the hopping sequence according to the channel parameters considered in order to achieve higher system capacity.

III. DPR-MAC MECHANISM DESCRIPTION

A. Channel Model and System Assumptions

Assume that each SU has only one transceiver. It means that SUs cannot transmit and receive messages at the same time. The transceiver of SU is Software Defined Radio (SDR) based that can dynamically use the channels assigned to PUs when they are not occupied. The same as in [7, 14], we assume also that there are G channels in the considered network and each channel assigned to PUs follows independent ON/OFF random process. The ON period means that the channel is occupied by the PU and the OFF period presents that the channel is vacant. Each licensed channel is time-slotted such that the PUs communicate with each other in a synchronized manner. The SUs, which are also synchronized with the PUs, opportunistically access the licensed spectrum when it is available [7]. The channel state for the ith channel can be found in Fig. A.2.

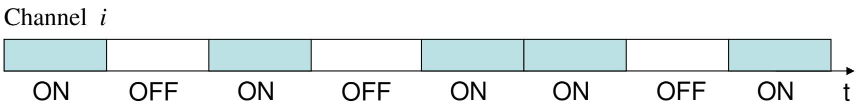

Figure A.2: The ON/OFF channel state for the ith channel.

Let α_i be the probability that the ith channel transits from state ON to state OFF and β_i be the probability that the ith channel transits from state OFF to state ON, where $1 \leq i \leq G$. Then the state can be modeled as a simple two-state Markov chain as shown in Fig. A.3 [7, 14]. Theoretically, the availability of the ith channel for SUs, denoted by γ_i, can be presented as the steady state probability of the corresponding Markov Chain of the OFF state, i.e., the channel is not occupied by the PUs, which can be presented as $\gamma_i = \alpha_i/(\beta_i + \alpha_i)$, $1 \leq i \leq G$.

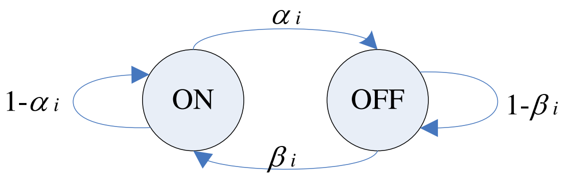

Figure A.3: ON/OFF channel state transferring model.

For the ON/OFF channel model, assume that the transceiver of SU can sense precisely the signal of PUs it receives in a particular channel that it tunes in. It is assumed that the statistic parameters of the PUs, i.e., the ON/OFF percentage in a channel is stable over a long enough time period compared with beacon intervals. The envisaged scenario for this investigation is that SUs are located in a limited geographic area while the coverage and distance scale of PUs are far larger than that of SUs, hence the SUs are covered by the same set of PU systems. This implies that the results of channel sensing by each SU in a particular channel is the same for all SUs. It is further assumed that all SUs are in close enough proximity to be able to communicate with each other using the same modulation scheme within a channel. We do not consider the mobility of SUs in this study.

Before giving the DPR-MAC mechanism description in details, we first discuss the channel parameters considered in DPR-MAC.

B. Channel Parameters Considered in DPR-MAC Design

In conventional multi-channel cases, it is often assumed that the channel conditions are the same, but in CRNs the parameters among channels may be different. We consider two parameters, maximum datarate R_i available for SUs and channel availability γ_i in channel i in our MAC design. In order to protect PUs, the transmission power of SUs should be below a specific value so that the interference generated could be lower than the threshold at the PU receivers[1]. Since the PU equipments and their locations could be different in different channels, the maximum transmission power for SUs in different channels could be different. Besides, the bandwidth that SUs are allowed to utilize may be different from channel to channel. Therefore, each of these channels may have different maximum datarates R_i available for SUs [18]. In addition to R_i, the channel availability, γ_i, may be different in different channels because the usage pattern of these channels by PUs might be different. In real implementation, γ_j in channel j can be estimated by an SU in the following way [15]: $\gamma_j = (i_j(t_o)+1)/(i_j(t_o)+b_j(t_o)+2)$, where $i_j(t_o)$ and $b_j(t_o)$ are the number of time slots that channel j is idle and busy respectively during time period t_o [15].

Considering the above two parameters, we define the channel carrier capability, η_i, as the product of maximum datarate of a channel and its availability for SUs:

$$\eta_i = R_i \times \gamma_i. \tag{1}$$

As defined above, the channel carrier capacity is an indicator which reflects not only the maximum bits per second an SU could transmit but also the percentage of time when this channel can be used by SUs.

C. Dynamic Parallel-Rendezvous MAC

Like other multi-rendezvous MAC mechanism, the proposed MAC mechanism does not need a control channel. The channel sensing and data transmission strategies of DPR-MAC are similar to that of DRI-MAC. The difference is, however, that the hopping pattern is designed according to the channel carrier capability in our case. In what follows, we will first describe the basic channel hopping sequences and then propose the channel carrier capability aware hopping sequence.

1) Basic Hopping Sequence:

We adopt the sequence generation method that is used in McMAC [12] to generate basic sequences. To reduce computational overhead, the length of the sequence should be fixed to a particular value as at least 10 times larger than the number of channels [12].

2) Channel Carrier Capability Aware Hopping Sequence:

SUs use their basic channel hopping sequences to switch across different channels but they may deviate from their basic sequences when the channel carrier ca-

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[1] Even if it is assumed that SUs can sense the signal of PUs' transmission precisely, the transmission power of SUs should be limited because PU receivers could be within SUs' interference range but its corresponding PU transmitters could be out of the SUs' sensing range. In this case, although a channel is sensed as idle, the transmission power of SUs should be kept within a threshold in order to protect the potential PU receivers in that channel.

pability η_i are different among channels. More specifically, a portion of the basic hopping sequence should be adjusted according to η_i, while the rest of the sequence will still remain on the basic hopping sequences. For example, there are two channels that offer different datarates for SUs. The carrier capability of Channel 1, η_1 is higher than that in Channel 2, η_2. Suppose a snapshot of an SU's basic hopping sequence is [1, 2, 2, 1, 2, 1, 1, 2], which means that initially SUs will jump evenly between Channel 1 and Channel 2. According to DPR-MAC, however, as $\eta_1 > \eta_2$, more hops will be preferred to be allocated in Channel 1. The resulted sequence could then look like [1, 2, 1, 1, 2, 1, 1, 1], which leads to higher chance for channel access of Channel 1.

At the same time, the adjustment method must be carefully designed to avoid the phenomenon of co-behaviors which means that most SUs may end up all adjustment to the same channel which has the highest channel carrier capability. This undesired phenomenon not only induces congestion in that channel and degradation to throughput, but also wastes channel vacancy. We present the following method to avoid this phenomenon.

Assume that the carrier capability of the ith channel is η_i, $1 \leq i \leq G$. Let SU(i) be the SU that jumps onto the ith channel according to its basic hopping sequences in its next hop. Let $\overline{\eta} = \sum_{j=1}^{G} \eta_j / G$ and $A = \{Channel\ j | \eta_j > \overline{\eta}, j = 1 \cdots G\}$. The deviation method works as follows:

1. If $\eta_i \geq \overline{\eta}$, SU($i$)s which will jump onto channel i will remain in the basic sequence and do not deviate from channel i.

2. Else

(1) With probability $\eta_i / \overline{\eta}$, SU(i)s which plan to jump onto channel i will remain in the basic hop and do not deviate from channel i.

(2)With probability $(1 - \eta_i/\overline{\eta}) \cdot (\eta_j - \overline{\eta}) / \sum_{k \in A} (\eta_k - \overline{\eta})$, SU($i$)s will select channel j, $j \in A$.

Following above mentioned steps, SUs will jump according to the channel carrier capability η_i instead of equal chance access of the available channels, and the co-behavior problem is also avoided. The proof is given in Appendix A.

3) Beacons Advertisement:

An SU generates and uses the basic hopping sequence first. Based on its own observation and the basic hopping sequence, the SU can make a decision on which hops need to be adjusted according to the above algorithm. It then needs to inform the others the adjustment results in its periodical beacons. Since there is no control channel, the beacon message cannot be received by SUs that are not in the current beacon-sender's channel. In order to let most SUs receive the beacon message earlier with minimal overhead, we adopt the following dissemination scheme considering two cases according to the number of SUs in the network. Denote the number of SUs as N. If the number of SUs is few, i.e., $N \leq 2G-1$, we adopt scheme one. When $N > 2G-1$, scheme two is adopted. The reason for distinguish these two cases is that if the second scheme is adopted when $N < 2G-1$, the number of beacons generated according to scheme two will be larger than when scheme one is used. The goal of the beacon dissemination scheme is to inform as many SUs as possible in the network about the adjusted sequence, within as short beacon intervals as possible.

(1) $N \leq 2G-1$: An SU transmits beacon information to all these SUs in a unicast way, i.e., informs its new sequence to others one by one individually based on each node's hopping sequence. In this scheme, there are altogether $N-1$ beacons generated.

(2) $N > 2G-1$: In this scheme, there are three steps:

a) An SU selects $G-1$ other SUs according to its local information about other SUs' current hopping sequences such that in a particular time slot, named as planned slot, these SUs, including the original SU itself, can cover all these G channels. If these SUs cannot cover all G channels, it chooses a slot that SUs spread on different channels to the largest extent.

b) The SU unicasts the beacon information to these $G-1$ selected SUs and let them re-broadcast the beacon information on behalf of the original SU in the planned slot. In this beacon information, the IDs of the channels onto which the original SU wants the other SUs to broadcast are also included.

c) When the planned time slot arrives, these SUs will re-broadcast the beacon together on those channels. If there are other packets waiting for transmission, the SU will broadcast the beacon message first.

If a particular channel is occupied by PUs or on-going SU transmissions, or the SUs which are responsible for broadcasting on that channel are transmitting or receiving on another channel at that planned slot, these SUs can broadcast the beacon in the planned slot of the next hopping sequence period. The new hopping sequence for an SU is validated at the beginning of the next beacon interval. With this scheme, there are altogether $2G-1$ beacons generated.

4) Negotiation and Transmission:

Each SU keeps a queue for each destination to avoid head-of-line blocking [12], which occurs whenever traffic waiting to be transmitted prevents or blocks traffic destined elsewhere from being transmitted. In each slot, if it is not occupied by a PU, SUs can negotiate for data transmission. Negotiation is needed because an intended receiver may be in another channel as a transmitter. Therefore there is a risk of packet loss if data is transmitted directly. Without negotiation, furthermore, it is possible that two or more transmitters jump onto the same channel for data transmission, resulting in collision. Negotiation which is done after the quiet period, can avoid such potential collisions. When negotiations are successfully done, data transmission can be carried out.

If two SUs cannot finish their transmission within a time slot, they will continue using the same channel for data exchange at the next time slot, which escapes the switching penalty. An ongoing transmission between two SUs may be interrupted by sudden channel occupancy of PUs. In this case, the communicating pairs will pause and hold transmission if the channel is occupied by any PUs again during their data transmission. In order to guarantee that the not-yet-finished transmission has the highest priority, the unfinished transmission can start immediately after the quiet period while new transmitters will sense the channel after the quiet period and negotiate for transmission.

IV. SYSTEM CAPACITY ANALYSIS

In this section, we analyze the system capacity of the DPR-MAC. System capacity here means the total amount of bits per second the SUs in this system can obtain, considering injected traffic load into the system and specific value of channel carrier capability. For ease of expression, we assume there are two types of channels with maximum datarate R_1, R_2 and channel availability γ_1, γ_2 respectively, each type having M channels. Thus the total number of channels is $2M$. Furthermore, it is also assumed in this analysis that there is no sensing failure in the channel sensing stage. The analysis is based on the situation when the adjustment information of SUs is ideally distributed. Table A. 1 gives the parameters used in the system capacity analysis.

Assume further that in different nodes, the average data flow length generated *in bytes* is the same and that the data flow length, which is integer multiples of the time slot length follows independent geometrical distribution. Since there are two type of channels with different datarates, different channel datarates will introduce different data flow length in number of time slots, i.e., different value of μ in geometrical distribution, denoted as μ_1 and μ_2. The probability of the length L_i of a data flow in time slots can therefore be expressed as $P(L_i = l_i)$=$\mu_i(1-\mu_i)^{l_i-1}$, $i = 1,2$ for channel type 1 and 2 respectively. Since a data flow is transmitted on the same channel, it has the same μ during its transmission, no matter how many slots it takes.

Table A.1: Parameters for performance analysis.

Notation	Parameters Description
$2M$	The number of channels in 2 kinds; M channels for R_1 & R_2 respectively. $G = 2M$.
N	The number of SUs.
N_r	The total number of SUs that is ready to transmit or receive at the beginning of the tth slot on all channels.
u_i	The number of SU pairs that successfully negotiate in the tth slot in channel type i, $i = 1,2$.
v_i	The number of SU communication pairs that finish data exchange at $(t-1)$th slot in channel type i, $i = 1,2$ and become ready at the beginning of the tth slot.
c_i	The number of channels which have at least one idle potential receiver in the tth slot in channel type i, $i = 1,2$.
e_i	The number of idle channels in the tth slot in channel type i, $i = 1,2$.
d_i	The number of channels that are idle and have at least one idle potential receiver in them in the tth time slot in channel type i, $i = 1,2$.
k_i	The number of communication pairs in the $(t-1)$th slot in channel type i, $i = 1,2$.
m_i	The number of communication pairs in the tth slot in channel type i, $i = 1,2$.
w	The number of SUs that have data to send in the tth slot.
λ	The probability that an idle SU generates data flow.
μ_i	The probability that a pair of transmitting SUs finish data exchange and release the channel in channel type i, $i = 1,2$.
γ_i	The probability that the PUs do not use the channels in channel type i, $i = 1,2$.

Denote the switching penalty as T_{sw}. The switching penalty happens only at the first time slot of a successful communication session. Therefore, the average switching penalty with the number of time slots that a data transmission uses in channel type 1 and 2 is adopted as $\overline{T}^{i}_{sw} = T_{sw}/\overline{L_i}$, where $\overline{L_i}$ is the average number of slots that a data flow transmission takes in channel type i, $i = 1,2$. Denote the datarate, the length of time slot, and the length of quiet period by R_i, T_s, and T_q. The average flow length in bytes can be presented by $(T_s - T_q - \overline{T_{swi}}) \cdot R_i/\mu_i$, where

$i = 1,2$. Given $T_s >> \overline{T_q}$ and $T_s >> \overline{T}^{i}_{sw}$, for the same average length of data flow in bytes, we can ignore $\overline{T}^{i}_{sw}$ and approximately get that $R_i/R_j = \mu_i/\mu_j$, $\forall \mu \leq 1$.

Based on the above discussions, in any time slot, the system state can be presented by the number of SU communicating pairs in two types of channels, i.e., (P_1, P_2). We can use a discrete-time Markov chain to analyze the system capacity. State transfer happens when at least one communication pair finishes transmission or a pair begins to transmission in either of these two channel types. Fig. A.4 presents a Markov chain in the case that there are two types of channels, and each type has only one channel in it. The first element presents the number of communicating pairs in channel type 1 and the second one presents that in channel type 2. For example, state 10 means that there is one communicating pair in channel type 1 and no communicating pair in channel type 2. In this example, there is only one channel of each type, the number of each element is up to 1 and there are altogether 4 states. It is easy to extend it to two types of channels with several channels in each type and the difference is that the number of states of the Markov chain will be much larger.

In the following subsections, we will deduce first the state transfer probability of the Markov chain from $t-1$ to t, i.e., $P(m_1, m_2|k_1, k_2)$ and then get the steady state probability $\pi_{i,j}$, where $i, j \in [0, M]$. Finally, based on the probabilities obtained, the system capacity can be calculated.

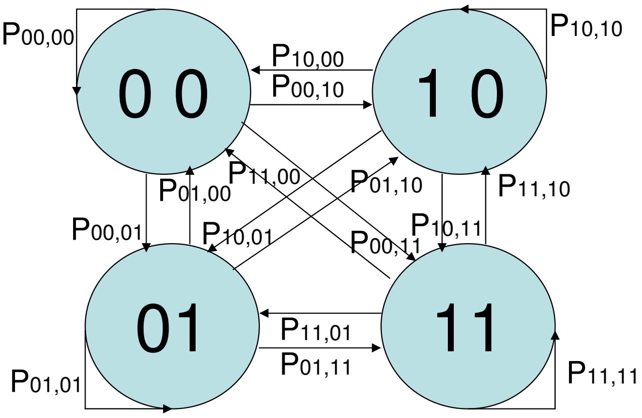

Figure A.4: A Markov chain model for system capacity analysis.

A. State Transition Probability

Given the number k_1 of communicating pairs in the $(t-1)$th time slot in channel type 1, the number v_1 of communicating pairs that become ready at the beginning of tth time slot follows binomial distribution, i.e., $P(v_1|k_1) = \binom{k_1}{v_1}(\mu_1)^{v_1}(1-\mu_1)^{k_1-v_1}$, $0 \leq v_1 \leq k_1$. The expression is similar for channel type 2. Then the number of nodes that is ready to transmit or receive at the beginning of the tth time slot N_r is: $N_r = N - 2(k_1 - v_1) - 2(k_2 - v_2), 0 \leq k_1, k_2, \leq \phi$, $\phi = min(M, N/2)$. The probability that w number of SUs have data to send at the tth time slot can be presented as $P(w|k_1, v_1, k_2, v_2) = \binom{N_r}{w}\lambda^w(1-\lambda)^{(N_r-w)}$, where $0 \leq w \leq N_r$. The number of idle SUs which are ready to receive data, denoted by potential receiver X_r, is $X_r = N_r - w$. Statistically, the idle SUs in channel type 1 and 2 denoted as X_{r1} and X_{r2} will be $X_{r1} = ||\eta_1/(\eta_1 + \eta_2) \cdot X_r||$ and $X_{r2} = X_r - X_{r1}$.

Denote by $P(c_1|k_1, v_1, X_{r1})$ the conditional probability of c_1 number of channels onto which at least one idle potential receiver will jump at the tth time slot, given that there are X_{r1} SUs potential receivers in channel type 1. This is analogous to put X_{r1} balls into M urns and then get the probability that there is c_1 urns that are not empty. The solution can be found in [14] even though there is a slight difference[2], as shown in Appendix B. As the probability of c_1 is not correlated to k_1, v_1, given X_{r1}, we get $P(c_1|k_1, v_1, X_{r1}) = P(c_1|X_{r1})$. The same result applies to channel type 2.

Denote by $P(e_1|k_1, v_1, X_{r1}, c_1)$ the probability that there are e_1 number of the idle channels in channel type 1, given that there are k_1 communication pairs in $(t-1)$th time slot and v_1 pairs of SUs that have finished communications at the end of $(t-1)$th time slot. Then,

$$\begin{aligned} &P(e_1|k_1, v_1, X_{r1}, c_1) = P(e_1|k_1, v_1) \\ &= \tbinom{M-k_1+v_1}{e_1}\gamma_1^{e_1}(1-\gamma_1)^{M-k_1+v_1-e_1}. \end{aligned} \tag{2}$$

Denote by $P(d_1|k_1, v_1, X_{r1}, c_1, e_1)$ the conditional probability that d_1 number of the channels that are idle and have at least one idle potential receiver, given e_1 idle channels and c_1 channels that have at least one idle potential receiver in channel type 1. According to the hypergeometric distribution [3, 14], we obtain

$$\begin{aligned} &P(d_1|k_1, v_1, X_{r1}, c_1, e_1) \\ &= P(d_1|c_1, e_1) = \tbinom{e_1}{d_1}\tbinom{M-e_1}{c_1-d_1}/\tbinom{M}{M-c_1}, \end{aligned} \tag{3}$$

where $0 \leq d_1 \leq c_1$.

For channel type 1, combining the above two equations, we get

$$\begin{aligned} &P(d_1|k_1, v_1, X_{r1}, c_1) = P(d_1|k_1, v_1, c_1) \\ &= \sum_{e_1=0}^{M-k_1+v_1} P(d_1|c_1, e_1)P(e_1|k_1, v_1) \end{aligned} \tag{4}$$

---

[2] In [14], capacity calculation of channel with exactly one transmitter is considered. In our analysis, we consider the channels with one or more available potential receivers, which include the situation that several transmitters may contend for channel access at the same time slot on the same channel. The successful communication pair will still be only one after the negotiation process.

$$= \sum_{e_1=0}^{M-k_1+v_1} \frac{\binom{e_1}{d_1}\binom{M-e_1}{c_1-d_1}}{\binom{M}{M-c_1}} \binom{M-k_1+v_1}{e_1} \gamma_1^{e_1} (1-\gamma_1)^{M-k_1+v_1-e_1}.$$

We approximate the probability that a receiver has data flow to be sent by a transmitter with $w/(N-1)$ [3]. Then we can approximately[3] calculate the probability that u_1 number of the SUs pairs that successfully negotiate on these d_1 channels at the tth time slot [14], $P(u_1|k_1,v_1,w,c_1,d_1)$, as

$$\begin{aligned} &P(u_1|k_1,v_1,w,c_1,d_1) = P(u_1|k_1,v_1,w,d_1) \\ &= \binom{d_1}{u_1}\left(\frac{w}{N-1}\right)^{u_1}\left(1-\frac{w}{N-1}\right)^{d_1-u_1}. \end{aligned} \tag{5}$$

Since $u_1 = m_1 - (k_1 - v_1)$, we give the probability

$$\begin{aligned} &P(m_1|k_1,v_1,w,c_1,d_1) = \\ &\binom{d_1}{m_1-(k_1-v_1)}\left(\frac{w}{N-1}\right)^{m_1-(k_1-v_1)}\left(1-\frac{w}{N-1}\right)^{d_1-(m_1-(k_1-v_1))}. \end{aligned} \tag{6}$$

For channel type 1, by using the Eqs. (4) and (6), and $P(c_1|X_{r1})$, we can obtain that

$$\begin{aligned} &P(m_1|k_1,v_1,w,Xr_1) \\ &= \sum_{c_1=0}^{M}\sum_{d_1=0}^{c_1} P(m_1|k_1,v_1,w,c_1,d_1)P(d_1|k_1,v_1,X_{r1},c_1)P(c_1|X_{r1}). \end{aligned} \tag{7}$$

Similar expression for Eqs. (2)-(7) can be easily found for channel type 2.

Note that $P(m_1|k_1,v_1,w,Xr_1)$ and the corresponding $P(m_2|k_2,v_2,w,Xr_2)$ are probabilities analyzed in different types of channels and they are independent. Thus the joint probability can be expressed as

$$\begin{aligned} &P(m_1,m_2|k_1,v_1,k_2,v_2,w,Xr_1,Xr_2) \\ &= P(m_1|k_1,v_1,w,Xr_1)\cdot P(m_2|k_2,v_2,w,Xr_2). \end{aligned} \tag{8}$$

With our hopping sequence adjustment method, statistically, the probability of Xr_1 and Xr_2 can be expressed as

$$\begin{aligned} &P(X_{r1} = j, X_{r2} = N_r - w - j) \\ &= \binom{N_r-w}{j}(\eta_1/(\eta_1+\eta_2))^{j}(\eta_2/(\eta_1+\eta_2))^{N_r-w-j}. \end{aligned} \tag{9}$$

---

[3] For simplicity, we approximate that the utilization probability of idle channels with more than one potential receiver is the same as the case with only one potential receiver in the analysis, since differentiating channels according to the number of potential receivers will introduce extreme complexity in the analysis. However, we are aware of that it is less likely that several intended receivers will be unavailable at the same time in practice.

Then, we can obtain

$$\begin{aligned} &P(m_1,m_2|k_1,v_1,k_2,v_2,w)\\ &=\sum_{j=0}^{N_r-w} P(m_1,m_2|k_1,v_1,k_2,v_2,w,Xr_1,Xr_2)P(X_{r1}=j,X_{r2}=N_r-w-j). \end{aligned} \tag{10}$$

It is obviously that $P(v_1|k_1)$ and $P(v_2|k_2)$ are independent, then it is found that

$$P(v_1,v_2|k_1,k_2)=P(v_1|k_1)P(v_2|k_2). \tag{11}$$

With the help of $P(w|k_1,v_1,k_2,v_2)$, we can finally compute

$$P(m_1,m_2|k_1,k_2)=\sum_{v_1=0}^{k_1}\sum_{v_2=0}^{k_2}\sum_{w=0}^{N_r} P(m_1,m_2|k_1,v_1,k_2,v_2,w)P(w|k_1,v_1,k_2,v_2)P(v_1,v_2|k_1,k_2). \tag{12}$$

B. Steady-State Probability

Known the transition probabilities, we can calculate the probability for steady-state of the Markov chain. The steady-state probability is given by

$$\Pi=\Pi\mathbf{P}, \tag{13}$$

where Π is a row vector whose elements, $\pi_{i,j}$, sum to 1 as shown in Eq. (14), and $\pi_{i,j}$ is the steady-state probability with i and j communicating pairs in channel type 1 and 2 respectively. $\mathbf{P}$ is the transition matrix, formed by $P(m_1,m_2|k_1,k_2)$, as

$$\mathbf{P}=\begin{bmatrix} P(0,0|0,0) & P(0,1|0,0) & \cdots & P(M,M|0,0)\\ P(0,0|0,1) & P(0,1|0,1) & \cdots & P(M,M|0,1)\\ \vdots & \vdots & \vdots & \vdots\\ P(0,0|M,M) & P(0,1|M,M) & \cdots & P(M,M|M,M) \end{bmatrix}.$$

The sum of all probabilities would be unity, as

$$\sum_{i,j}\pi_{i,j}=1. \tag{14}$$

By solving Eqs. (13) and (14), we can find all steady-state probabilities, $\pi_{i,j}$, for $0\le i,j\le M$.

If the Markov chain is irreducible and aperiodic, then there is a unique stationary distribution. In this case, $\mathbf{P}^{\kappa}$ converges to a rank-one matrix in which each row is the steady distribution Π, i.e.,

$$lim_{\kappa\longrightarrow\infty}\mathbf{P}^{\kappa}=\mathbf{E}\Pi, \tag{15}$$

where $\mathbf{E}$ is the column vector with all entries equaling to 1 and κ is the exponent of $\mathbf{P}$. This character of Markov chains can be used to verify the validity of our analysis[4].

C. System Capacity

The transmissions that are not finished in $(t-1)$th time slot may be buffered in the tth time slot because of the presence of PUs. Denote $\overline{N_{t1}}(k_1, v_1, \gamma_1)$ as the average number of ongoing communication pairs of SU that exchange data in tth time slot in channel type 1 [14] as,

$$\overline{N_{t1}}(k_1, v_1, \gamma_1) = \sum_{i=0}^{k_1-v_1} i\binom{k_1-v_1}{i}\gamma_1^i(1-\gamma_1)^{k_1-v_1-i}. \tag{16}$$

Then the total system capacity, denoted as S which is the sum of data transmitted over channel type 1 and 2, denoted as S_1 and S_2, can be expressed as:

$$S = S_1 + S_2. \tag{17}$$

where

$$S_1 = (T_s - \overline{T_{sw1}} - T_q)\cdot R_1/T_s \times \sum_{k_1=0}^{\phi}\sum_{k_2=0}^{\phi}\sum_{m_1=0}^{\phi}\sum_{m_2=0}^{\phi}\sum_{v_1=0}^{k_1}\sum_{v_2=0}^{k_2} P(k_1, m_1, v_1, k_2, m_2, v_2)\times[\overline{N_{t1}} + m_1 - (k_1 - v_1)], \tag{18}$$

and

$$\begin{aligned} P(k_1, m_1, v_1, k_2, m_2, v_2) &= P(m_1, v_1, m_2, v_2|k_1k_2)\pi_{k_1,k_2} \\ &= P(v_1, v_2|k_1, k_2, m_1, m_2)P(m_1, m_2|k_1k_2)\pi_{k_1,k_2} \\ &= P(v_1, v_2|k_1, k_2)P(m_1, m_2|k_1k_2)\pi_{k_1,k_2}. \end{aligned} \tag{19}$$

Similar expressions can be found for S_2 from Eqs. (16), (18) and (19).

The above analysis result can also be extended to a more general case where there are more than two types of channels. That is, denote N_c as the number of channel types, we can form a Markov chain with N_c elements and each element stands for the number of communicating pairs on channels with the same datarate. In this case, Eq. (9) should be revised as a multinomial distribution instead of binomial distribution, as shown in Eq. (20).

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[4] Indeed, we calculated $lim_{\kappa\longrightarrow\infty}\mathbf{P}^{\kappa}$ and find that it converges to Π and $\sum_{i,j}\pi_{i,j} = 1$ from the numerical results. The validity of the analysis is therefore verified.

$$P(X_{r_1} = x_{r_1}, X_{r_2} = x_{r_2}, \cdots X_{r_{N_c}} = x_{r_{N_c}}) \tag{20}$$
$$= \begin{cases} \frac{(N_r-w)!}{x_{r_1}!\cdots X_{r_{N_c}}!} \quad (\frac{\eta_1}{\eta_1+\cdots\eta_{N_c}})^{x_{r_1}} \cdots (\frac{\eta_{N_c}}{\eta_1+\cdots\eta_{N_c}})^{x_{r_{N_c}}}, \ when \ \sum_{i=1}^{N_c} x_{r_i} = N_r - w. \\ \\ 0, \qquad otherwise. \end{cases}$$

Correspondingly, Eq. (10) can be expressed as:

$$\begin{aligned} & P(m_1, \cdots m_{N_c} | k_1, v_1, \cdots k_{N_c}, v_{N_c}, w) \\ & = \sum_{\sum_{i=1}^{N_c} x_{r_i} = N_r - w} P(X_{r_1} = x_{r_1}, X_{r_2} = x_{r_2}, \cdots X_{r_{N_c}} = x_{r_{N_c}}) \\ & \times P(m_1, \cdots m_{N_c} | k_1, v_1, \cdots k_{N_c}, v_{N_c}, w, X_{r_1}, \cdots X_{r_{N_c}}). \end{aligned} \tag{21}$$

Other parts of the analysis when there are more than two types of channels are quite similar to that of two types of channels. With the analysis of probability, we can find the steady state of Markov chain and finally get the total system capacity in this more complicated case.

D. An Estimation of Beacon Messages Dissemination

In this subsection, the probability of the beacon messages dissemination after a given period is estimated, and the probability of a particular node that can receive the beacon information after a certain numbers of beacon intervals is also given. In this estimation, we focus on the second scheme in Subsection III-C-3), when $N > 2G - 1$.

Assume that there are two types of channels with the same channel availability γ but different datarates R_1 and R_2, and $R_1 > R_2$. Let $P_{og,2}$ be the probability of an SU transmission that has not finished in the previous time slot in channel type 2. Given the same flow length in bytes and traffic load in both of the channel types, the same probability for channel type 1, $P_{og,1}$, could be expressed as $P_{og,2}R_2/R_1$. For the simplicity of estimation, we consider the stage when uniform distributed hopping sequences are used in our following calculation.

1) Probability for Successful Beacon Dissemination:

Since the second step in scheme 2 consumes time in slots scale while the third step uses time in hopping sequence periods scale, we consider the dissemination period used for SUs broadcasting beacon messages in the planned slot on behalf of the original SU. As the beacon dissemination time is determined by the latest distributed beacon on a channel, we analyze the probability for channel type 2, i.e., the low datarate channel. On a low-datarate channel, the probability that a channel is occupied could be expressed as $P_{occ} = 1 - \gamma + \gamma P_{og,2}$. The probability, $P_{succ|idle}$, that an SU can successfully broadcast the beacon in the planned slot when the channel is idle is $P_{succ|idle} = (1 - \frac{2MP_{og,1}+2MP_{og,2}}{N})P_{access}$, where $P_{access} = min(1, \frac{G}{N-2MP_{og,1}-2MP_{og,2}})$, and it is the probability that the SU can successfully access the channel in the worst case when all the SUs within that channel are receivers, given the equal channel access probability of each SU on that channel. Then the successful beacon transmission probability in a planned slot can be obtained by $P_{succ} = P_{succ|idle}P_{idle} = P_{succ|idle}(1 - P_{occ})$. The successful transmission probability after ι planned slots, i.e., ι hopping sequence periods, $P_{succ,\iota}$ could be expressed as $P_{succ,\iota} = 1 - (1 - P_{succ})^{\iota}$. Given the length of hopping sequence and time of each slot, the probability of the beacon messages dissemination after a particular time can then be estimated.

2) Probability of Beacon Information Reception for an SU:

In this paragraph, we estimate the probability of a particular node that can successfully receive beacon information after a beacon broadcast period. According to the scheme, we can imagine that the best case is that the beacon could be sent in the planned slot simultaneously on all these channels, and all the SUs can hear it. The worst case happens when beacons on different channels occur in planned slots in different sequence periods.

When an SU unicasts the beacon to another SU, the probability that an SU on the same channel happens to overhear the beacon, P_{oh}, is $(1 - \frac{2MP_{og,1}+2MP_{og,2}}{(N-1)})/G$. After this procedure, the probability, P_{unic}, which indicates the cases when an SU does not receive the beacon is $\frac{N-1-(G-1)}{N-1}(1 - P_{oh})^{G-1}$. When an SU broadcasts the beacon on the SU's channel according to the SU's sequence in a planned slot, the probability, P_{no_hm}, that the SU happens not to be on that channel is $\frac{2MP_{og,1}+2MP_{og,2}}{N-1} + \lambda_o(1 - \frac{2MP_{og,1}+2MP_{og,2}}{N-1})$, where λ_o is the probability that the SU leaves the sequence denoted channel. The probability, P_{out}, that when the same beacon is broadcast on other channels and the SU happens to hear it is $\lambda_o(1 - \frac{2MP_{og,1}+2MP_{og,2}}{N-1})\frac{1}{N-1}\frac{N}{G}$. Then the probability, P_{no_recv} that an SU cannot recieve a beacon can be expressed as: $P_{unic}P_{no\_hm}(1 - P_{out})^{G-1}$. The probability that a beacon was received after a beacon interval is 1-P_{no_recv}. Then the probability that after U intervals could be approximated[5] by $1 - P_{no\_recv}^{U}$.

V. NUMERICAL RESULTS AND DISCUSSIONS

In this section, based on the analysis in IV, the numerical results and comparison of DPR-MAC and DRI-MAC are given. We investigate the performance in term of

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[5] Since after the first beacon interval, the SU will use the new adjusted sequence, then the probability is an approximation.

system capacity with respect to channel datarate, channel availability, and channel carrier capability. In the first part we assume that the two kinds of channels have the same value of channel availability γ, i.e., $\gamma_1 = \gamma_2$, and the results are according to the channel datarate R_i. In the second part we will show the results that the two types of channels have the same datarate but different channel availabilities γ_i. In the third part we give the results with both different channel availabilities γ_i and different datarates R_i, namely, channel carrier capability. The last part is the overhead and the beacon dissemination estimation.

A. Performance Evaluation given Identical Channel Availability γ

1) Parameters Configuration:

In this section, we will give the results when the two kinds of channels have the same channel availability γ but with different datarates R_i. The parameters used to calculate the system capacity is as follows: $T_s = 1000\ \mu s$, $T_q = 10\ \mu s$, $T_{sw} = 100\ \mu s$, $R_1 = 2\ Mbps$, and $R_2 = 10\ Mbps$. With this time slot and datarate, it is enough to finish negotiation in a small portion of a time slot [3] and we have also $T_s >> T_q$ and $T_s >> \overline{T}^i_{sw}$, which are in accordance with the discussions in Section IV.

2) System Capacity as a Function of λ*:*

Fig. A.5 depicts the system capacity according to λ by using the DPR-MAC and DRI-MAC protocols, where the number of channels at each carrier capability is set as $M = 3$ and $M = 4$ respectively. Other parameters are fixed as $N = 20$, $\gamma = 0.7$ and $\mu_1 = 0.05$, $\mu_2 = 0.25$. With these parameter settings, we can estimate that the average data flow length is $2Mbps * (1000\mu s - 10\mu s - 100\mu s/20)/0.05/8 \approx 5KB$. This implies that the time slots needed for transmitting this data flow are respectively 20 slots at R_1 and 4 slots at R_2, on average.

From Fig. A.5, one can observe that the system capacity is 0 when $\lambda = 0$ or 1. This is because that when $\lambda = 0$, there is no traffic and in the case of $\lambda = 1$, there are no receivers. When $\lambda = 1$, all SUs have data to transmit. SUs will leave their own channels and come to the intended receivers' channels for communication. In this case, theoretically, every SU deviates from its hopping sequence denoted channel thus these SUs cannot find each other. When λ is small, SUs do not generate many data flows. This means that the totally generated traffic load by SUs is so light that it does not even saturate the channels that have lower datarate. As a result, the system capacity difference between these two MAC protocols is not significant in this case, with both $M = 4$ and $M = 3$. However, when traffic load becomes heavier, the advantage of the proposed mechanism is evident. As shown in Fig. A.5, over a wide range of λ, significant system capacity improvement has been achieved by DPR-MAC, compared with what is obtained by its counterpart, DRI-MAC. For

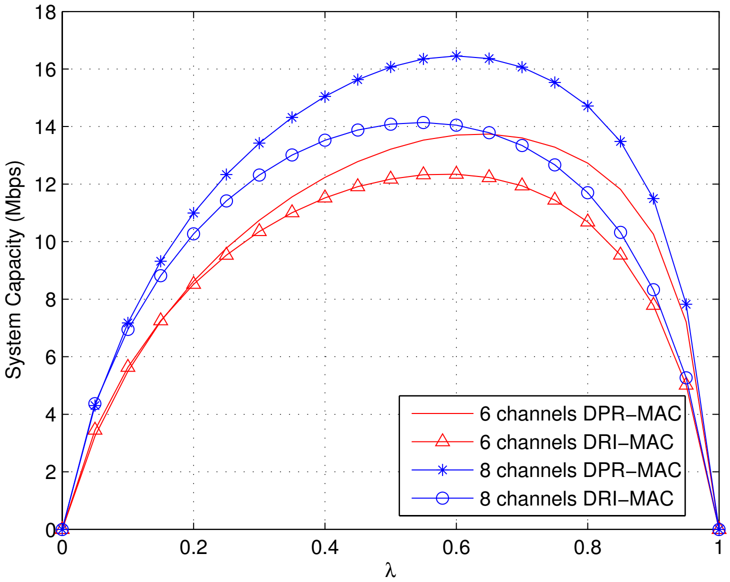

Figure A.5: System capacity comparison of DPR-MAC and DRI-MAC as a function of λ.

example, at $\lambda = 0.5$, DPR-MAC reaches capacity of 16 $Mbps$ while 14 $Mbps$ is obtained by DRI-MAC, indicating that an improvement of 14% has been achieved.

Comparing the difference between $M = 3$ and $M = 4$, one can observe that when the channel number is larger, the enhancement is more significant. This is because that when M is greater, more channels with high datarate are available for SUs. With our proposed method, SUs get better chance to transfer their data flows over the higher datarate channel, leading to increased total system capacity.

Note also that in [14], the peak value of system capacity is achieved around $\lambda = 0.25$ and the system capacity becomes lower when λ gets larger. It is because that in [14] it calculates the channels with exact one transmitter in $P(c_1|k_1, v_1, X_{r1})$. When the sending probability (λ) becomes larger, the probability of channels with exact one transmitter will be lower. Consequently, the system capacity is lower. In contrast, in our scheme, we consider the channel with one or more potential receivers (see footnote 2), which means that the number of channels that has two or more transmitters are also counted in, because after negotiation these channels can also be used. Consequently, the DRI-MAC curves shown in Fig. A.5 are also obtained considering one or more receivers. Therefore, the peak value is obtained when λ is around 0.55 for DRI-MAC.

3) Impact of PUs Channel Occupancy on System Capacity:

Fig. A.6 shows the performance with different value of channel availability γ, when $\lambda = 0.7$, $N = 20$ and $\mu_1 = 0.05$, $\mu_2 = 0.25$. The differences between the system capacity achieved by DPR-MAC and DRI-MAC grow with the rising of γ. The enhancement between the two methods when $M = 4$ is larger than that when $M = 3$, which means the proposed method is more beneficial when the number of channels is larger.

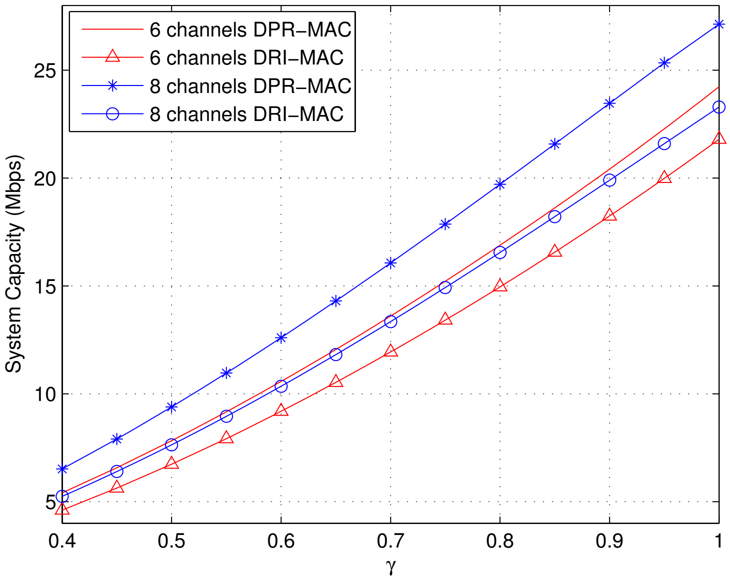

Figure A.6: System capacity comparison of DPR-MAC and DRI-MAC as a function of γ.

When $\gamma = 1$, which means that there are no PUs in the channels, the maximal system capacity and the enhancement between the two methods are observed. In this case, when all channels are available for SUs, an improvement of 17.5% and 11.2% has been observed for $M = 4$ and $M = 3$ respectively.

4) Impact on System Capacity by the Number of SUs:

Fig. A.7 shows the system capacity of DPR-MAC and DRI-MAC with the number of SUs N when $\lambda = 0.7$, $\gamma = 0.7$, $\mu_1 = 0.05$, $\mu_2 = 0.25$. In Fig. A.7, DPR-MAC outperforms DRI-MAC for all ranges of the investigated values. This is because that more SUs jump to the higher datarate channels according to the proportion of datarate in two types of channels rather than uniform hopping sequences, leading to higher total system capacity. Interestingly in this case, larger differences are observed when N is smaller, with both $M = 3$ and $M = 4$. It is because that when the number of SUs is smaller, the system is far from saturation. At the same time, idle SUs have many data flows to send since $\lambda = 0.7$ which indicates a high transmission probability for SUs. Once one communication pair is re-allocated from the low datarate channel to high datarate channel, it contributes more to the achieved total system capacity. For instance, assume that there are four ongoing data flows in

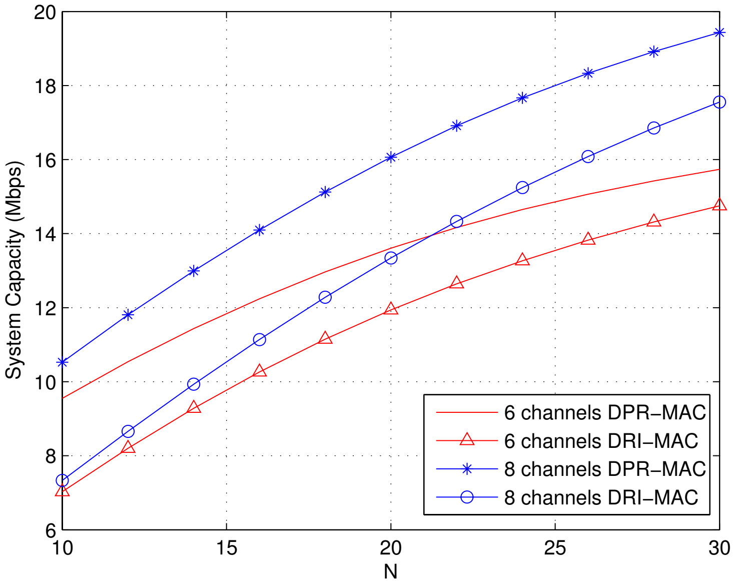

Figure A.7: System capacity comparison of DPR-MAC and DRI-MAC as a function of N.

the system, two of each type. If one of the two low datarate flows is re-allocated to the high datarate channel, the total capacity will be significantly increased since we have now three out four flows using the high capacity channel. When the number of SUs gets larger, the probability that more channels are occupied by communicating pairs will be higher. In other words, with a large N the channels are close to saturation and there is less room for capacity improvement no matter how you balance the hop sequences of the SUs. This explains why the difference between the two methods becomes smaller as N increases.

5) Impact on System Capacity by Channel Datarate:

Fig. A.8 depicts the differences between DPR-MAC and DRI-MAC when the datarate of R_1 is fixed into 2 $Mbps$ and $\lambda = 0.7$, $\gamma = 0.7$, $N = 20$, while datarate of R_2 is as a variable. In order to ensure the average length of data flows *in bytes* on different channels are the same, μ_1 is fixed as 0.05 while μ_2 is 0.05, 0.1, 0.15, 0.2, 0.25, 0.3 when R_2 equals to 2, 4, 6, 8, 10, 12 $Mbps$ respectively.

Fig. A.8 illustrates that the improvement of the new method increases when the datarate of R_2 increases because the difference between channels is larger. Note that when $R_2 = R_1$, the capacity of different methods is the same because in this case, the hops according to the new strategy is also uniform distributed, which implies that DRI-MAC is actually a special case of DPR-MAC. The enhancement is evident when R_2 is three or more times larger than R_1. When R_2 is two times larger than R_1, the improvement is not obvious. Considering the beacon overhead, if the R_2 is less

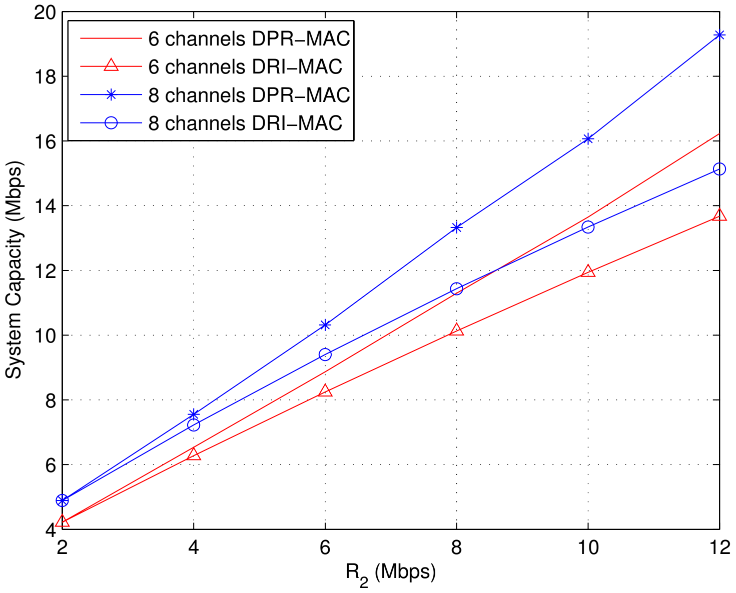

Figure A.8: System capacity comparison of DPR-MAC and DRI-MAC as R_2 varies.

than two times of R_1, the DRI-MAC can be adopted.

B. Performance Evaluation given Identical Datarate

1) Parameters Configuration:

In this case, we give the results when the two types of channels have the same datarate R_i but different channel availabilities γ_i. The parameters used are as follows: $R_1 = R_2 = 10$ $Mbps$, $\mu = 0.2$, $\gamma_1 = 0.9$, $\gamma_2 = 0.6$,. $T_s = 1000$ μs, $T_{sw} = 100$ μs, and $T_q = 10$ μs.

2) System Capacity as a Function of λ:

Fig. A.9 shows the system capacity of different MAC mechanisms as λ varies, when $N = 20$, $M = 3$ and 4 respectively. From the figure we can observe that the trend of Fig. A.9 and Fig. A.5 is quite similar, but the difference is that for the performance between the two MAC mechanisms, the difference in Fig. A.9 is slight. The reason is as follows. From the adjustment method we proposed, in statistic sense, it has a probability of $\gamma_1/(\gamma_2+\gamma_2) = 3/5$ for each SU to jump into the higher γ side. Compared with the probability in different datarates cases, like 2 $Mbps$ in channel type 1 and 8 $Mbps$ in channel type 2 which introduce $R_1/(R_1+R_2) = 4/5$, the probability in the first case is lower. On the other hand, from Eq. (18), we can see that if the datarate in channel type 2 is four times higher than that in channel type 1, the improvement will be more significant compared with the different channel availabilities cases when the datarates on different channels are equal. Consequently, the improvement of the new method in the case with identical R_i is not as much as that when R_i is different.

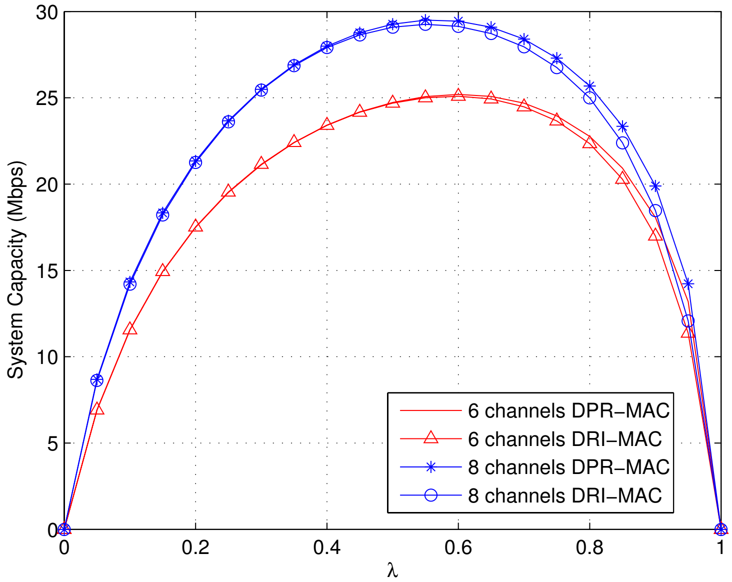

Figure A.9: System capacity comparison of DPR-MAC and DRI-MAC with λ.

3) Impact on System Capacity by the Number of SUs:

Fig. A.10 gives the system capacity with the variable of the number of SUs. The trend of these curves is close to that in Fig. A.7, but the difference between these curves in Fig. A.10 is smaller than that in Fig. A.7. The reason for the similar performance between these curves in Fig. A.10 is the same as we discussed in the above paragraph.

Fig. A.10 also illustrates that when the number of SUs gets larger, the performance between these two MAC mechanisms gets closer, and it is more evident than that in Fig. A.7. The reason for this is the same as we discussed above that with the increasing number of N, the channels are close to saturation and there is less room for capacity improvement no matter how to balance the hop sequences of the SUs.

4) Impact of PUs Channel Occupancy on System Capacity:

In this case, the system capacity as a function of γ_2 is given in Fig. A.11 when γ_1 is fixed as 0.9. From this figure we can see that when γ_2 is smaller, which means the difference between γ_1 and γ_2 is larger, the performance of DPR-MAC is much better than that of DRI-MAC. The reason is quite obvious, since the larger difference between the channels' availabilities, the more benefit the MAC can get if it can adjust there hop sequences to the higher availability channel rather than the equal chance hopping sequence.

From Figs. A.9-A.11, as a whole, it can be observed that the improvement of DPR-MAC is not as significant as that in Figs. A.5-A.8. This is because that the datarate R_i between different channels could be quite large and its effect is more straightforward in different datarates cases while the difference of channel availabilities γ between channels in real cases is not often so large.

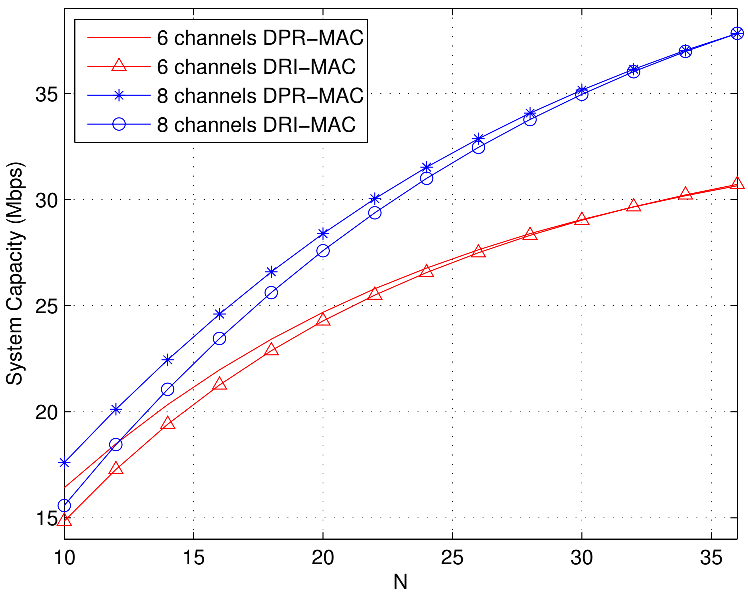

Figure A.10: System capacity comparison of DPR-MAC and DRI-MAC with N.

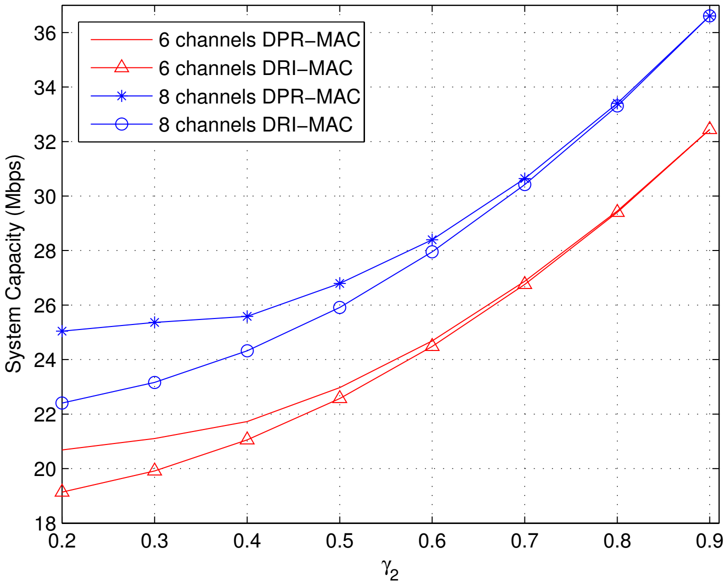

Figure A.11: System capacity comparison of DPR-MAC and DRI-MAC with γ_2.

Furthermore, in all the above numerical results and discussions, there has been an important assumption that the channel sensing is accurate. If there are any sensing errors, say, SUs failed to sense the existence of PUs' activities, there will be a high probability of transmission failure due to packet collision. In this case, the channel availability will affect the performance more than what is observed from our analysis. In a more constrained case, if a successful transmission of a packet needs several consecutive time slots that is not occupied by PUs, the system capacity is more sensitive to channel availability. For example, if a packet needs 3 consecutive free time slots for successful transmission and if $\gamma = 0.9$, the approximate successful transmission probability is $0.9^3 = 0.729$ while for $\gamma = 0.6$ this probability would be only 0.216. Then in this case, channel availability would have higher impact on the total system capacity. Correspondingly, the channel hopping adjustment strategy should also be revised in order to adapt to this situation.

C. System Capacity with Channel Carrier Capability

The above results are either from given identical channel availability or from given identical channel datarate, which are special cases of channel carrier capability. In the following paragraphs, the results of system capacity as a function of the combined parameters are given.

1) Parameters Configuration:

The parameters used to calculate the system capacity is as follows: $N = 20$, $M = 4$, $T_s = 1000\ \mu$s, $T_{sw} = 100\ \mu$s, $T_q = 10\ \mu$s, $\mu_1 = 0.05$, $\mu_2 = 0.25$, $R_1 = 2$ *Mbps*, and $R_2 = 10$ *Mbps*. In this subsection, we only examine the system capacity as a function of λ.

2) System Capacity as a Function of λ:

Fig. A.12 illustrates the results of DPR-MAC and DRI-MAC when R_i and γ_i are different and channel carrier capability is adopted. For comparison, it also shows the results of adjusting hopping sequences according to one of these two parameters, i.e., R_i and γ_i in this case. In Fig. A.12, *Channel availability only* means that SUs adjust the hopping sequences according to channel availability without considering R_i. It is the same case with *datarate only*. In this figure, we have γ_1=0.6 and γ_2=0.9. It is shown that the hopping adjustment according to the channel carrier capability η is the most efficient mechanism and the DRI-MAC is the worst one. Note that both the datarate and the channel availability of channel type 2 are higher than that in channel type 1, the results of adjustment according to channel availability and datarate are better than the DRI-MAC. Adjusting according to datarate is more efficient than adjusting according to channel availability because the former one leads to larger difference in carrier capability. But both of them are not as good

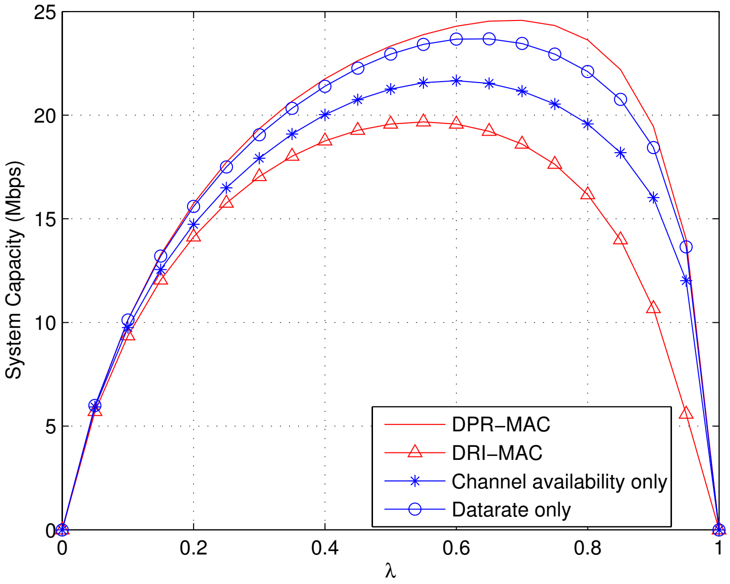

Figure A.12: System capacity comparison among different hopping strategies when $R_1 < R_2$ and $\gamma_1 < \gamma_2$.

as the adjustment according to channel carrier capability η.

Fig. A.13 shows the results of DPR-MAC and DRI-MAC when R_i and γ_i are different when channel carrier capability is adopted. The different parameters used in Fig. A.13 compared with that in Fig. A.12 are that the channel availabilities in two types of channels are exchanged, i.e., γ_1= 0.9 and γ_2=0.6. It is illustrated in the figure that the adjustment according to γ alone is not as good as the DRI-MAC because the adjustment according to γ leads more SUs to low carrier capability channels, i.e. channel type 1. On the other hand, the result of adjustment according to datarate which brings more SUs to jump onto the channels with higher channel carrier capability is quite close to that of the DPR-MAC. Even if adjustment according to the datarate brings more SUs in the type of channels with higher channel carrier capability, the result of this adjustment is not better than in the way of adjusting according to the channel carrier capability, which verifies the rationale of adjusting hopping sequence according to channel carrier capability η.

D. Extra Overhead Estimation of DPR-MAC

Now we approximately calculate the extra overhead introduced by DRA-MAC due to the required dissemination of the hop sequence adjustment information. In the estimation, the calculation is based on an assumption that the whole hopping sequence is disseminated, which reflects the highest possilbe overhead for beacon information dissemination. Assume that there are 20 SUs, 4 channels with 2 *Mbps* and 4 channels with 10 *Mbps*, the hopping period is 128 hops and beacon interval

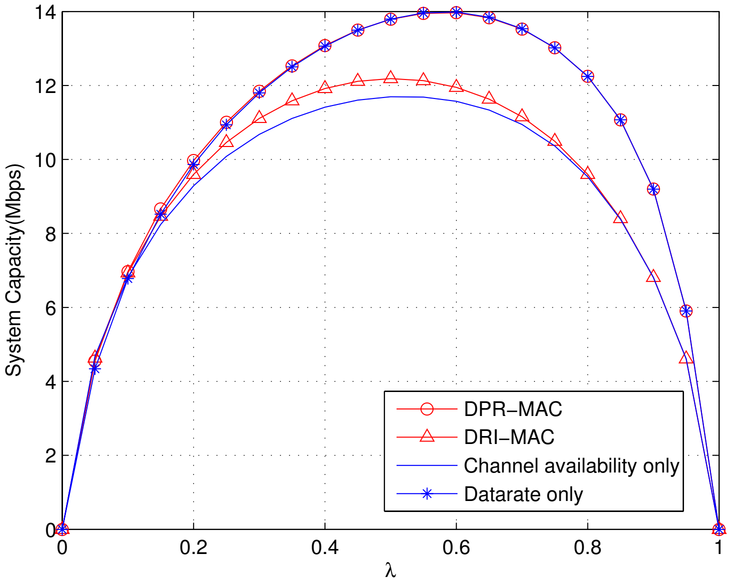

Figure A.13: System capacity comparison among different hopping strategies when $R_1 < R_2$ but $\gamma_1 > \gamma_2$.

is 5 seconds. We can get the average overhead as [128*3*1+(128*3+3)*7+(128*3+48)*7]*20/5=24.468 *Kbps*, where 128 means that there are 128 hops, 3 means that 8 channels can be presented in 3 bits. The calculation has three parts. The first part presents the beacons that are broadcast by the SU itself. The second part presents beacons in the unicast procedure by the original SU. The third part presents the beacons that are re-broadcast by other SUs. Since the other SUs that re-broadcast the beacon in the planned slot have to attach the MAC address of original SU, it has extra 48 bits due to the length of a MAC address.

From the above estimation, we can conclude that the extra overhead introduced by DPR-MAC is pretty small. This indicates that the additional mechanism cost by the proposed MAC is pretty low, typically in the order of a few *Kbps*, in order to achieve possibly a few *Mbps* capacity improvement. Anyhow, it is beneficial to consider this effect for our mechanism design, so that further improvement can be achieved.

E. Beacon Dissemination of DPR-MAC

Now we estimate the dissemination time of a beacon and the probability an SU can receive a beacon after beacon intervals. The parameters used in this analysis is as follows: $\gamma = 70\%$, $P_{og,2} = 70\%$, $R_1 = 10\ Mbps$, $R_2 = 2\ Mbps$, $G = 2M = 8$, $N = 20$, $\lambda_o = 50\%$, the sequence has 128 hops and $T_s = 1\ ms$.

From our estimation in Subsection IV. D, the probability that a beacon is delivered on the low datarate channel after 2, 3, 4, 5, 6 seconds is 73.18%, 86.71%, 93.41%, 96.73%, 98.23% respectively. The probability of an SU that can receive such beacon information can after 1, 2, 3, 4 beacon intervals is 82.51%, 96.94%, 99.47%, 99.91% respectively. Note that the probability is calculated considering the worst case. In the normal cases, the same probability could be achieved in shorter time. These values indicate that the beacon information could be delivered with a high probability within 5 seconds, and in this case, an SU could receive this information with high probability within two beacon intervals, i.e., 10 seconds.

VI. CONCLUSIONS

In this paper we have proposed a channel-hopping based dynamic parallel -rendezvous channel carrier capability aware MAC mechanism for cognitive radio networks with one transceiver. Based on our scheme, SUs can adjust their hopping sequences according to either datarate, channel availability or a combination of them (as carrier capability) in order to improve system performance. A mathematical model has been developed to analyze the performance of the proposed MAC mechanisms. Numerical results and comparison between DPR-MAC and DRI-MAC show that our proposed mechanism generally outperforms the existing one. The difference of the achieved system capacity between DRI-MAC and DPR-MAC is more obvious in the case of identical channel availability than in the case of identical datarate. Moreover, adjusting the channel sequence according to channel carrier capability leads to the best system capacity gain in the examined cases. The improvement compared with DRI-MAC is more significant when more channels are available for SUs, fewer SUs are in the network, and the carrier capabilities between difference channels are larger.

APPENDIX I PROOF OF CHANNEL HOPPING MECHANISM

Proposition: Let L_i be the likelihood of an SU that will hop onto the channel i after using the above mentioned method. For every channel i, $L_1{:}L_2\cdots L_G{=}\eta_1{:}\eta_2\cdots\eta_G$.

Proof: Because the SUs jumps according to the uniformly generated sequence before adjustment, the probability of an SU jumps onto channel $i, 1 \le i \le G$, is equal. Let us arrange the set of G channels according to the value of η_j as $\{1,2,\cdots,l, l+1,\cdots,G\}$ such that $\eta_j \le \overline{\eta} \Leftrightarrow j \le l$ and $\eta_j \le \eta_i \Leftrightarrow i < j$. Let $B \in \{channel\ j|\eta_j < \overline{\eta}, j = 1,2,\cdots G\}$. After the adjustment, we can see that

$$L_{1,2\cdots l} = \eta_{1,2\cdots l}/\overline{\eta} \quad and$$

$$L_{l+1,l+2\cdots G} = 1 + \frac{\sum_{i\in B}(1-\eta_i/\overline{\eta})\cdot(\eta_{l+1,l+2,\cdots G}-\overline{\eta})}{\sum_{k\in A}(\eta_k-\overline{\eta})}.$$

We should prove that

$$1+\frac{\sum_{i\in B}(1-\eta_i/\overline{\eta})\cdot(\eta_{l+1,l+1,\cdots G}-\overline{\eta})}{\sum_{k\in A}(\eta_k-\overline{\eta})}=\eta_{l+1,l+2\cdots G}/\overline{\eta}.$$

When $j>l$, we can see that

$$\begin{aligned}
&1+\sum_{i\in B}(1-\eta_i/\overline{\eta})\cdot(\eta_j-\overline{\eta})/\sum_{k\in A}(\eta_k-\overline{\eta})\\
&=1+\frac{\sum_{i\in B}(\overline{\eta}-\eta_i)}{\sum_{k\in A}(\eta_k-\overline{\eta})}\cdot\frac{\eta_j-\overline{\eta}}{\overline{\eta}}\\
&=\frac{\sum_{i\in\eta}(\overline{\eta}-\eta_i)}{\sum_{k\in A}(\eta_k-\overline{\eta})}\cdot\frac{\eta_j}{\overline{\eta}}+1-\frac{\sum_{i\in B}(\overline{\eta}-\eta_i)}{\sum_{k\in A}(\eta_k-\overline{\eta})}\\
&=\frac{\sum_{i\in B}(\overline{\eta}-\eta_i)}{\sum_{k\in A}(\eta_k-\overline{\eta})}\cdot\frac{\eta_j}{\overline{\eta}}+\frac{\sum_{k\in A}(\eta_k-\overline{\eta})+\sum_{i\in B}(\eta_i-\overline{\eta})}{\sum_{k\in A}(\eta_k-\overline{\eta})}\\
&=\frac{\sum_{i\in B}(\overline{\eta}-\eta_i)}{\sum_{k\in A}(\eta_k-\overline{\eta})}\cdot\frac{\eta_j}{\overline{\eta}}\\
&=\frac{\eta_j}{\overline{\eta}}.
\end{aligned}$$

Now we can conclude that:
$L_1{:}L_2\cdots L_G{=}\eta_1/\overline{\eta}{:}\eta_2/\overline{\eta}\cdots\eta_G/\overline{\eta}\ {=}\eta_1{:}\eta_2\cdots\eta_G$.

APPENDIX II

We give the solution for the probability, $P(c|\vartheta,M)$, that there is c non-empty urns if we put ϑ balls into M urns by the model given in [14].

Let $o(\vartheta)$ be the stochastic process representing the number of urns each of which has exactly one ball given there are ϑ balls, and $n(\vartheta)$ as the stochastic process representing the number of urns each of which has at least two balls. Then, we obtain a two-dimensional process $\{o(\vartheta),\ n(\vartheta)\}$ that is a discrete-time Markov chain as shown in Fig. A.14 [14].

The one-step transition probabilities are as follows [14]:

$$\begin{cases}
p(i,j|i,j)=\frac{j}{M}, & 0\le i,j\le M\\
p(i+1,j|i,j)=1-\frac{i+j}{M}, & 0\le i\le(M-1),j\ge 0\\
p(i-1,j+1|i,j)=\frac{i}{M}, & 0\le i\le M,0\le j\le(M-1)\\
p(x,y|i,j)=0; & |x-i|\ge 2\text{ or }|y-j|\ge 2
\end{cases}$$

where $(i+j)\le M$ holds.

Then the probability that c non-empty urns given ϑ balls and M urns can be calculated as:

$$P(c|\vartheta,M)=\sum_{o(\vartheta)+n(\vartheta)=c}P_\vartheta(o(\vartheta),n(\vartheta)),$$

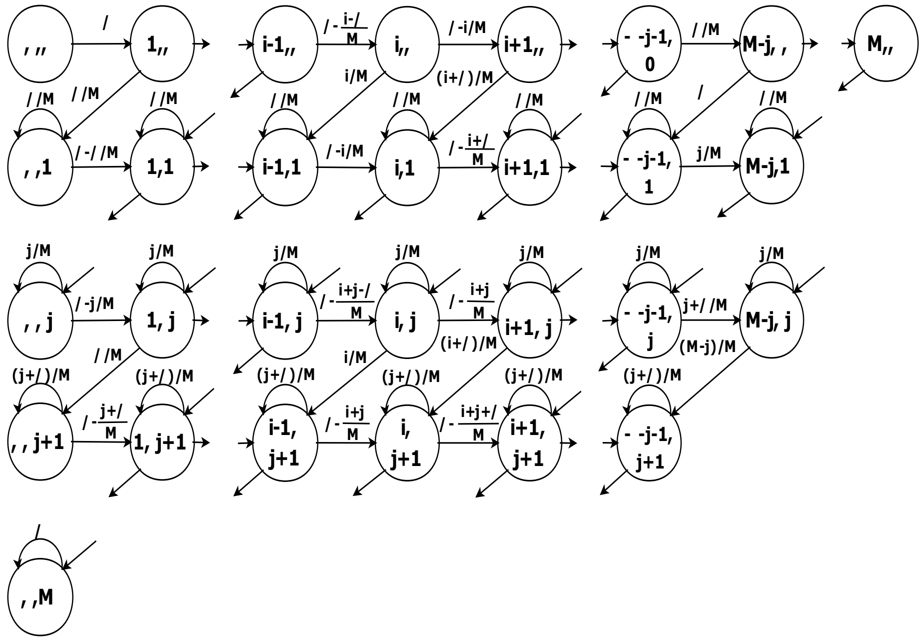

Figure A.14: The two-dimensional Markov chain for the probability that there is c non-empty urns if we put ϑ balls into M urns [14].

where $P_{\vartheta}(o(\vartheta), n(\vartheta))$ is the state probability of $\{o(\vartheta), n(\vartheta)\}$ after ϑ steps.

REFERENCES

[1] S. Haykin, "Cognitive radio: brain-empowered wireless communications," *IEEE JSAC*, vol. 23, no.2, pp. 201-220, Feb. 2005.

[2] IEEE 802.22 WG on WRANs. http://www.ieee802.org/22/.

[3] J. Mo, H. -S. W. So and J. Walrand, "Comparison of multichannel MAC protocols," *IEEE Trans. Mobile Comput.*, vol. 7, no. 1, pp. 50-65, Jan. 2008.

[4] J. C. Jia and Q. Zhang, "HC-MAC: A hardware-constrained cognitive MAC for efficient spectrum management," *IEEE JSAC*, vol. 26, no.1, pp. 106-117, Jan. 2008.

[5] L. Long and E. Hossain, "OSA-MAC: A MAC protocol for opportunistic spectrum access in cognitive radio networks," in *Proc. IEEE WCNC*, Las Vegas, USA, Mar. 2008.

[6] B. Hamdaoui and K. G. Shin, "OS-MAC: An efficient MAC protocol for spectrum-agile wireless networks," *IEEE Trans. Mobile Comput.*, vol. 7, no. 8, pp. 915-930, Aug. 2008.

[7] H. Su and X. Zhang, “Cross-layer based opportunistic MAC protocols for QoS provisionings over cognitive radio mobile wireless networks,” *IEEE JSAC*, vol. 26, no. 1, pp. 118-129, Jan. 2008.

[8] H. Su and X. Zhang, “The cognitive radio based multi-channel MAC protocols for wireless ad hoc networks,” in *Proc. IEEE GLOBECOM*, Washington DC, USA, Nov. 2007.

[9] Q. Zhao, L. Tong, A. Swami and Y. X. Chen,“Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework,” *IEEE JSAC*, vol. 25, no. 3, pp. 589 - 600, Apr. 2007.

[10] C. Cordeiro and K. Challapali, “C-MAC: A cognitive MAC protocol for multi-channel wireless networks,” in *Proc. IEEE DySPAN*, Dublin, Ireland, Apr. 2007.

[11] Y. Yuan, P. Bahl, R. Chandra, P. A. Chou, J. I. Ferrell, T. Moscibroda, S. N. and Y. Wu, “KNOWS: cognitive radio networks over white spaces,” in *Proc. IEEE DySPAN*, Dublin, Ireland, Apr. 2007.

[12] H. -S. W. So, J. Walrand and J. Mo, “McMAC: A parallel rendezvous multi-channel MAC protocol,” in *Proc. IEEE WCNC*, Hong Kong, China, Mar. 2007.

[13] V. Bahl, R. Chandra and J. Dunagan, “SSCH: Slotted seeded channel hopping for capacity improvement in ad hoc networks,” in *Proc. ACM MOBICOM*, Philadelphia, USA, Sep. 2004.

[14] H. Su and X, Zhang, “Channel-hopping based single transceiver MAC for cognitive radio networks,” in *Proc. IEEE CISS*, Princeton, USA, Mar. 2008.

[15] A. Motamedi and A. Bahai, “MAC protocol design for spectrum-agile wireless networks: Stochastic control approach,” in *Proc. IEEE DySPAN*, Dublin, Ireland, Apr. 2007.

[16] A. Fehske, J. D. Gaeddert, J. H. Reed, “A new approach to signal classification using spectral correlation and neural networks,” in *Proc. IEEE DySPAN*, Baltimore, USA, Nov. 2005.

[17] S. K. Park and K. W. Miller, “Random Number Generators: Good Ones are Hard to Find,” *Communications of the ACM*, vol.31, no.10, pp. 1192-1201, Oct. 1988.

[18] P. N. Anggraeni, N. H. Mahmood, J. Berthod, N. Chaussonniere, and L. My, H. Yomo, "Dynamic channel selection for cognitive radios with heterogenous primary bands," *Wireless Personal Communications*, vol. 45, issue 3, pp. 369-384, May, 2008.

Paper B

Title: Modeling and Performance Analysis of Channel Assembling in Multichannel Cognitive Radio Networks with Spectrum Adaptation

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Modeling and Performance Analysis of Channel Assembling in Multichannel Cognitive Radio Networks with Spectrum Adaptation

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Abstract — **To accommodate spectrum access in multichannel cognitive radio networks (CRNs), the channel-assembling technique, which combines several channels together as one channel, has been proposed in many medium access control (MAC) protocols. However, analytical models for CRNs enabled with this technique have not been thoroughly investigated. In this paper, two representative channel-assembling strategies that consider spectrum adaptation and heterogeneous traffic are proposed, and the performance of these strategies is evaluated based on the proposed continuous-time Markov chain (CTMC) models. Moreover, approximations of these models in the quasistationary regime are analyzed, and closed-form capacity expressions are derived in different conditions. The performance of different strategies, including the strategy without assembling, is compared with one another based on the numerical results obtained from these models and validated by extensive simulations. Furthermore, simulation studies are also performed for other types of traffic distributions to evaluate the validity and the preciseness of the mathematical models. Through both analyses and simulations, we demonstrate that channel assembling represented by the investigated strategies can improve the system performance if a proper strategy is selected with appropriate system parameter configurations.**

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Keywords—Channel assembling, cognitive radio networks (CRNs), continuous-time Markov chain (CTMC) models, performance analysis, spectrum adaptation.

I. INTRODUCTION

Consider typical scenarios in cognitive radio networks (CRNs) [1] where multiple channels exist. There are two options for channel access. On the one hand, secondary users (SUs) can follow the original channel structure for primary users (PUs), as proposed in many CRN MAC designs [2, 3, 5, 4]. On the other hand, with the support of more sophisticated hardware, SUs can make a decision on whether to assemble multiple idle channels together as one channel for providing higher data rate or still treat them as separate channels. In the latter case, when two or more channels in the frequency domain are idle, they can be combined together as one channel using channel assembling. This technique has, indeed, been utilized in many CRN MAC protocols [6]-[10].

The research work on CRN spectrum access can be categorized into two phases. The first phase is MAC protocol design itself, aiming at proposing feasible strategies in order to allow CRNs access spectrum in a more efficient way [2]-[11]. The second phase is to build analytical models in order to help us better understand the theory behind these protocols and evaluate the performance of different strategies [12]-[17]. In this study, we aim at the second phase and focus on the performance analysis of channel assembling. This paper is motivated by the observation that, although widely discussed in CRN MAC protocols, the performance of CRNs with channel assembling itself has not been thoroughly analyzed through recognized mathematical models. For example, the performance of an SU network when a PU channel could be divided into several SU channels is analyzed based on a continuous-time Markov chain (CTMC) model in [13, 14, 15]. In our previous work [16], the performance of several channel-assembling strategies when spectrum adaptation is not enabled is studied through CTMC models. In a similar study [17], channel aggregation for CRNs is mathematically analyzed with and without spectrum handover. However, only homogeneous traffic is considered in CRNs in all those studies, and none of them systematically analyze channel-assembling strategies with spectrum adaptation through mathematical modeling.

The meaning of spectrum adaptation is twofold. On the one hand, it is inherited from spectrum handover, which allows SUs to switch an ongoing SU transmission to a vacant channel that is not occupied by PUs or SUs, if it exists, when a PU activity appears on the current channel. On the other hand, it is meant that an ongoing SU service can adaptively adjust the number of assembled channels according to the availability of channels as well as other SUs' activities. How spectrum adaptation is utilized depends on specific channel-assembling strategies. Furthermore, spectrum adaptation can be performed either by a base station centrally or by the cognitive radios themselves through a suitable distributed protocol. Because spectrum adaptation is one of the essential principles of CRNs, i.e., sensing the radio environment and adapting to it accordingly, we propose and investigate two representative channel-assembling strategies with spectrum adaptation in this study. Based on these proposed strategies, we present CTMC models to analyze their performance. Then, the models in the quasistationary regime (QSR), i.e., when the time scale of PU activities is much larger than that of the SU activities, are introduced. Although various assembling strategies exist in different systems, similar modeling process can be developed, and we believe that, with minor modifications, the models we develop for these two strategies can also be applied to many other strategies. Thirdly, numerical results obtained from mathematical models are analyzed and compared, and the correctness of the mathematical models is validated by extensive simulations. Finally, to evaluate the preciseness and the robustness of the mathematical models, the results under traffic distributions rather than the distributions used in CTMC models are examined by simulations and compared with the analytical results from the CTMC models.

In brief, the major contributions of this paper can be outlined as follows:

- Two representative channel-assembling strategies for CRNs that consider heterogeneous traffic are proposed and thoroughly investigated. Although the strategies may be complex from an implementation point of view, their analyses are still significant, because they provide theoretical insight into the performance gain that can be obtained by channel assembling.

- Mathematical models for analyzing these strategies are proposed using CTMCs. This allows us to examine the performance of those strategies theoretically by assuming Poisson traffic arrival processes and exponential service time distributions for PUs and SUs.

- The approximations for these models in the QSR are introduced. With these approximations, closed-form expressions for capacity calculation are derived for different types of traffic.

- Other more realistic traffic patterns which may not follow the Poisson arrival and the exponential service time assumptions are evaluated through extensive simulations. Therefore, the rationality and the robustness as well as the applicability of the proposed mathematical models are verified to a much larger extent.

The rest of this paper is organized as follows. Section II summarizes the related work. The system model and assumptions are given in Section III. After the channel-assembling strategies are described in Section IV, different CTMC models are built in Section V in order to analyze the performance of these strategies. Furthermore, the models of these strategies in the QSR is analyzed in Section VI, followed by numerical results and corresponding discussions presented in Section VII. Finally, the paper is concluded in Section VIII.

II. RELATED WORK

In this section, we summarize the state-of-the-art CTMC models that were established for different channel access strategies and application scenarios in CRNs.

In [13, 14] and [15], the case when a PU channel could be split into several SU channels are modeled through CTMCs. The authors of [13] and [14] mainly focus on the cases when there are infinite number of users, and both spectrum handover and non-handover cases are considered. In [15], it is analyzed the performance of the secondary network in the cases with a finite user population. In [12], three spectrum access schemes are proposed and analyzed through CTMCs. However, channel assembling is not considered in that paper.

In [16] and [17], channel assembling is investigated mathematically from different angles. In [16], the performance of the secondary network with different channel-assembling strategies is studied when spectrum adaptation is not implemented. Three strategies, i.e., without channel assembling, with a fixed number of assembled channels, and assembling all idle channels when SU services access the system, are investigated and compared. Similarly, in [17], three channel-assembling strategies with and without spectrum handover are studied. However, the CTMC models and some parameters that were used in [17] are not appropriately adjusted. Moreover, the second meaning of spectrum adaptation, i.e., the number of assembled channels for which ongoing SU services can be adapted, is not considered in these studies. In our recent work [18], different channel-assembling strategies with spectrum adaptation are studied. Based on these preliminary studies, we propose two representative channel-assembling strategies considering spectrum adaptation and heterogeneous traffic, and investigate them in depth afterwards.

III. SYSTEM MODEL AND ASSUMPTIONS

Before we describe channel-assembling strategies, the system model and the assumptions are given as follows. Assume that there are two types of radios, PUs and SUs, operating in the same frequency band which consists of $M \in \mathbb{N}^+$ channels for

PUs, where $\mathbb{N}^+$ denotes the set of positive natural numbers. PUs have priority to utilize the spectrum and can acquire the channels being used by SUs at any time. Each PU service occupies only one channel while SUs can assemble multiple channels. Those multiple channels can be either neighboring to or separated from one another in the spectrum domain.

In this paper, we consider the following two heterogeneous SU traffic types: 1) elastic traffic and 2) real-time traffic. For elastic traffic, like file downloading, the service time will be reduced if more channels are utilized for the same service due to higher data rate. On the other hand, for a real-time traffic flow, like a real-time voice conversation, sufficient service quality is provided given a fixed number of channels, and its service time is fixed even if more channels are assembled[1]. Because channel assembling is more beneficial for elastic traffic because of its flexibility, our focus will be mainly on the elastic traffic in this analysis. An admission control phase which can provide further tradeoff between both types of SU services can be applied according to the calculated blocking probability based our models of various strategies. Once accepted, the SU services will experience stable services without interruption due to channel fading through advanced underlying physical layer techniques.

For conciseness, we refer to traffic flows as services and use events to indicate the arrival and departure of services for both PUs and SUs. In the following analysis, we focus on the performance of the secondary network. It is assumed that the services of the secondary network are independent of each other. PUs are not aware of the existence of SU activities, and SUs can detect PU activities with high-enough spectrum-sensing accuracy. We further assume that the sensing and spectrum adaptation latency is much shorter than the duration of the service events. In other words, the arrivals or departures of services are unlikely to happen during the sensing and spectrum adaptation period. Furthermore, it is assumed that a protocol runs among SUs to support channel assembling and spectrum adaptation.

IV. CHANNEL-ASSEMBLING STRATEGIES

To study SU performance with channel assembling, two strategies with spectrum adaptation are proposed, as presented below. For the first strategy, i.e., the *Static* (a,W,V) strategy, referred to as $S(a,W,V)$, the first meaning of spectrum adaptation, i.e., spectrum handover only, is applied. The second strategy, *Dynamic* (a,W,V), referred to as $D(a,W,V)$, uses the full meaning of spectrum

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[1] Of course the quality of the voice conversation will be improved up to a limit when more channels are assembled.

adaption, i.e., not only the spectrum handover is adopted, but also the number of the assembled channels for an ongoing SU service is adjustable. In our notations, parameter $a \in \mathbb{N}^+$ indicates the number of channels assembled by a real-time SU service in the network. Parameters W, $V \in \mathbb{N}^+$ represent, respectively, the lower and the upper bounds of the number of assembled channels for an elastic SU service. The values of them are pre-defined for a given strategy and network configuration, at the network initiation phase. Let $N \in \mathbb{N}^+$, $W \leq N \leq V$, denote the number of channels that an elastic SU service assembles, which may vary from one elastic SU service to another, and may also vary along time for an ongoing elastic SU service when the dynamic strategy is employed. However, the number of channels for a real-time service is always fixed. Denote a real-time SU service and an elastic SU service by SU_r and SU_e respectively.

A. $S(a,W,V)$

In this strategy, upon an SU_r arrival, the service can commence if the number of idle channels is larger than or equal to a. When an SU_e tries to access channels, if the number of idle channels, denoted by I_c, is larger than or equal to W at this moment, it can commence with the number of assembled channels as $\min\{V, I_c\}$. If not enough idle channels exist, i.e., the number of idle channels is lower than W for an SU_e or a for an SU_r, the service will be blocked. *Static* here means that once an SU service starts, the number of assembled channels can no longer be changed. In other words, during an SU service time period, even if new idle channels emerge, for instance when any PUs or other SUs finish their transmissions, ongoing SU services will not assemble those newly available channels. On the other hand, when an arriving PU takes any one of the assembled channels that is in use by an ongoing SU service, the SU service will switch to an idle channel which is not occupied by PUs or SUs, if it exists. Otherwise, the SU service is forced to terminate.

A special case of this strategy is $a = W = V = 1$, which represents the legacy channel access strategy without channel assembling. We denote it as no assembling (*NA*) and its performance will be compared with the proposed two strategies later in this paper.

B. $D(a,W,V)$

If there are enough idle channels upon an SU arrival, i.e., the number is larger than or equal to W for an SU_e or a for an SU_r, it will react in the same way as in the static strategy. However, if there are not enough idle channels for a newly arrived SU service, instead of blocking it, ongoing SU_es will share their occupied channels to the newly arrived SU service, as long as they can still keep at least W channels and the number is sufficient for the new SU service to commence after sharing.

When an SU service needs the channels shared by ongoing SU_es to commence and there are several SU_es in the system, the one that occupies the maximum number of channels will donate first, due to the consideration of fairness among SU services. If the SU_e with the maximum number cannot provide enough channels, the one with the second maximum number will share its channels then, and so on. The newly arrived SU_e will join the network as long as W channels are gathered, including both the idle channels and the ones released by other SU_es, if the number of idle channels is lower than W. If the number of idle channels together with the number of channels to be released by all SU_es is still not enough, i.e., the number is lower than W for an SU_e or a for an SU_r, the new SU arrival is blocked.

In this strategy, if any channels become idle, the ongoing SU_es with less than V channels will assemble those newly available channels up to V. In the presence of multiple SU_es that can utilize newly vacant channels, it designates the one which currently has the minimum number of channels to occupy them first, again, due to the aforementioned fairness consideration. If the SU_e with the minimum number of channels assembles V channels after adjustment and there are still vacant channels, other SU_es will occupy the remaining ones according to the same principle, until all those vacant channels are utilized or all existing SU_es have V channels.

On the other hand, when PU services arrive and there is no idle channel available, SU_es can flexibly adjust downwards the number of assembled channels, as long as the remaining number of channels is still not fewer than W. If an arriving PU acquires any one of the channels that is occupied by an SU_e with exactly W channels and there is no idle channel, this already commenced SU_e is forced to terminate. To give higher priority to SU_r, if any one of the channels being used by an SU_r is taken by an arriving PU and there is no idle channel at the moment, the SU_e with the maximum number of channels will donate one channel from its occupied set. In this way, the SU_r can be kept. A forced SU_r termination happens only if it is interrupted by a PU arrival when all SU_es occupy exactly W channels and if no idle channel exists.

V. CTMC MODELS FOR CHANNEL-ASSEMBLING STRATEGIES

To model different strategies with channel assembling, we develop CTMCs by assuming that the arrivals of both SU and PU services are Poisson processes. The SU service arrival rates are λ_S and λ'_S for elastic and real-time services respectively, and the PU service arrival rate is given by λ_P. Upon a PU service arrival, it will access one of the channels that are not occupied by ongoing PU services with the same probability. Similarly, the service times are exponentially distributed. The service rates of PU services and SU real-time services are μ_P and μ_S' respectively, and the service rate for elastic SU services is μ_S in one channel. For real-time traffic, the service rate is constant as stated earlier. For elastic traffic, the service rate will be higher if several channels are accumulated for the same service. Assume further that all the channels are homogeneous. Then the average data rate is approximately linearly increasing with the number of assembled channels. Therefore, the service rate of the N assembled channels for an SU elastic service is approximated as N times of that in one channel, i.e., $N\mu_S$. The unit for these parameters could be services/unit time. Given concrete values for these services, the system capacity could be expressed in kilobits per second or megabits per second. For this reason, in our analysis and results illustrated later, the unit of system capacity is not explicitly expressed.

According to the aforementioned strategies, different CTMC models can be built[2]. The states of these CTMC models can be represented by $x = (i, g_a, j_W, ... j_k, ..., j_V)$, where i is the number of PU services, g_a is the number of SU$_r$s assembling a channels, while j_k is the number of SU$_e$s that assemble $k = W, W+1, \dots, V$ channels. Denote by $b(x)$ the total number of utilized channels at state x, as $b(x) = i + ag_a + \sum_{k=W}^{V} kj_k$. We start from modeling the static strategy first.

A. CTMC Analysis for $S(a,W,V)$

Let $\mathscr{S}$ be the set of feasible states, as $\mathscr{S} = \{x \mid i, g_a, j_W, \dots, j_V \geq 0;\ b(x) \leq M\}$. Table B.1 summarizes the state transitions in this strategy. Given feasible states and their transitions in a CTMC, we can construct the global balance equations and the normalization equation. That is, the equations that indicate that, in steady-state, for each state the average incoming transition rate is equal to the outgoing rate, and that the sum of the probabilities of all states is equal to one. From these equations, the state possibilities, denoted by $\pi(x)$ as the probability of state x, are obtained. Given the state probabilities $\pi(x)$, system performance parameters can be developed as follows.

The blocking probability of a type of SU services is the sum of the probabilities of states that cannot accommodate more SU services of that type. Let P_b and P_b' be the blocking probability of SU$_e$ and SU$_r$ respectively, expressed by

$$P_b = \sum_{\substack{x \in \mathscr{S}, \\ M - b(x) < W}} \pi(x); \quad P_b' = \sum_{\substack{x \in \mathscr{S}, \\ M - b(x) < a}} \pi(x). \tag{1}$$

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[2] The protocol overhead for each strategy is different; for example, the dynamic strategy requires highest control overhead in order to support access flexibility. To keep our analysis simple and consistent for all strategies, the protocol overhead is not included in our models presented below.

Table B.1: Transitions from a generic state $x = (i, g_a, j_W, \ldots, j_V)$ of $S(a,W,V)$

Activity	Destination state	Trans. rate	Conditions
PU DP[3].	$(i-1, g_a, j_W, \ldots, j_V)$	$i\mu_P$	$i > 0$.
PU AR, no FT.	$(i+1, g_a, j_W, \ldots, j_V)$	λ_P	$b(x) < M$.
PU AR, FT in an SU$_r$.	$(i+1, g_a-1, j_W, \ldots, j_V)$	$\frac{ag_a}{M-i}\lambda_P$	$b(x) = M$; $i < M$; $g_a > 0$.
PU AR, FT in an SU$_e(k)$.	$(i+1, g_a, j_W, \ldots, j_k-1, \ldots, j_V)$	$\frac{kj_k}{M-i}\lambda_P$	$b(x) = M$; $i < M$; $j_k > 0$; $W \le k \le V$.
SU$_r$ DP.	$(i, g_a-1, j_W, \ldots, j_V)$	$g_a\mu'_S$	$g_a > 0$.
SU$_e(k)$ DP.	$(i, g_a, j_W, \ldots, j_k-1, \ldots, j_V)$	$kj_k\mu_S$	$j_k > 0$; $W \le k \le V$.
SU$_r$ AR.	$(i, g_a+1, j_W, \ldots, j_V)$	λ'_S	$M - b(x) \ge a$.
SU$_e$ AR.	$(i, g_a, j_W, \ldots, j_k+1, \ldots, j_V)$	λ_S	$k = \min\{V, M-b(x)\} \ge W$.

The capacity of a type of SU services is defined as the average service rate of SUs in that type, i.e., the average number of SU service completions per time unit [13]. Let ρ and ρ' be the capacity of SU$_e$ and SU$_r$ respectively, shown as follows:

$$\rho = \sum_{x \in \mathscr{S}} \sum_{k=W}^{V} kj_k\mu_S\pi(x); \quad \rho' = \sum_{x \in \mathscr{S}} g_a\mu'_S\pi(x). \tag{2}$$

Forced termination represents a preemption of an ongoing SU service. In this work, we consider the fraction of forced terminations over commenced SU services. Therefore, the forced-termination probability can be expressed as the mean forced-termination rate (denoted by R_f for SU$_e$ and R'_f for SU$_r$) divided by the rate of the commenced SU services [14] (denoted by λ^*_S for SU$_e$ and λ'^*_S for SU$_r$). Let P_f and P'_f be the forced-termination probability of SU$_e$ and SU$_r$ respectively. They are obtained as follows.

$$\begin{aligned} P_f &= \frac{R_f}{\lambda^*_S} = \frac{\lambda_P}{\lambda^*_S} \sum_{\substack{x \in \mathscr{S}, \\ b(x)=M, i<M}} \sum_{k=W}^{V} \frac{kj_k}{b(x)-i}\pi(x); \\ P'_f &= \frac{R'_f}{\lambda'^*_S} = \frac{\lambda_P}{\lambda'^*_S} \sum_{\substack{x \in \mathscr{S}, \\ b(x)=M, i<M}} \frac{ag_a}{b(x)-i}\pi(x), \end{aligned} \tag{3}$$

where $\lambda^*_S = (1-P_b)\lambda_S$, and $\lambda'^*_S = (1-P'_b)\lambda'_S$.

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[3] For convenience of illustration, we use AR to indicate an arrival event, DP to indicate a departure event, and FT to indicate a forced-termination event in Table B.1. Notation SU$_e(k)$ represents an SU$_e$ with k channels in this table. Similar notations apply to Tables B.2, B.3 and B.4 as well.

The average service rate per ongoing SU service, i.e., at which rate an ongoing SU service is processed on average, is defined as the capacity divided by the average number of ongoing SU services of the same type. Let μ_{ps} and μ'_{ps} be the average service rate per ongoing SU service of SU$_e$ and SU$_r$ respectively, shown as follows,

$$\mu_{ps} = \rho / \sum_{x\in\mathscr{S}} \sum_{k=W}^{V} j_k \pi(x); \quad \mu'_{ps} = \rho' / \sum_{x\in\mathscr{S}} g_a \pi(x) = \mu'_S. \tag{4}$$

B. CTMC Analysis for $D(a,W,V)$

The feasible states in this strategy can be expressed as $\mathscr{S} = \{(i, g_a, 0, ..., 0, j_V) | i + a g_a + V j_V < M\} \cup \{x \,| b(x) = M\}$. Tables B.2, B.3, and B.4 summarize the state transitions in this strategy.

Similar to the analysis for $S(a,W,V)$, the state probability of $\pi(x)$ can be obtained, and then, the system performance parameters can be computed. For $D(a,W,V)$, the capacity and the service rate per ongoing SU service share the same expressions as (2) and (4) respectively, whereas the blocking probability becomes,

$$\begin{aligned} P_b &= \sum_{\substack{x\in\mathscr{S}, \\ M-b(x)+\sum_{k=W+1}^{V}(k-W)j_k<W}} \pi(x); \\ P'_b &= \sum_{\substack{x\in\mathscr{S}, \\ M-b(x)+\sum_{k=W+1}^{V}(k-W)j_k<a}} \pi(x). \end{aligned} \tag{5}$$

Correspondingly, the forced-termination probability is obtained as

$$\begin{aligned} P_f &= \frac{R_f}{\lambda_S^*} = \sum_{\substack{x\in\mathscr{S}, b(x)=M, \\ j_W>0, i<M}} \frac{\lambda_P W j_W}{(M-i)\lambda_S^*} \pi(x); \\ P'_f &= \frac{R'_f}{\lambda_S'^*} = \sum_{\substack{x\in\mathscr{S}, b(x)=M, i<M, \\ j_r=0, \forall r>W}} \frac{\lambda_P a g_a}{(M-i)\lambda_S'^*} \pi(x), \end{aligned} \tag{6}$$

where $\lambda_S^* = (1-P_b)\lambda_S$, and $\lambda_S'^* = (1-P'_b)\lambda'_S$.

VI. ANALYSIS IN THE QUASISTATIONARY REGIME

In the QSR, it is assumed that the distribution of SU services reaches equilibrium between consecutive PU events, i.e., PU activities are so slow compared with the ones of SUs, where almost no forced SU termination happens[4]. Therefore, when

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[4] Forced-terminations will still occur but there will be, at most, one at each arrival of PU services. Because between two consecutive arrivals of PUs an infinitely large number of SU arrivals occur, the probability of forced termination is zero.

Table B.2: Transitions from a generic state $x = (i, g_a, j_W, \ldots, j_k, \ldots, j_V)$ of $D(a,W,V)$, $W \le k \le V$ when an SU service arrives

Activity	Destination state	Trans. rate	Conditions
SU$_e$ AR. Enough idle channels exist.	$(i,\ g_a,\ j_W,\ \ldots,\ j_k+1,\ \ldots,\ j_V)$	λ_S	$k = \min\{M-b(x), V\} \ge W$.
SU$_e$ AR. The SU$_e$ with the maximum number of channels, m, donates channel(s) to the newly arrived service.	$(i,\ g_a,\ j_W+1,\ \ldots,\ j_n+1,\ \ldots,\ j_m-1,\ \ldots,\ j_V)$	λ_S	$m = \max\{r \mid j_r > 0, W+1 \le r \le V\}$; $n = m - [W-(M-b(x))]$, $W \le n < m$; $V > W$.
SU$_e$ AR. Two SU$_e$s, m and h, donate channels.	$(i,\ g_a,\ j_W+2,\ \ldots,\ j_n+1,\ \ldots,\ j_h-1,\ \ldots,\ j_m-1,\ \ldots,\ j_V)$	λ_S	$m = \max\{r \mid j_r > 0, W+1 \le r \le V\}$; $h = \max\{r \mid j_r > 0, W+1 \le r \le m-1\}$ if $j_m = 1$, or $h = m$ if $j_m > 1$; $n = h+m-2W+M-b(x)$, $W \le n < h$; $V > W > 1$.
…	…	…	…
SU$_e$ AR. All SU$_e$s with more than W channels donate channel(s).	$(i,\ g_a,\ j_W+q,\ 0,\ \ldots,\ 0,\ j_n+1,\ 0,\ \ldots,\ 0)$	λ_S	$q = \sum_{m=W+1}^{V} j_m$; $n = \sum_{m=W+1}^{V} (m-W) j_m + M - b(x)$, $W \le n < \min\{r \mid j_r > 0, W+1 \le r \le V\}$; $V > W$.
SU$_r$ AR. Enough idle channels exist.	$(i,\ g_a+1,\ j_W,\ \ldots,\ j_k,\ \ldots,\ j_V)$	λ'_S	$M - b(x) \ge a$.
SU$_r$ AR. The SU$_e$ with the maximum number of channels, m, donates channel(s).	$(i, g_a+1, j_W, \ldots, j_n+1, \ldots, j_m-1, \ldots, j_V)$	λ'_S	$m = \max\{r \mid j_r > 0, W+1 \le r \le V\}$; $n = m - [a-(M-b(x))]$, $W \le n < m$; $V > W$.
SU$_r$ AR. Two SU$_e$s, m and h, donate channels.	$(i, g_a+1, j_W+1, \ldots, j_n+1, \ldots, j_h-1, \ldots, j_m-1, \ldots, j_V)$	λ'_S	$m = \max\{r \mid j_r > 0, W+1 \le r \le V\}$; $h = \max\{r \mid j_r > 0, W+1 \le r \le m-1\}$ if $j_m = 1$, or $h = m$ if $j_m > 1$; $n = h+m-W-a+M-b(x)$, $W \le n < h$; $V > W$; $a > 1$.
…	…	…	…
SU$_r$ AR. All SU$_e$s with more than W channels donate channel(s).	$(i, g_a+1, j_W+q-1, 0, \ldots, 0, j_n+1, 0, \ldots, 0)$	λ'_S	$q = \sum_{m=W+1}^{V} j_m$; $n = \sum_{m=W+1}^{V} (m-W) j_m + M - b(x) - a + W$, $W \le n < \min\{r \mid j_r > 0, W+1 \le r \le V\}$; $V > W$.

Table B.3: Transitions from a generic state $x=(i,g_a,j_W,\ldots,j_k,\ldots,j_V)$ of $D(a,W,V)$, $W\le k\le V$ when a PU service arrives

Activity	Dest. state	Trans. rate	Conditions
PU AR. At least an idle channel exists.	$(i+1,\, g_a,\, j_W,\, \ldots,\, j_k,\, \ldots,\, j_V)$	λ_P	$b(x)<M$.
PU AR. An SU$_e(k)$ is interrupted and reduces its channels.	$(i+1,\, g_a,\, j_W,\, \ldots,\, j_{k-1}+1,\, j_k-1,\, \ldots,\, j_V)$	$\frac{k\,j_k}{M-i}\lambda_P$	$b(x)=M$; $j_k>0, k>W$; $V>W$.
PU AR. FT in an SU$_e(W)$. No spectrum adaptation.	$(i+1,\, g_a,\, j_W-1,\, \ldots,\, j_k,\, \ldots,\, j_V)$	$\frac{W\,j_W}{M-i}\lambda_P$	$j_W=1$; $j_k=0$, $W+1\le k\le V-1$; $b(x)=M$; $W>1$. Or $j_W\ge 1$; $b(x)=M$; $W=1$. Or $j_W\ge 1$; $b(x)=M$; $W=V$.
PU AR. FT in an SU$_e(W)$ and releases channel(s). The SU$_e$ with the minimum number of channels, h, uses all the vacant channel(s).	$(i+1,\, g_a,\, j_W-1,\, \ldots,\, j_h-1,\, \ldots,\, j_l+1,\, \ldots,\, j_V)$	$\frac{W\,j_W}{M-i}\lambda_P$	$j_W>1$; $h=W$; $l=h+W-1\le V$; $V>W>1$; $b(x)=M$. Or $j_W=1$; $h=\min\{r\mid j_r>0, W+1\le r\le V-1\}$; $l=h+W-1\le V$; $V>W>1$; $b(x)=M$.
$\ldots$	$\ldots$	$\ldots$	$\ldots$
PU AR. FT in an SU$_e(W)$. All other SU$_e$s with fewer than V channels use the vacant channel(s) and achieve V.	$(i+1,\, g_a,\, 0,\, \ldots,\, 0,\, \ldots,\, 0,\, \ldots,\, j_V+q)$	$\frac{W\,j_W}{M-i}\lambda_P$	$b(x)=M$; $q=\sum_{m=W}^{V-1} j_m-1$; $V>W>1$; $W-1\ge\sum_{m=W}^{V-1}(V-m)\,j_m-(V-W)$.
PU AR. An SU$_r$ is interrupted and the SU$_e$ with the maximum number of channels, k, donates a channel.	$(i+1,\, g_a,\, j_W,\, \ldots,\, j_{k-1}+1,\, j_k-1,\, \ldots,\, j_V)$	$\frac{a g_a}{M-i}\lambda_P$	$b(x)=M$; $j_k>0$, $k=\max\{r\mid j_r>0, W+1\le r\le V\}$; $V>W$.
PU AR. FT in an SU$_r$. No spectrum adaptation.	$(i+1, g_a-1, j_W, \ldots, j_k, \ldots, j_V)$	$\frac{a g_a}{M-i}\lambda_P$	$b(x)=M$; $a=1$; $g_a\ge 1$; $j_r=0$, $W+1\le r\le V$. Or $b(x)=M$; $j_k=0$, $W\le k\le V$; $g_a\ge 1$; $V>W$. Or $g_a\ge 1$; $b(x)=M$; $W=V$.
PU AR. FT in an SU$_r$ and releases channel(s). An SU$_e(W)$ uses all the vacant channel(s).	$(i+1, g_a-1, j_W-1, \ldots, j_k+1, \ldots, j_V)$	$\frac{a g_a}{M-i}\lambda_P$	$b(x)=M$; $a>1$; $g_a\ge 1$; $j_r=0$, $W+1\le r\le V$; $j_W\ge 1$; $k=a+W-1\le V$; $V>W$.
$\ldots$	$\ldots$	$\ldots$	$\ldots$
PU AR. FT in an SU$_r$. All SU$_e$s use the vacant channel(s) and achieve V.	$(i+1,\, g_a-1,\, 0,\, \ldots,\, 0,\, \ldots,\, 0,\, \ldots,\, j_V+q)$	$\frac{a g_a}{M-i}\lambda_P$	$b(x)=M$; $a>1$; $g_a\ge 1$; $j_r=0$, $W+1\le r\le V$; $q=j_W\ge 1$; $a-1\ge j_W(V-W)$; $V>W$.

Table B.4: Transitions from a generic state $x = (i, g_a, j_W, \ldots, j_k, \ldots, j_V)$ of $D(a,W,V)$, $W \leq k \leq V$ upon a service departure for both PU and SU services

Activity	Dest. state	Trans. rate	Conditions
PU DP. An SU$_e(k)$ uses the vacant channel.	$(i-1,\ g_a,\ j_W,\ \ldots,\ j_k-1,\ j_{k+1}+1, \ldots, j_V)$	$i\mu_P$	$j_k > 0$, $k = \min\{r \mid j_r > 0, W \leq r \leq V-1\}$; $i > 0$; $V > 1$.
PU DP. SU$_e$s cannot use the vacant channel.	$(i-1, g_a, j_W, \ldots, j_k, \ldots, j_V)$	$i\mu_P$	$j_k = 0$, $W \leq k < V$; $i > 0$. Or $W = V$; $i > 0$.
SU$_e$(k) DP. Other SU$_e$s, if exist, cannot use the vacant channel(s).	$(i, g_a, j_W, \ldots, j_k - 1, \ldots, j_V)$	$k j_k \mu_S$	$j_k = 1, k < V$; $j_m = 0, \forall m < V$ and $m \neq k$; $V > W$. Or $j_k > 0$, $k = V$; $j_m = 0$, $\forall m < V$; $V > W$. Or $j_k > 0$, $k = W = V$.
SU$_e(k)$ DP. The SU$_e$ with the minimum number of channels, h, uses all the vacant channel(s).	$(i, g_a, j_W, \ldots, j_h - 1, \ldots, j_k - 1, \ldots, j_l + 1, \ldots, j_V)$	$k j_k \mu_S$	$j_k > 1$; $h = \min\{r \mid j_r > 0, W \leq r \leq V-1\}$; $l = k+h \leq V$; $V > W$. Or $j_k = 1$; $h = \min\{r \mid j_r > 0, r \in \{W, \ldots, k-1, k+1, \ldots, V-1\}\}$; $l = k+h \leq V$; $V > W$.
…	…	…	…
SU$_e(k)$ DP. All other SU$_e$s with fewer than V channels use the vacant channel(s) and achieve the upper bound, V.	$(i,\ g_a,\ 0,\ \ldots,\ 0,\ \ldots,\ 0,\ \ldots,\ j_V + q)$	$k j_k \mu_S$	$q = \sum_{m=W}^{V-1} j_m - 1$; $V > W$; $k \geq \sum_{m=W}^{V-1} (V-m) j_m - (V-k)$.
SU$_r$ DP. Other SU$_e$s, if exist, cannot use the vacant channel(s).	$(i, g_a - 1, j_W, \ldots, j_k, \ldots, j_V)$	$g_a \mu_S'$	$g_a \geq 1$; $j_m = 0$, $\forall m < V$; $V > W$. Or $g_a \geq 1$, $W = V$.
SU$_r$ DP. The SU$_e$ with the minimum number of channels, h, uses all the vacant channel(s).	$(i,\ g_a - 1,\ j_W,\ \ldots,\ j_h - 1,\ \ldots,\ j_l + 1, \ldots, j_V)$	$g_a \mu_S'$	$g_a \geq 1$; $h = \min\{r \mid j_r > 0, W \leq r \leq V-1\}$; $l = a + h \leq V$; $V > W$.
…	…	…	…
SU$_r$ DP. All other SU$_e$s with fewer than V channels use the vacant channel(s) and achieve the upper bound, V.	$(i, g_a - 1, 0, \ldots, 0, \ldots, j_V + q)$	$g_a \mu_S'$	$g_a \geq 1$; $q = \sum_{m=W}^{V-1} j_m$; $V > W$; $a \geq \sum_{m=W}^{V-1} (V-m) j_m$.

i PU services exist in the system, $M-i$ channels are available and these channels are, in a sense, dedicated for SU services. Then, the state probability of the system can be expressed as the combination of the state probability in two Markov chains, which represent PU and SU activities, respectively. Let $\pi(\phi,i)$ be the state probability of the system, where i denotes the number of PU services and ϕ represents the corresponding state for SU services, which might be multi-dimensional for a particular strategy. Then, we have $\pi(\phi,i)=\pi(\phi|i)\pi(i)$, where $\pi(i)$ is the state probability of having i PU services, and $\pi(\phi|i)$ is the conditional probability of state ϕ, which represents SU services, given i PU services. In the QSR, $\pi(\phi|i)$ can be calculated as the probability of state ϕ given $M-i$ channels dedicated for SUs.

In general, the state probability of PU services, $\pi(i)$, can be derived from an $M+1$-state birth and death process (BDP) with $\pi(i)=(\frac{\lambda_P}{\mu_P})^i\frac{1}{i!}\left[\sum_{k=0}^{M}(\frac{\lambda_P}{\mu_P})^k\frac{1}{k!}\right]^{-1}$.

To calculate $\pi(\phi|i)$ in this regime, we *only* need to consider the events of SU services, given $M-i$ dedicated channels. For a given i, state ϕ contains two types of SU services, and its transitions and the corresponding rates are also illustrated in Tables B.1-B.4, with PU events ignored. In the following discussion, we focus on special cases when only *one* type of SU traffic exists in the network, in which the closed-form expressions can be further derived. We use capacity as an example but other performance parameters can also be derived in a similar way. We start from the case without real-time traffic.

Proposition 1 *In the QSR, the capacity of SU_es for the dynamic strategy when real-time traffic does not exist is given as follows,*

$$\rho_e^d=\left[1-\sum_{i=0}^{M}\pi(I|i)\pi(i)\right]\lambda_S, \tag{7}$$

where

$$\pi(j|i)=\begin{cases}\left(\frac{\lambda_S}{V\mu_S}\right)^j\frac{\pi(0|i)}{j!}, & \forall\, 1\le j\le C,\\ \left(\frac{\lambda_S}{Q\mu_S}\right)^j\frac{Q^C}{V^C}\frac{\pi(0|i)}{C!}, & \forall\, C<j\le I,\end{cases} \tag{8}$$

$$\pi(0|i)=\left[\sum_{j=0}^{C}\left(\frac{\lambda_S}{V\mu_S}\right)^j\frac{1}{j!}+\sum_{j=C+1}^{I}\left(\frac{\lambda_S}{Q\mu_S}\right)^j\frac{Q^C}{V^C C!}\right]^{-1}. \tag{9}$$

In addition, $Q=M-i$, $I=\left\lfloor\frac{Q}{W}\right\rfloor$, and $C=\left\lfloor\frac{Q}{V}\right\rfloor$.

The proof is deferred to Appendix A. More detailed inspection of the proof reveals that the expression for the capacity in the dynamic strategy given in (7) can actually be applied to a broader class of strategies which exhibit the following common features: 1) ongoing SU$_e$s will always occupy as many idle channels as they are able to; 2) if there are fewer than W idle channels upon an SU$_e$ arrival, ongoing SU$_e$s will donate their occupied channels to the newcomer, as long as $N \geq W$ is still satisfied for all SU$_e$s after donating.

Proposition 2 *In the QSR, the capacity of SU$_e$s for the static strategy when real-time traffic does not exist is upper bounded by ρ_e^{su},*

$$\rho_e^{su} = \sum_{i=0}^{M}\left(\sum_{j=1}^{C} jV\mu_S\pi(j|i)\pi(i) + Q\mu_S\psi_i\pi(C+1|i)\pi(i)\right), \tag{10}$$

where $\psi_i = \left\lfloor \frac{Q-CV}{W} \right\rfloor$ indicates whether the state with $C+1$ services exists ($\psi_i = 1$) or not ($\psi_i = 0$) for a given i, and the $\pi(j|i)$ is calculated as follows. If $Q-CV < W$, $\pi(j|i) = (\frac{\lambda_S}{V\mu_S})^j\frac{1}{j!}\left[\sum_{k=0}^{C}(\frac{\lambda_S}{V\mu_S})^k\frac{1}{k!}\right]^{-1}$. Otherwise, $\pi(j|i)$ is given by Eqs. (8) and (9) using $I = C+1$.

The proof is shown in Appendix B. Note that, although the closed-form capacity is not available in this strategy, we are still able to calculate its value through its CTMC model in the QSR.

Now, we consider the case without elastic SU traffic, and the following result is derived.

Proposition 3 *In the QSR, the capacity of SU$_r$s when elastic traffic does not exist is,*

$$\rho_r = \sum_{i=0}^{M}\sum_{j=0}^{\lfloor (M-i)/a \rfloor} j\mu_S'\pi(j|i)\pi(i), \tag{11}$$

where $\pi(j|i) = (\frac{\lambda_S'}{\mu_S'})^j\frac{1}{j!}\left[\sum_{k=0}^{\lfloor (M-i)/a \rfloor}(\frac{\lambda_S'}{\mu_S'})^k\frac{1}{k!}\right]^{-1}$.

The mathematical proof of this result is similar to Proposition 1 when $W = V = a$. Hence, we do not show the detailed proof to save space.

VII. NUMERICAL RESULTS AND DISCUSSIONS

In this section, the obtained numerical results under different conditions are presented. In Section VII-A, the performance of the investigated strategies with pure elastic SU traffic is illustrated. In Section VII-B, we observe the results when both types of SU traffic co-exist. Furthermore, the results in the QSR are plotted in comparison with the results from the original CTMC models in Section VII-C, and the results under diverse traffic distributions are illustrated in Section VII-D.

In order to verify the mathematical models, the simulation results obtained from a custom-built MATLAB simulator together with the analytical results are plotted in Figs. B.1–B.5. In these figures, the solid lines represent the analytical results while the marks are obtained from simulations. From these curves, we can observe that the simulation results precisely coincide with the analytical results. Therefore, the correctness of the mathematical analysis is validated.

The simulations are conducted as follows. Each round of the simulation is performed for 10 000 time units. Each time unit, denoted as T, is further divided into n subintervals each with duration h, i.e., $T = nh$, where h is the minimum unit in this simulation and it is configured sufficiently small so that the probability of simultaneous events is ignorable. Then the probability that exactly one PU, SU$_e$, or SU$_r$ arrival occurs in each subinterval is $\lambda_P h$, $\lambda_S h$, or $\lambda'_S h$, and the probability of no arrival is $1-\lambda_P h$, $1-\lambda_S h$, or $1-\lambda'_S h$ respectively. The lengths of PU and SU services are integer times of h, following exponential distributions with parameters corresponding to various services. For an ongoing PU service, after each h, the integer will decrease by one, which means that part of this PU service has elapsed. The same principle applies to SU$_r$. However, for an ongoing SU$_e$ with N channels, after each h, the integer will decrease by N because the service rate will increase N times. In each subinterval, the events of both PUs and SUs are checked and processed according to the employed strategy. The service is considered as finished when this integer number reaches zero. In the end of each simulation, the statistics of the system can be calculated. For example, the capacity is obtained from the total number of successful SU services averaged by the total simulated time units.

A. Performance Illustration with Pure Elastic SU Traffic

Because only SU$_e$s will contribute to the system performance with channel assembling, we first examine the cases where only SU$_e$s exist in the secondary network first. In this subsection, ρ, P_b, P_f, and μ_{ps} are plotted in Figs. B.1–B.4 respectively, given $M = 6$, $\lambda'_S = 0$, $\lambda_S = 1.5$, $\mu_S = 0.82$, and $\mu_P = 0.5$. In the labels of strategies in these figures, a is not given a specific value because SU$_r$s do not exist. In order to compare the effects of different threshold values, we plot two groups of results for each strategy: 1) $W = 1$ and $V = 3$ and 2) $W = 3$ and $V = 6$. The results of *NA* are also illustrated for the comparison purpose.

1) System Capacity:

As shown in Fig. B.1, the system capacity of SU$_e$s decreases for all strategies with an increasing λ_P, because SUs get fewer chances to start their services when

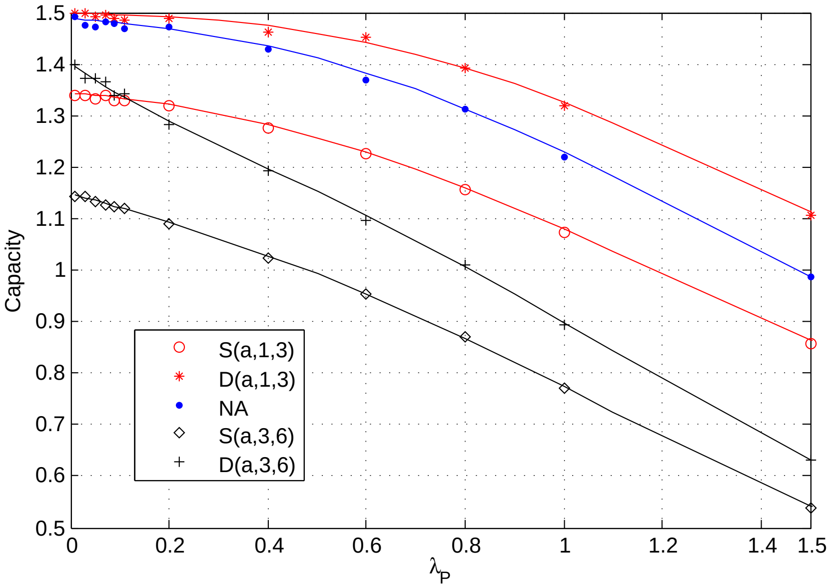

Figure B.1: System capacity as a function of λ_P for pure elastic SU traffic.

PUs become more active. Interestingly, most of the channel-assembling strategies do not perform better than *NA* does, except $D(a,1,3)$. The advantage of *NA* is because that a larger number of parallel services, i.e., j_k in (2), could contribute to system capacity significantly. Dynamic strategies achieve higher capacity than static ones with the same parameter configuration. Comparing the group $W = 1$, $V = 3$ with $W = 3$, $V = 6$, the results in the former group for each strategy are better than the corresponding results in the latter group. The reason is that in the latter group, the strategies require at least three vacant channels out of a total number of six channels in order to start an SU service, leading to wasted spectrum opportunities compared with the strategies in the former group.

2) Blocking Probability:

Fig. B.2 depicts the blocking probability of SUs. One can observe that $D(a,1,3)$ has the lowest blocking probability because it needs only one channel for initiating an SU service and can dynamically adjust the number of assembled channels upon different events. Similarly, *NA* has the second lowest blocking probability as compared with the other strategies. Comparing the group $W = 1$, $V = 3$ with $W = 3$, $V = 6$, the blocking probability is generally higher in the latter group. The reason is straightforward because more channels are required in the latter case before a service request can be accepted.

3) Forced-Termination Probability:

To examine the forced-termination probability of the commenced SU services, we plot P_f in Fig. B.3. As expected, P_f becomes higher for all strategies as λ_P

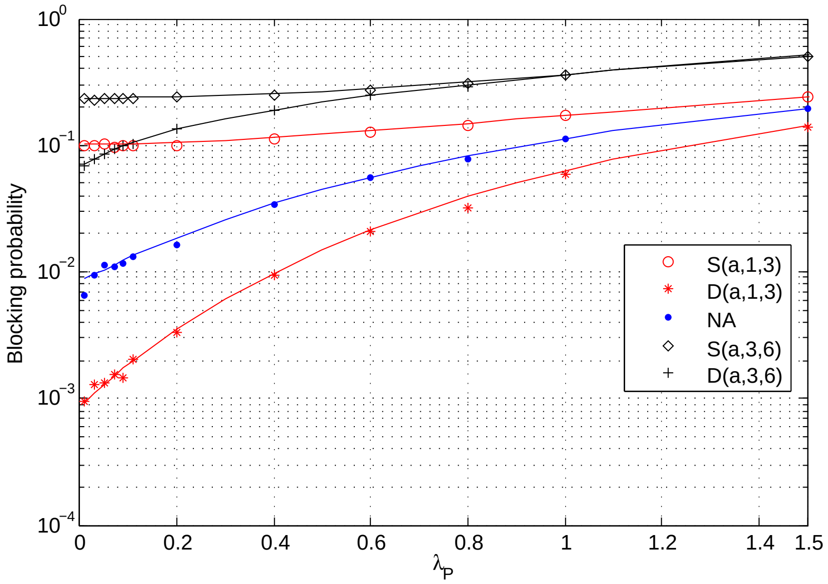

Figure B.2: Blocking probability as a function of λ_P for pure elastic SU traffic.

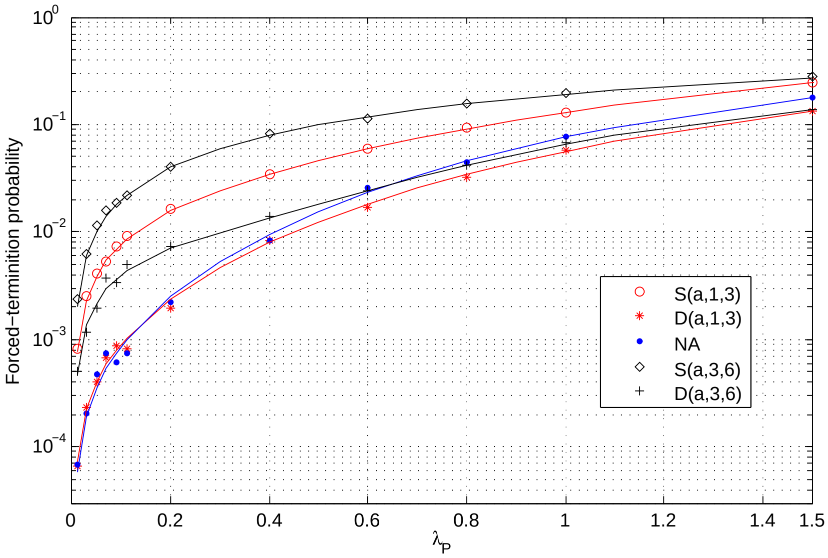

Figure B.3: Forced-termination probability as a function of λ_P for pure elastic SU traffic.

increases because PUs become more active. The forced-termination probability in *NA* is not as good as that of the $D(a,1,3)$, and increases even higher than that of $D(a,3,6)$ when λ_P is large. It means that a lower P_f could be achieved if an appropriate strategy and suitable threshold values are selected. For the static strategies, because they will assemble multiple channels and the number of assembled channels is not adjustable, services would be more likely forced to terminate than the dynamic cases.

4) Average Service Rate per Ongoing SU Service:

Fig. B.4 illustrates the average service rate per ongoing SU service, i.e., μ_{ps}. This value indicates the rate that an ongoing SU service will be processed on average. As illustrated in this figure, the larger the number of channels an SU service assembles, the higher the average service rate per ongoing service a strategy can achieve. For *NA*, the μ_{ps} value does not change with different λ_P values because each SU service occupies only one channel all the time thus $\mu_{ps} = \mu_S$, whereas the other curves decline as λ_P increases.

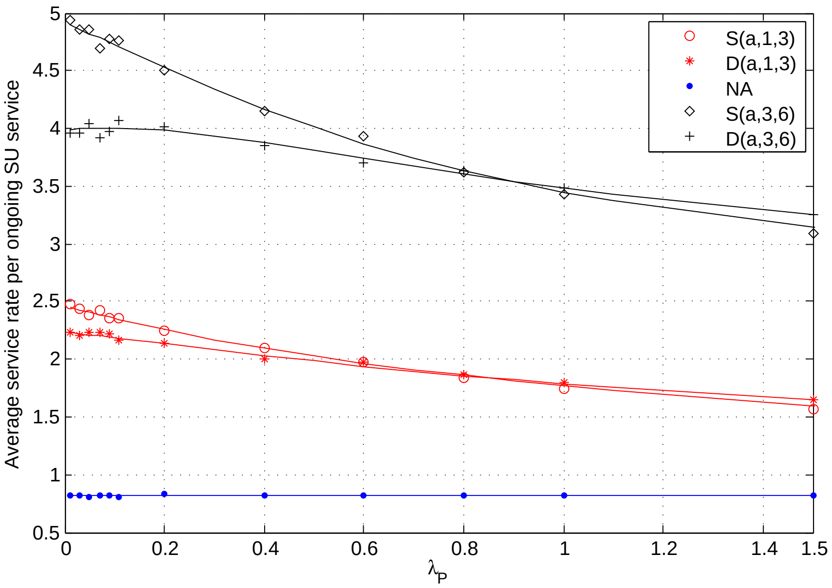

Figure B.4: Average service rate per ongoing SU service as a function of λ_P for pure elastic SU traffic.

It is worth mentioning that μ_{ps} shown in Fig. B.4 is the average service rate per ongoing SU service, which is different from the total average service rate for SU services, i.e., capacity, ρ, shown in Fig. B.1. As can be observed from (4), μ_{ps} is equal to the capacity value, ρ, divided by the average number of ongoing SU services, meaning that a strategy with a larger μ_{ps} value does not necessarily lead to higher capacity. For example, $S(a,3,6)$ has the highest μ_{ps}; however, the lowest capacity when λ_P is small, as observed in Fig. B.1. The reason is that with a small λ_P the forced termination probability and the blocking probability for this strategy are higher than those of other strategies. Indeed we observe in our simulations a much lower average number of ongoing SU services in the system with this strategy, even though each ongoing SU service occupies more channels.

B. Performance Illustration with Heterogenous Traffic

In Fig. B.5, it is illustrated the achieved capacity of the strategies in the presence of heterogenous traffic. We adopt $a = 1$, $\lambda'_S = 1$ and $\mu'_S = 0.6$ for the real-time traffic

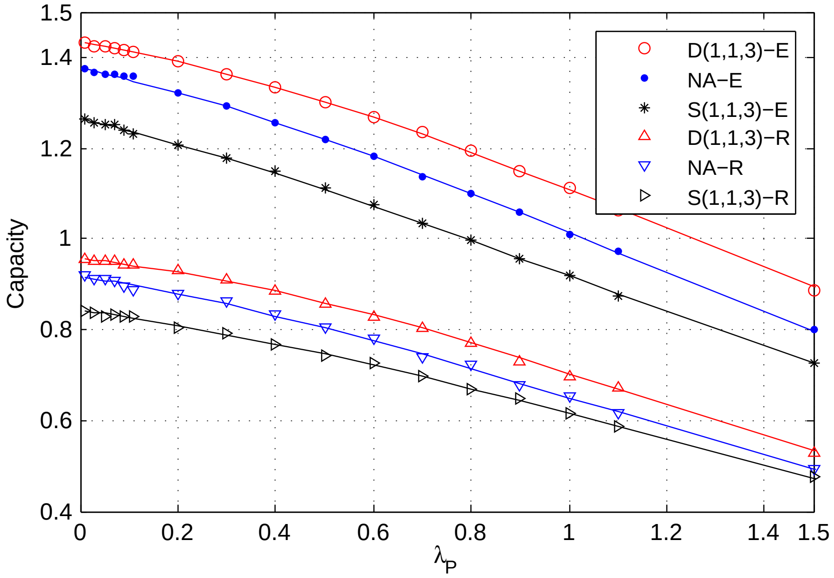

Figure B.5: Capacity as a function of λ_P for heterogeneous traffic. In this figure, *E* indicates elastic traffic while *R* denotes real-time traffic.

and utilize the same parameter for PUs and SU$_e$s as in the previous subsection. From Fig. B.5, one can observe that the capacity for SU$_e$s of all these strategies is lower than the one shown in Fig. B.1 because the resource is shared with real-time traffic. Compared with *NA*, the dynamic strategy achieves higher capacity in both SU$_e$ and SU$_r$, which means that the advantage of channel assembling in SU$_e$s is shared among these two traffic types. In contrast, the static ones cannot provide any benefit in terms of capacity. The advantage of the dynamic channel-assembling strategy is also observed in all other performance parameters however not shown here due to page limit. The main observation here is that the benefit of channel assembling using the dynamic strategy is obvious and the advantage obtained by SU$_e$ is shared with real-time flows. However, the static strategy has poorer performance than *NA* except when μ_{ps} is investigated.

C. Performance in the QSR

In Fig. B.6, the results from the analytical models in the QSR and those from the precise models developed in Section V, are illustrated. In this subsection, we introduce a scaler, f, to reflect the dynamics of PU activities while keeping the offered load constant for both PU and SU services, as $\lambda_P = 1 \times f$, $\mu_P = 0.5 \times f$, $\lambda'_S = 0$, $\lambda_S = 1.5$, $\mu_S = 0.82$, and $M = 6$.

As illustrated in Fig. B.6, when $f \ll 1$, meaning that the service time of PUs is quite long, whereas the arrival rate is low, i.e., PUs sporadically appear, and PU services are long lasting, the system capacity deduced from the precise models fits the results in the QSR well. When f becomes larger, as $1 < f < 10^3$, meaning

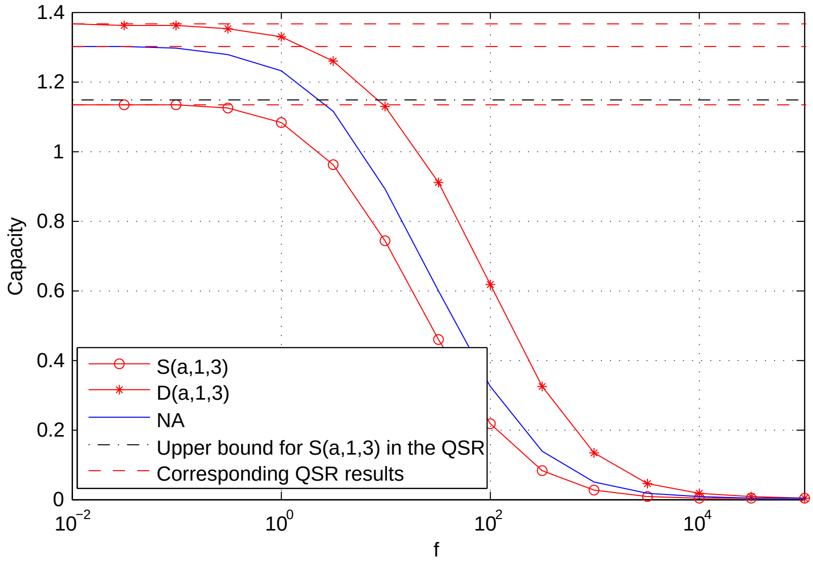

Figure B.6: System capacity as a function of f. The dynamic behavior of PU activities is represented by a traffic intensity scale f. The results in the QSR of $D(a,1,3)$ is calculated based on (7), and that of *NA* is also achieved by the same equation given $V = W = 1$. The upper bound for $S(a,1,3)$ in the QSR is plotted according to (10), while its precise capacity in the QSR is calculated through its CTMC model in this regime.

that PUs are more dynamic, the capacity obtained from the precise models deviates much more from the corresponding results in the QSR, due to the fact that more SU connections are abruptly terminated by PUs. Moreover, when f becomes even larger as $f > 10^4$, the capacity is close to zero for all the investigated strategies, because PUs are so active such that SU services cannot survive from preemption.

Not surprisingly, the dynamic strategy has again achieved the best performance when comparing the results in the QSR among different strategies, followed by the one without channel assembling. Moreover, the static strategy has lower capacity than its upper bound given by (10) in the QSR, confirming Proposition 2.

D. Traffic Pattern with Various Distributions

In our previous discussions, Poisson arrival and exponentially distributed service time are assumed. In real life, however, the traffic patterns might be quite different from those ones. This observation triggers our motivation to further investigate the applicability and the preciseness of our Markov-chain-based analytical models, by applying the same simulation programs mentioned earlier to diverse PU and SU traffic distributions.

As an example, Fig. B.7 illustrates the forced-termination probability of two sample strategies with pure elastic SU traffic, i.e., *NA* and $D(a,1,3)$ as a function

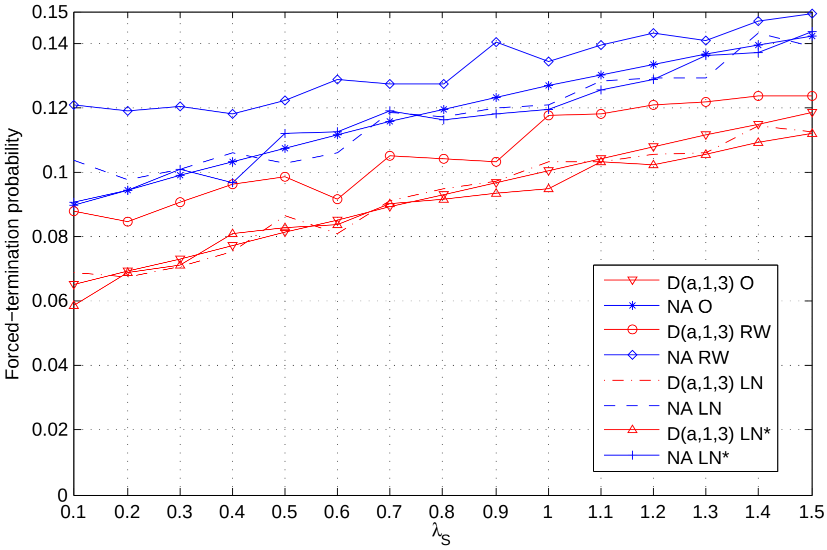

Figure B.7: Forced-termination probability as a function of λ_S when various distributions are utilized.

of λ_S, under two traffic models based on real-life traffic observations [20, 19]. For traffic pattern 1, Poisson arrival and log-normal distributed service time for both PU and SU services are utilized. Within this traffic type, we consider further two cases. The first case is that both the mean values and the variances of the log-normal distributions equal to those of the corresponding original exponential distributions, labeled *LN*. The other case is that the variance values of log-normal distributions are greater than those of the original exponential distributions while the mean values are kept the same, labeled LN^*. The reason for using larger variance values in LN^* is that it can model more precisely the traffic in modern data networks where high variability has been observed in flow sizes [20]. More specifically, we adopt a squared coefficient of variation SCV=4.618 [20] (SCV= variance/mean^2). For traffic pattern 2, a random-walk model for PU activities [19], and Poisson arrival and log-normal distributed service time for SU services are adopted, labeled *RW*. For the log-normal distribution of SU service time used in this case, we make the mean value and the variance equal to those of the original exponential distribution. The results from the original distributions in our mathematical models are also plotted for comparison purpose, labeled as *O*.

From this figure, we can observe that the results of *LN* and LN^* are quite close to the analytical ones, which reveals the fact that these results are not sensitive to the distribution type of service time as long as Poisson arrival is kept. Moreover, although the results under *RW* do not coincide with the analytical results precisely, those curves still exhibit similar results to a large extent. Other simulation results with different parameter configurations, even though not explicitly illustrated here, yield also similar results. Therefore, the results under different traffic models are comparatively close to the ones obtained based on Poisson arrival and exponential service time distributions. These observations demonstrate that although different distributions exist, the mathematical analysis presented in this paper can be adopted as a robust reference model for analyzing the performance of channel-assembling strategies in CRNs.

In more details, Fig. B.7 are obtained as follows. There are altogether $M = 6$ channels and the SU service rate is $\mu_S = 0.5$ in the original exponential service time distribution. For equal comparison, we set $\lambda_P = 0.5$ and $\mu_P = 0.15601$ in the original distributions for PUs. This configuration gives three PU-occupied channels in the system on average, which is equal to the average number of PU-occupied channels in the random-walk model [19]. Then the average time interval between two PU events in the random-walk model, τ, is computed as $\tau = 1/(2\mu_P E) = 1.0683$, where $E = 3$ is the average number of PU-occupied channels.

E. Further Discussions

Consider channel allocation from a contrary perspective in which an SU service requires less than one channel, i.e., one or several subchannels within one ordinary channel. In this case, known as channel splitting, more SU services can be accommodated in a system given the assumption that SU services may be provided based on one or multiple subchannels. In the QSR, because idle channels are in a sense dedicated for SUs, the same analysis as illustrated in Section VI can be applied to channel splitting on a subchannel basis. However, without the QSR assumption, the arrival of one PU service may influence multiple SU services and the analysis will then become more sophisticated.

Finally, to make our channel-assembling strategies smarter, the lower and upper bounds, i.e., W and V, can be adjusted dynamically according to different parameters. For example, the value of V in $D(a,1,3)$ can be tuned according to the arrival rate of PUs. As shown in Fig. B.1, when λ_P is less than 0.1, the performance of *NA* and $D(a,1,3)$ is quite close to each other. Therefore, $V = 1$, i.e., *NA* is recommended because it can achieve similar capacity without employing complicated channel-assembling algorithm. When λ_P becomes larger, however, $V = 3$ will be selected in order to achieve better performance. In real life, a measurement-based estimation of the arrival intensities can be utilized to feed our analytical models for parameter calculations so that W and V can be adjusted accordingly on the fly.

VIII. CONCLUSION

In this paper, channel-assembling approaches represented by the two proposed strategies in multichannel CRNs have thoroughly been investigated, considering heterogeneous SU traffic types, and their performance is evaluated and compared with each other and with the legacy no assembling strategy through both mathematical analyses and simulations. The numerical results demonstrate that the dynamic strategy can achieve better performance than the strategy without assembling does in the investigated cases. For the static strategy, however, its overall performance is poorer than the no-channel-assembling case except one aspect, i.e., a higher average service rate per ongoing SU service. Therefore, we would recommend the dynamic strategy as the most appropriate alternative for channel assembling in multichannel CRNs.

APPENDIX A
PROOF OF PROPOSITION 1

Proof Without SU$_r$s, g_a can be eliminated from ϕ. However, $\phi = (j_W, \ldots, j_V)$ may still be multidimensional for a given i. In the follow discussion, we will first map the process for SU services from a multidimensional Markov chain into a BDP as shown in Fig. B.8 for a given i, and then calculate the capacity based on the BDP.

Consider all states of SU services for a given i. Let us rearrange these states according to the number of ongoing SU services that these states have, i.e., using an integer pair (r,l) to represent a state, where r denotes the number of ongoing SU services and l represents a particular state among all the states with r SU services. Let $L(r)$ be the number of states that have r SU services; therefore, we have $l \in \{1, \ldots, L(r)\}$. Let $\pi'(r,l)$ be the corresponding state probability. Denote $|\phi|$ as the number of ongoing SU services at state ϕ. For a generic state ϕ, say, the lth state with $|\phi| = r$ SU services, where $r \in \{1, \ldots C-1\}$, the balance equation can be expressed as:

$$(\lambda_S + rV\mu_S)\pi^{'}(r,l) = \sum_{n=1}^{L(r-1)} P_{r-1,n,l}\lambda_S\pi^{'}(r-1,n) + \sum_{n=1}^{L(r+1)} P'_{r+1,n,l}(r+1)V\mu_S\pi^{'}(r+1,n), \tag{12}$$

where $P_{r-1,n,l}$ is the probability from state $(r-1,n)$ to state (r,l) upon an SU arrival whereas $P'_{r+1,n,l}$ is the probability from state $(r+1,n)$ to state (r,l) upon an SU departure. $P_{r-1,n,l}$ and $P'_{r+1,n,l}$ represent different ways of access upon an event in this strategy. Note that $\sum_{m=1}^{L(r)} P_{r-1,n,m} = 1$ and $\sum_{m=1}^{L(r)} P'_{r+1,n,m} = 1$. If we sum up all these equations of states with r SU services, the left-hand side can be expressed as a common factor of outgoing rates by the sum of the probabilities of the states with r SU services. Similarly, on the right-hand side, the transitions indicating SU arrivals share the common factor λ_S whereas the transitions indicating SU departures share the same $rV\mu_S$. Consequently, the following equation holds,

$$(\lambda_S + rV\mu_S)\sum_{l=1}^{L(r)}\pi^{'}(r,l) = \lambda_S \sum_{n=1}^{L(r-1)} \pi^{'}(r-1,n) + (r+1)V\mu_S \sum_{n=1}^{L(r+1)} \pi^{'}(r+1,n). \quad (13)$$

If we regard the sum of the probabilities of all states that satisfy $|\phi| = r$ as a whole, (13) is the same as the balance equation for the state with r services in the BDP as shown in Fig. B.8. Therefore, the sum of the probabilities of all states with $|\phi| = r$ can be regarded as one state probability with r services in the corresponding BDP. Similar analysis applies to $r \in \{C, \ldots I\}$. To calculate the capacity, knowing the sum of the probability of the states that have the same number of SU services given i PU services is sufficient, because the service rates are identical for all these states.

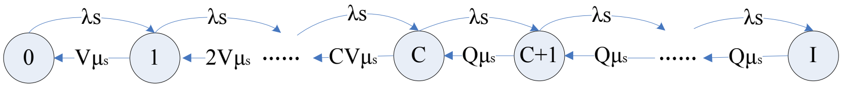

Figure B.8: The birth and death process of SU services for a given i.

The state probability for the BDP for a given i is derived as shown in Eqs. (8) and (9). Considering all possible i, the blocking probability for SU services becomes $P_b = \sum_{i=0}^{M} \pi(I|i)\pi(i)$. Because capacity can be represented by the completed SU services over time, i.e., the commenced and survived (not forced to terminate) ones among all arrivals, we have $\rho = (1-P_b)(1-P_f)\lambda_S$. Considering $P_f = 0$ in this regime, the capacity can be expressed as shown in (7).

APPENDIX B
PROOF OF PROPOSITION 2

Proof Without SU$_r$s, g_a can be eliminated from ϕ. Therefore, $\phi = (j_W, \ldots, j_V)$. In the static strategy, since ongoing SU services cannot adjust the number of their channels, the states that have the same number of ongoing SU services may have different assembled service rates given i PU services. Let us label all states satisfying $|\phi| = r$ in two dimensions as (r,l), indicating the lth state which has r SU services. For a generic state (r,l), denote $b(r,l)$ as the number of channels that all ongoing SU services assemble at state (r,l), i.e., $b(r,l) = \sum_{k=W}^{V} k j_k$ for $(r,l) \Leftrightarrow (j_W, \ldots, j_k, \ldots, j_V)$. Then the balance equation for (r,l) can be expressed as

$$
\begin{aligned}
(\lambda_S + b(r,l)\mu_S)\pi'(r,l) = \sum_{n=1}^{L(r-1)} P_{r-1,n,l}\lambda_S \pi'(r-1,n) \\
+ \sum_{n=1}^{L(r+1)} P'_{r+1,n,l} b(r+1,n)\mu_S \pi'(r+1,n),
\end{aligned} \tag{14}
$$

where $\pi'(r,l)$, $L(r)$, $P_{r-1,n,l}$, and $P'_{r+1,n,l}$ have the same definition as in Appendix A.

Let $m(r) = \max_l(b(r,l))$. Summing up all the balance equations for states with $|\phi| = r$, we have (15).

$$
\begin{aligned}
&\mu_S\left(m(r) - \frac{\sum_{l=1}^{L(r)}(m(r)-b(r,l))\pi'(r,l)}{\sum_{l=1}^{L(r)}\pi'(r,l)}\right)\sum_{l=1}^{L(r)}\pi'(r,l) + \lambda_S\sum_{l=1}^{L(r)}\pi'(r,l) \qquad (15)\\
&= \mu_S\left(m(r+1) - \frac{\sum_{l=1}^{L(r+1)}(m(r+1)-b(r+1,l))\pi'(r+1,l)}{\sum_{l=1}^{L(r+1)}\pi'(r+1,l)}\right)\sum_{l=1}^{L(r+1)}\pi'(r+1,l)\\
&+ \lambda_S\sum_{n=1}^{L(r-1)}\pi'(r-1,n).
\end{aligned}
$$

Consider the service rate for states with r services on the top half of (15). Clearly, $m(r) \leq rV$, i.e., $m(r)$ is less than or equal to the maximum number that r SU services can utilize. Note that $\frac{\sum_{l=1}^{L(r)}(m(r)-b(r,l))\pi'(r,l)}{\sum_{l=1}^{L(r)}\pi'(r,l)}$ is non-negative. Therefore $\left(m(r) - \frac{\sum_{l=1}^{L(r)}(m(r)-b(r,l))\pi'(r,l)}{\sum_{l=1}^{L(r)}\pi'(r,l)}\right) \leq rV$. The service rate on the bottom half of the equation, i.e., the one corresponds to states with $r+1$ services, follows the same principle. Consequently, for the state with r SU services in the BDP based on the static strategy, the service rate will not be higher than the maximum service rate achieved among all the states with r services in the static strategy. Let the service rates for all states with r services be equal to the maximum possible service rate, i.e., $b(r,l) = m(r)$, the capacity can be derived in closed form, as shown in (10). With a service rate in each state for the static strategy lower than or an equal to the one shown in (10), the capacity, i.e., the average number of SUs that can be served at a time unit, will be upper bounded by ρ_e^{su}.

REFERENCES

[1] Y. -C. Liang, K. -C. Chen, G. Y. Li, and P. Mähönen, "Cognitive radio networking and communications: An overview", *IEEE Trans. Veh. Technol.,* vol. 60, no. 7, pp. 3386-3407, Sep. 2011.

[2] B. Hamdaoui and K. G. Shin, “OS-MAC: An efficient MAC protocol for spectrum-agile wireless networks,” *IEEE Trans. Mobile Comput.,* vol. 7, no. 8, pp. 915-930, Aug. 2008.

[3] Q. Chen, Y. -C. Liang, M. Motani, and W. -C. Wong, “A two-level MAC protocol strategy for opportunistic spectrum access in cognitive radio networks”, *IEEE Trans. Veh. Technol.,* vol. 60, no. 5, pp. 1-23, Jun. 2011.

[4] S. Huang, X. Liu, and Z. Ding, “Optimal transmission strategies for dynamic spectrum access in cognitive radio networks,” *IEEE Trans. Mobile Comput.,* vol. 8, no. 12, pp. 1636-1648, Nov. 2009.

[5] H. Su and X. Zhang, “Channel-hopping based single transceiver MAC for cognitive radio networks,” in *Proc. IEEE CISS,* Princeton, NJ, USA, Mar. 2008, pp. 197-202.

[6] H. Su and X. Zhang, “Cross-Layer based opportunistic MAC protocols for QoS provisionings over cognitive radio mobile wireless networks,” *IEEE J. Select. Areas Commun.,* vol. 26, no. 1, pp. 118-129, Jan. 2008.

[7] Y. Yuan, P. Bahl, R. Chandra, P. A. Chou, J. I. Ferrell, T. Moscibroda, S. Narlanka and Y. Wu, “KNOWS: Cognitive radio networks over white spaces,” in *Proc. IEEE DySPAN,* Dublin, Ireland, Apr. 2007, pp. 416-427.

[8] IEEE 802.22 WG, *IEEE Standard for Wireless Regional Area Networks Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands,* IEEE Standard, July 2011.

[9] J. Jia, Q. Zhang, and X. Shen, “HC-MAC: A hardware-constrained cognitive MAC for efficient spectrum management,” *IEEE J. Select. Areas Commun.,* vol. 26, no. 1, pp. 106-117, Jan. 2008.

[10] H. A. B. Salameh, M. M. Krunz, and O. Younis, “MAC protocol for opportunistic cognitive radio networks with soft guarantees,” *IEEE Trans. Mobile Comput.,* vol. 8, no. 10, pp. 1339-1352, Oct. 2009.

[11] A. C. Hsu, D. S. L. Wei, and C. -C. J. Kuo, “A cognitive MAC protocol using statistical channel allocation for wireless ad-hoc networks,” in *Proc. IEEE WCNC,* Hong Kong, China, Mar. 2007, pp. 105-110.

[12] P. K. Tang, and Y. H. Chew, "On the modeling and performance of three opportunistic spectrum access schemes," *IEEE Trans. Veh. Technol.,* vol. 59, no. 8, pp. 4070-4078, Oct. 2010.

[13] X. R. Zhu, L. F. Shen, and T. -S. P. Yum, "Analysis of cognitive radio spectrum access with optimal channel reservation," *IEEE Commun. Lett.,* vol. 11, no. 4, pp. 304-306, Apr. 2007.

[14] J. Martinez-Bauset, V. Pla, and D. Pacheco-Paramo, "Comments on 'Analysis of cognitive radio spectrum access with optimal channel reservation'," *IEEE Commun. Lett.,* vol. 13, no. 10, pp. 739, Oct. 2009.

[15] E. W. M. Wong, and C. H. Foh, "Analysis of cognitive radio spectrum access with finite user population," *IEEE Commun. Lett.,* vol. 13, no. 5, pp. 294-296, May 2009.

[16] L. Jiao, V. Pla, and F. Y. Li, "Analysis on channel bonding/aggregation for multi-channel cognitive radio network," in *Proc. European Wireless,* Lucca, Italy, Apr. 2010, pp. 468-474.

[17] J. Lee, and J. So, "Analysis of cognitive radio networks with channel aggregation," in *Proc. IEEE WCNC,* Sydney, Australia, Apr. 2010, pp. 1-6.

[18] L. Jiao, F. Y. Li, and V. Pla, "Dynamic channel aggregation strategies in cognitive radio networks with spectrum adaptation," in *Proc. IEEE GLOBECOM,* Houston, TX, USA, Dec. 2011, pp. 1-6.

[19] D. Willkomm, S. Machiraju, J. Bolot, and A. Wolisz, "Primary users behavior in cellular networks and implications for dynamic spectrum access," *IEEE Commun. Mag.,* vol. 47, no. 3, pp. 88-95, Mar. 2009.

[20] P. Barford and M. Crovella, "Generating representative Web workloads for network and server performance evaluation," in *Proc. ACM SIGMETRICS*, Madison, WI, USA, Jul. 1998, pp. 151-160.

Paper C

Title:	Capacity Upper Bound of Channel Assembling in Cognitive Radio Networks with Quasistationary Primary User Activities
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Capacity Upper Bound of Channel Assembling in Cognitive Radio Networks with Quasistationary Primary User Activities

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Abstract — **In cognitive radio networks with multiple channels, various channel assembling strategies may be applied to secondary users, resulting in different achieved capacity. However, there is no previous work on determining the capacity upper bound of channel assembling for secondary users under given system configurations. In this paper, we derive the capacity upper bound for cognitive radio networks with channel assembling through Markov chain modeling when PU activities are relatively static compared with SU services. We first deduce a closed-form capacity upper bound expression of a dynamic channel assembling strategy, and then demonstrate that no other channel assembling strategy can provide higher capacity than the one achieved by this dynamic strategy.**

Keywords—Cognitive radio networks, channel assembling, capacity upper bound, continuous time Markov chain models, quasistationary regime.

I. INTRODUCTION

Spectrum access schemes in cognitive radio networks (CRNs) [1] can be classified into two categories. The first category is without channel assembling (ChA), i.e., secondary users (SUs) treat each channel as an individual channel [2]. The other one is to assemble several channels together as one channel in order to support SU services with a higher data rate [3, 4, 5]. ChA has been proposed by many MAC protocols.

In general, there are two types of ChA strategies, i.e., *dynamic* strategies in which spectrum adaptation is enabled and *static* strategies where only spectrum

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handover is allowed. As explained in [6], the meaning of spectrum adaptation is twofold. Firstly, it is inherited from spectrum handover, which allows SUs to switch an ongoing SU service to a vacant channel that is not occupied by PUs or SUs, if it exists, when a PU activity appears on the current channel. Secondly, it is meant that ongoing SU services can adaptively adjust the number of assembled channels according to the availability of channels as well as other SUs' activities. Without spectrum adaptation, the number of assembled channels for an ongoing SU service cannot be changed once it is started.

Although ChA has been widely utilized in MAC protocols and studied by mathematical modeling [7, 8, 6], how much benefit in terms of capacity a secondary network can achieve *at most* with ChA is still unknown. Capacity here is defined as the average number of service completions per time unit in a secondary network. In this work, we derive a closed form expression for the theoretical capacity upper bound (UB) of a secondary network with ChA in the quasistationary regime (QSR) based on Markov modeling. In the QSR, it is assumed that PUs appear sporadically and PU services are long-lasting compared with SU services. The motivation to study the capacity UB in the QSR is that the requirement of relatively static PUs has been identified as one of the conditions that lead to the successful deployment of CRNs [9]. Furthermore, many existing MAC protocols, for example, [3, 10], have been designed under this condition. As a continuation of our previous work in [6], the capacity UB of a dynamic ChA strategy is derived in the QSR in this study and it is demonstrated thereafter that the capacity of any other strategies will not be higher than this UB in the same regime. Continuous time Markov chain (CTMC) models are utilized for the UB derivation. Note that the derived UB is attainable, and as a result of the mathematical proof, the conditions that a strategy should meet to achieve this UB are obtained.

The rest of the paper is organized as follows. In Sec. II, the system model is described. In Sec. III, a dynamic ChA strategy used for the UB derivation is proposed and its capacity UB is calculated in the QSR. The fact that the capacity of a general strategy cannot be higher than the derived capacity UB is unveiled in Sec. IV, followed by numerical results and further discussions in Sec. V. Finally, we conclude the paper in Sec. VI.

II. SYSTEM MODEL

Consider two types of radios, PUs and SUs, operating in the same spectrum with $M \in \mathbb{N}^+$ non-overlapping channels for PUs, where $\mathbb{N}^+$ denotes a set of positive natural numbers. The channels can be utilized by SUs only if they are not occupied by PUs. PUs are not aware of the existence of SUs and can access the spectrum at any time. When any PU arrives, SUs must release their channel occupancy immediately. Each PU occupies only one channel. However, SUs may assemble multiple channels for one service transmission. The assembled channels can be either adjacent or separated in the spectrum domain.

We assume that there is a protocol with ignorable overhead to support ChA and spectrum adaptation. By utilizing spectrum sensing [11], SUs can detect PU activities efficiently. Assume further that the sensing and spectrum adaptation latency is much shorter than the duration between two consecutive service events. It is thus clear that the arrival or departure of services will not happen during the sensing and spectrum adaptation period.

As discussed in [6], only elastic traffic, i.e., the traffic type that its service rate will be increased if multiple channels are assembled, can get benefit in terms of capacity by employing ChA. Therefore, we consider elastic traffic type only in this paper. Denote by W and V the minimum number and the maximum number of assembled channels in order to support a single SU service respectively, where $1 \leq W \leq V \leq M$, and $W, V \in \mathbb{N}^{+}$. In this expression, $W \geq 1$ means that a service needs at least one channel, and $V \leq M$ means that at most M channels can be assembled by one SU service. In what follows, by selecting a proper strategy and tuning W and V, we will derive the highest possible capacity for a secondary network in the QSR when ChA is employed.

III. STRATEGY DESCRIPTIONS AND ITS CTMC MODEL ANALYSIS

As mentioned above, two categories of ChA strategies exist, i.e., dynamic or static ones. The characteristic of a dynamic strategy with spectrum adaptation is that the number of assembled channels for ongoing SU services can be adjusted. However, in a static strategy, the number of assembled channels cannot be changed any longer once a service is started. In what follows, we will propose a dynamic strategy, which is different from the dynamic ones proposed in [6, 8], in order to derive the theoretical capacity UB of CRNs with ChA.

A. A Strategy with Full Adaptation and Full Channel Sharing

A dynamic strategy, referred to as full adaptation and full sharing strategy (FAFS), is proposed in this subsection. The strategy has the following properties: all the ongoing SU services will always utilize as many channels as possible and they will *always equally* share[1] the available channels. Once channels become idle due to a PU or SU service completion or an SU service forced termination, the remaining

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[1] To enable this equally sharing, an ongoing SU service is allowed to assemble non-integer number of channels, as long as the number is in between of W and V.

Table C.1: Transitions from a generic state $x = (i, j)$ for FAFS.

Activity	Dest. state	Tran. rate	Conditions
PU arrival, no SU forced termination	$(i+1, j)$	λ_P	$i < M$ and $M-i-1 \geq jW$.
PU arrival, an SU forced termination	$(i+1, j-1)$	λ_P	$i < M$ and $M-i-1 < jW$.
PU departure	$(i-1, j)$	$i\mu_P$	$i > 0$.
SU arrival	$(i, j+1)$	λ_S	$M-i \geq (j+1)W$.
SU departure	$(i, j-1)$	$\min(M-i, jV)\mu_S$	$j > 0$.

ongoing SU services will equally share these channels. When a new SU service arrives, it will be allowed to commence if the number of assembled channels per SU service is not less than W after the new arrival. Correspondingly, when a PU service arrives, ongoing SU services will continue their services but reduce the number of occupied channels as long as at least W channels are kept for each ongoing SU service after the PU service arrival. However, one ongoing SU service will be forced to terminate if and only if the average number of assembled channels is less than W for ongoing SU services after the PU appearance.

In the following, we develop CTMCs to model this strategy by assuming that the arrivals of both SU and PU services follow Poisson process with rates λ_S and λ_P respectively. Correspondingly, the service times are exponentially distributed with service rates μ_S and μ_P in *one* channel. Assume further that all channels are homogeneous with the same data rate. Therefore, the service rate of an SU service with N assembled channels is $N\mu_S$. The unit for service rate is services/time unit. Given concrete values for these parameters, the capacity can be expressed in kbps or Mbps. For this reason, the unit of capacity is not explicitly expressed in our analysis.

B. The Precise CTMC Model for FAFS

Let i be the number of ongoing PU services and j be the number of ongoing SU services. The state in the Markov chain of FAFS can be expressed as (i, j), and the transitions from state (i, j) are shown in Table C.1. Based on these transitions, global balance equations can be established. Then the steady state probability, $\pi(i, j)$, can be calculated based on the balance and the normalization equations. The capacity of the secondary network based on the precise model, ρ_p, i.e., the average number of SU service completions per time unit [12], is given by

$$\rho_p = \sum_{i=0}^{M} \sum_{j=1}^{\lfloor (M-i)/W \rfloor} \min(M-i, jV)\mu_S \pi(i, j). \tag{1}$$

C. The CTMC in the QSR for FAFS

In the QSR, the distribution of SU services reaches equilibrium between consecutive PU events, i.e., PU activities are so slow that forced SU termination is negligible. Therefore, when i PU services exist, there are $M-i$ channels available and those channels are in a sense dedicated to SU services. Then, the state probability of the system can be expressed by utilizing the state probabilities in $M+2$ irreducible Markov chains presenting PUs and SUs respectively.

Let $\pi(i,j)=\pi(j|i)\pi(i)$ be the state probability of the system. The process of PUs can be modeled as an Erlang-B model, with state probability $\pi(i)$, as

$$\pi(i)=(\frac{\lambda_P}{\mu_P})^i\frac{1}{i!}\left[\sum_{k=0}^{M}\left(\frac{\lambda_P}{\mu_P}\right)^k\frac{1}{k!}\right]^{-1},0\le i\le M. \tag{2}$$

In the QSR, the number of ongoing SU services with $M-i$ dedicated channels (there are i ongoing PU services) can be modeled by a birth and death process (BDP) as shown in Fig. C.1, where $Q=M-i$, $I=\left\lfloor\frac{Q}{W}\right\rfloor$ and $C=\left\lfloor\frac{Q}{V}\right\rfloor$. In this process, the service rate of the rth state is $rV\mu_S$ when $r\le C$ and $Q\mu_S$ when $r>C$. Fig. C.2 illustrates an example from the system point of view in the QSR, given $W=1$, $V=2$, and $M=3$ respectively. The column on the left-hand side indicates the Erlang-B model for PUs. The right-hand side of the figure illustrates the BDPs for SUs given different instantaneous values of i. For example, if there is one PU service, the corresponding SU process is modeled in the second row in Fig. C.2, where $I=2$ and $C=1$.

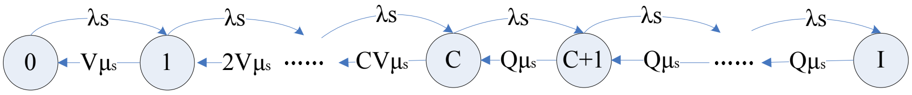

Figure C.1: BDP for SU services given $M-i$ dedicated channels.

With the balance equations, i.e., $\lambda_S\pi(0|i)$=$V\mu_S\pi(1|i)$, …, $\lambda_S\pi(I-1|i)$=$Q\mu_S\pi(I|i)$, of the BDPs in Fig. C.1, together with $\sum_{\forall j\in\{0,\ldots,I\}}\pi(j|i)=1$, the state probability is derived as

$$\pi(0|i)=\left[\sum_{j=0}^{C}\left(\frac{\lambda_S}{\mu_S}\right)^j\frac{V^{-j}}{j!}+\sum_{j=C+1}^{I}\left(\frac{\lambda_S}{\mu_S}\right)^j Q^{C-j}\frac{V^{-C}}{C!}\right]^{-1},$$

$$\pi(j|i)=\begin{cases}(\lambda_S/\mu_S)^j V^{-j}(j!)^{-1}\pi(0|i), & \forall\, 1\le j\le C,\\ (\lambda_S/\mu_S)^j Q^{C-j}V^{-C}(C!)^{-1}\pi(0|i), & \forall\, C<j\le I.\end{cases}$$

Note that the sum of the right-hand expressions in the above balance equations is the capacity of SUs given i PU services. This capacity can be expressed as

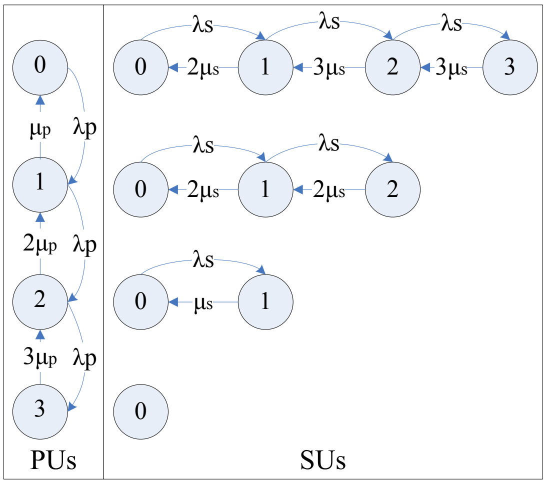

Figure C.2: An exemplary CTMC model in the QSR for FAFS when $W = 1$, $V = 2$, and $M = 3$.

$[1 - \pi(I|i)]\lambda_S$, i.e., the sum of the left-hand expressions in the balance equations. Therefore the total capacity in the QSR, ρ_q can be expressed as

$$\rho_q = \sum_{i=0}^{M} \pi(i)\,[1 - \pi(\lfloor (M-i)/W \rfloor\,|i)]\,\lambda_S. \tag{3}$$

In what follows, we give two propositions to acquire the capacity UB of FAFS in the QSR.

D. Capacity UB Calculation

Consider a general BDP with $K+1$ states, where the transition rate from the mth to the $(m+1)$th state (arrival rate), $m \in \{1, \ldots, K\}$, is λ, and the transition rate from the $(n+1)$th to the nth state (service rate), $n \in \{1, \ldots, K\}$ is μ_n. Define the average service rate of this process, i.e., capacity, by $\rho' = \sum_{i=1}^{K} \pi_i \mu_i$, where π_i is the state probability of the ith state.

Proposition 1 *With fixed Markov chain length and arrival rate, the average service rate of the BDP, ρ', will increase monotonically if μ_i increases, $\forall i \in \{1, \ldots, K\}$.*

The proof is deferred to Appendix A. Proposition 1 tells us that with fixed chain length $K+1$ and arrival rate, ρ' is maximized if the service rate for each state is maximized. Applying this proposition into the model described in Sec. III-C, with fixed I, ρ' will increase when C decreases, and it will reach its maximum value when $C = 0$, i.e., $V = M$. Note that $V = M$ indicates that an SU system utilizes all available channels with just one ongoing SU service.

Proposition 2 *The average service rate of the BDP will increase if one state (denoted as state $K+1$) is added after the last state (denoted as state K), and the* *service rate that corresponds to the newly added state,* μ_{K+1}*, satisfies* $\mu_{K+1} \geq \max\{\mu_i\}, i \in \{1,\ldots,K\}$.

The proof is deferred to Appendix B. This proposition tells us that higher ρ' can be possibly achieved if the Markov chain becomes longer with corresponding service rate not lower than any of the previous service rates in the chain. Applying this proposition into the model described in Sec. III-C, it indicates that higher ρ' can be possibly achieved if I is larger, i.e., W is smaller. Therefore, with fixed C, the maximum average service rate is achieved when $W = 1$.

From Proposition 2, we can also conclude that blocking new arrivals of SU services in order to protect ongoing SU service cannot get benefit in terms of maximizing capacity since the number of ongoing SU services in the system will be lower, i.e., the chain length is reduced.

Considering the results from both Propositions 1 and 2, the highest ρ' is achieved when $W = 1$ and $V = M$ for the BDP for any given i. Note that ρ' is, indeed, the capacity of SUs given i PU services. For various i which corresponds to different BDPs for SUs, the same principle applies. Therefore, we can conclude that the capacity of this strategy achieves its UB when $W = 1$ and $V = M$ in the QSR.

The above obtained capacity UB is derived from a specific dynamic strategy, i.e., FAFS. In the next section, we will show the relationship of any other strategies to FAFS, and further state that no other strategy can achieve higher capacity than the above mentioned UB.

IV. CAPACITY OF GENERAL STRATEGIES IN THE QSR

For FAFS with $W = 1$ and $V = M$, for a given i, it achieves the maximum chain length, i.e., $M - i + 1$, and the maximum service rate, i.e., $(M - i)\mu_S$, for each state except state zero in the BDP. For any other strategy, by transforming its states from its own state space which might be multi-dimensional into a single dimension, i.e., finding its equivalent BDP, we can compare this BDP with the BDP based on FAFS in order to check the optimality. By arguing that the chain length and the corresponding service rates in the equivalent BDP of *any other* strategy cannot be longer than $M - i + 1$ and higher than $(M - i)\mu_S$, $\forall i \in \{0,\ldots,M\}$, we conclude that the derived UB based on FAFS is also the UB for any type of strategy.

Clearly, for any strategy with given M and i, the number of ongoing SU services cannot exceed $\lfloor (M - i)/W \rfloor$ and this number achieves its maximum value, i.e., $M - i$, when $W = 1$. This means that the maximum chain length of the equivalent BDP represented by the number of ongoing SU services in the system cannot exceed $M - i + 1$ for any strategy. Note that this maximum chain length, i.e., $M - i + 1$, is achieved by FAFS when $W = 1$. Therefore, the chain length of a general strategy cannot be longer than the one achieved by FAFS with $W = 1$, given the same values for M and i. To conclude finally that (3) gives the capacity UB, we only need to check the service rate of the equivalent BDP in a general strategy.

Denote by (i, ϕ) a general state of a general strategy, where i is the number of PU services while ϕ represents the state for SU services, which might be in multiple dimensions. The state probability of (i, ϕ) can be expressed as $\pi(i, \phi) = \pi(\phi|i)\pi(i)$, where $\pi(i)$ is given by (2). In the QSR, with i ongoing PU services, $\pi(\phi|i)$ can be calculated by modeling the SU services with $M - i$ dedicated channels.

Consider a state of SU services, ϕ, for a general strategy with $M - i$ dedicated channels. Denote by $|\phi|$ the number of ongoing SU services at state ϕ. Let us re-arrange the states of SU services according to the number of ongoing SU services, i.e., using an integer pair (r, l) to represent a state, ϕ, where r denotes the number of its ongoing SU services in state ϕ and l represents a particular state among all the states that have r SU services. Let $L(r)$ be the number of states that have r SU services. We have $l \in \{1, \ldots, L(r)\}$. Let $\pi'(r, l)$ be the state probability of (r, l). Furthermore, let $\zeta_r(l, l')$ be the transition rate from state (r, l) to state (r, l'), $1 \leq l, l' \leq L(r)$, $l \neq l'$, considering that in a general strategy the channel allocation for SU services can vary even without arrivals or departures of PU or SU services. For a general state, say, the lth state with r SU services, denote $b(r, l)$ as the total number of channels that all ongoing SU services assemble at state (r, l). Then the balance equation for the lth state with r services can be expressed as:

$$\begin{aligned}
&(\lambda_S + b(r,l)\mu_S)\pi'(r,l) + \pi'(r,l) \sum_{l'=1, l' \neq l}^{L(r)} \zeta_r(l,l') = \sum_{n=1}^{L(r-1)} P_{r-1,n,l}\lambda_S \pi'(r-1,n) + \\
&\sum_{n=1}^{L(r+1)} P'_{r+1,n,l} b(r+1,n)\mu_S \pi'(r+1,n) + \sum_{l'=1, l' \neq l}^{L(r)} \pi'(r,l')\zeta_r(l',l), \qquad (4)
\end{aligned}$$

where $P_{r-1,n,l}$ represents the probability of transition from state $(r-1, n)$ to state (r, l) upon an SU arrival while $P'_{r+1,n,l}$ is the probability of transition from state $(r+1, n)$ to state (r, l) upon an SU departure. $P_{r-1,n,l}$ and $P'_{r+1,n,l}$ represent different ways of access upon an event in a specific strategy. Note that $\sum_{m=1}^{L(r)} P_{r-1,n,m} = 1$ and $\sum_{m=1}^{L(r)} P'_{r+1,n,m} = 1$.

Let $g(r) = \max_l(b(r,l))$. If we sum up all these equations of states with r SU services, the following equation holds,

$$\lambda_S \sum_{l=1}^{L(r)} \pi'(r,l) + \sum_{l=1}^{L(r)} \pi'(r,l) \sum_{l'=1,l'\neq l}^{L(r)} \zeta_r(l,l') + \mu_S \left(g(r) - \frac{\sum_{l=1}^{L(r)} (g(r)-b(r,l))\,\pi'(r,l)}{\sum_{l=1}^{L(r)} \pi'(r,l)} \right) \sum_{l=1}^{L(r)} \pi'(r,l)$$
$$= \lambda_S \sum_{n=1}^{L(r-1)} \pi'(r-1,n) + \sum_{l=1}^{L(r)} \sum_{l'=1,l'\neq l}^{L(r)} \pi'(r,l')\zeta_r(l',l)$$
$$+ \mu_S \left(m(r+1) - \frac{\sum_{l=1}^{L(r+1)} (m(r+1)-b(r+1,l))\,\pi'(r+1,l)}{\sum_{l=1}^{L(r+1)} \pi'(r+1,l)} \right) \sum_{l=1}^{L(r+1)} \pi'(r+1,l). \tag{5}$$

Clearly,

$$\sum_{l=1}^{L(r)} \pi'(r,l) \sum_{l'=1,l'\neq l}^{L(r)} \zeta_r(l,l') = \sum_{l=1}^{L(r)} \sum_{l'=1,l'\neq l}^{L(r)} \pi'(r,l')\zeta_r(l',l). \tag{6}$$

Consequently,

$$\lambda_S \pi''(r) + \mu_S \left(g(r) - \frac{\sum_{l=1}^{L(r)} (g(r)-b(r,l))\,\pi'(r,l)}{\pi''(r)} \right) \pi''(r) \tag{7}$$
$$= \lambda_S \pi''(r-1) + \mu_S \left(m(r+1) - \frac{\sum_{l=1}^{L(r+1)} (m(r+1)-b(r+1,l))\,\pi'(r+1,l)}{\pi''(r+1)} \right) \pi''(r+1),$$

where $\pi''(r) = \sum_{l=1}^{L(r)} \pi'(r,l)$.

Now (7) has the same format as the balance equation of the rth state in a BDP. Look at the part that corresponds to the service rate for states with r services on the top half of (7). Since $\frac{\sum_{l=1}^{L(r)}(g(r)-b(r,l))\pi'(r,l)}{\pi''(r)}$ is non-negative, $\left(g(r) - \frac{\sum_{l=1}^{L(r)}(g(r)-b(r,l))\pi'(r,l)}{\pi''(r)}\right) \leq g(r)$ holds. Similarly, the part which represents the service rate on the bottom half of the equation, i.e., the one that corresponds to states with $r+1$ services, follows the same observation. Apparently, $g(r) \leq M-i$. Therefore, for any ChA strategies, their corresponding SU service rates in their equivalent BDPs are *lower than or equal to* the service rate of the BDP in FAFS with $W=1$ and $V=M$, i.e., $(M-i)\mu_S$. Recall that the chain length will not be longer than that in FAFS given $W=1$ and $V=M$, i.e., the number of ongoing SU services cannot be larger than $M-i$. Based on Propositions 1 and 2, we ascertain that for any strategy with any integer W and V values, its capacity in the QSR will not exceed the capacity in (3) for FAFS when $W=1$ and $V=M$.

Moreover, from (7), we have $\frac{\sum_{l=1}^{L(r)}(g(r)-b(r,l))\pi'(r,l)}{\pi''(r,l)} = 0$ when $b(r,l) = g(r)$, $\forall l \in \{1,\ldots,L(r)\}$, meaning that the maximum service rate, i.e., $(M-i)\mu_S$, is achievable if $b(r,l) = g(r) = M - i$, $\forall l \in \{1,\dots,L(r)\}$. Therefore, if there exists a strategy that fits the following two requirements, the UB derived from FAFS can also be achieved by such a strategy. The first requirement is that the length of the equivalent BDP can reach $M - i + 1$, $\forall i \in \{0,\dots,M\}$. The other requirement is that for any $i \in \{0,\dots,M\}$, each of its states with r services is able to utilize $M - i$ channels, i.e., $b(r,l) = M - i$, $\forall l \in \{1,\dots,L(r)\}$, and $\forall r \in \{1,\dots,M - i\}$. Exemplary strategies rather than FAFS are the dynamic strategies with $W = 1$ and $V = M$ presented in [6, 8]. Note that only dynamic strategies can meet these requirements, since ongoing SU services must be able adjust their assembled channels in order to always utilize all channels not occupied by PUs. For static strategies, since ongoing SU services cannot adjust the numbers of their channels, the states that have the same number of ongoing SU services may have different aggregated service rates, thus resulting in a lower overall service rate in the corresponding BDP.

Finally, it is worth mentioning that in the above analyses, $W \geq 1$ is a prerequisite, i.e., an SU service will utilize at least one channel. More generally, if $W < 1$ is allowed, meaning that an SU service may be accommodated with a portion of one channel and that the simultaneous ongoing SU services can be larger than M, the capacity UB in the QSR will become larger because the chain length of the corresponding BDP is longer. The capacity UB expression in this case anyhow has the same form as (3) in the QSR.

V. NUMERICAL RESULTS AND FURTHER DISCUSSIONS

We illustrate the capacity UB with given parameters in the QSR in Fig. C.3. The relationship between the capacity values derived based on the precise models and the ones in the QSR is presented in the same figure. More specifically, we plot the numerical results of typical strategies, i.e., FAFS with different W and V, an exemplary static strategy [6], and the strategy without ChA for comparison. To represent the dynamic feature of PU activities, we introduce a scaler, f, to reflect the dynamic of PU activities while keeping the offered load constant for both PUs and SUs, as $\lambda_P = 1 \times f$, $\mu_P = 0.5 \times f$, $\lambda_S = 1.5$, and $\mu_S = 0.82$ given $M = 6$. As can be observed from Fig. C.3, the capacity UB in the QSR, i.e., 1.3658, is achieved by FAFS $1 \leq N \leq 6$ with $f \ll 1$, followed by FAFS $1 \leq N \leq 3$ with value 1.3635 in the same regime. The static strategy and the one without ChA achieve lower capacity in the QSR.

The relationship between the capacity values in the QSR and the results from the precise models can be observed as f varies. When $f \ll 1$, meaning that PUs appear sporadically and PU services are long-lasting, the capacity values from the precise models fit the results in the QSR well. When f becomes larger, meaning that PUs become dynamic, the capacity values from the precise models deviate more and more from the quasistationary results, due to the fact that more and more SU connections are interrupted as PUs become more active. Note that although a formal mathematical proof that the capacity under any strategy increases when the dynamic of PUs is scaled down is not available, the claim is intuitively true and it is further backed up by the above numerical results. Therefore, we conjecture that the UB obtained in the QSR also applies to a general case when PU activities are dynamic.

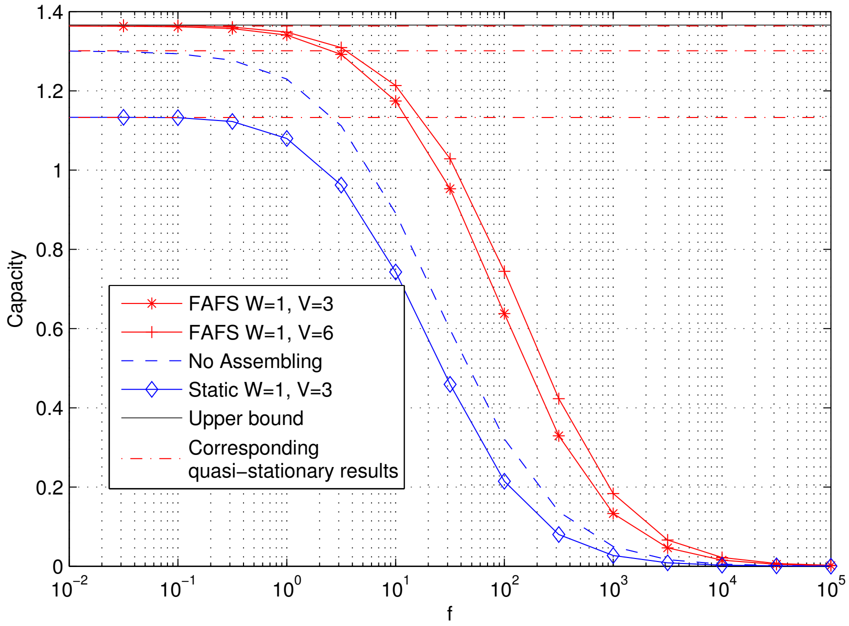

Figure C.3: Capacity of various channel assembling strategies as a function of f.

VI. CONCLUSION

In this paper, a closed-form capacity upper bound in the QSR using ChA in CRNs is developed through CTMC modeling. That is, given λ_P, λ_S, μ_P and μ_S, the capacity with ChA in CRNs cannot be higher than the value given by (3) with V being the maximum number of channel ($V = M$) and W being the lowest possible value ($W = 1$ if $W \in \mathbb{N}^+$) in the QSR, regardless which kind of assembling strategy is adopted.

APPENDIX A

Proof As discussed in Sec. III-C, $\rho' = (1-\pi_K)\lambda$ in the QSR. In the following, we show that π_K decreases with an increasing μ_i, $i \in \{1,\dots,K\}$.

From the system balance equations, we have $\pi_k = \prod_{i=1}^{k}(\lambda/\mu_i)\pi_0$, $k \in \{1,\dots,K\}$. Consider the state with k services, $k \in \{1,\dots,K\}$, we have

$$\begin{aligned}1 &= \sum_{i=0}^{K}\pi_i = \left[1+\sum_{i=1}^{K}\prod_{j=1}^{i}\left(\frac{\lambda}{\mu_j}\right)\right]\pi_0 = \left[1+\sum_{i=1}^{k-1}\prod_{j=1}^{i}\left(\frac{\lambda}{\mu_j}\right)+\left(\frac{\lambda}{\mu_k}\right)\sum_{i=k}^{K}\prod_{j=1,j\neq k}^{i}\left(\frac{\lambda}{\mu_j}\right)\right]\pi_0\\ &= [A+\lambda/\mu_k B]\pi_0,\end{aligned} \tag{8}$$

where $A = 1+\sum_{i=1}^{k-1}\prod_{j=1}^{i}(\lambda/\mu_j)$ and $B = \sum_{i=k}^{K}\prod_{j=1,j\neq k}^{i}(\lambda/\mu_j)$. We can solve (8) for π_0. Note that

$$\begin{aligned}\pi_K &= \left[\prod_{j=1}^{k-1}(\lambda/\mu_j)\times(\lambda/\mu_k)\times\prod_{j=k+1}^{K}(\lambda/\mu_j)\right]\pi_0 = \lambda/\mu_k\prod_{j=1,j\neq k}^{K}(\lambda/\mu_j)[A+(\lambda/\mu_k)B]^{-1}\\ &= \frac{\lambda\prod_{j=1,j\neq k}^{K}(\lambda/\mu_j)}{A\mu_k+B\lambda}.\end{aligned} \tag{9}$$

It is obvious that (9) is a monotonically decreasing function of μ_k. Therefore, the average service rate will increase as μ_k increases monotonically.

APPENDIX B

Proof As discussed in Sec. III-C, $\rho' = (1-\pi_K)\lambda$ in the QSR. Therefore, we need only to compare probability π_K in the process before we add the new state and probability $\hat{\pi}_{K+1}$ in the process after the new state is appended. If the proposition is true, $\pi_K \geq \hat{\pi}_{K+1}$ must be satisfied, or equivalently,

$$\frac{1}{1+\sum_{i=1}^{K}\prod_{j=1}^{i}\frac{\lambda}{\mu_j}} \geq \frac{\frac{\lambda}{\mu_{K+1}}}{1+\sum_{i=1}^{K}\prod_{j=1}^{i}\frac{\lambda}{\mu_j}+\prod_{j=1}^{K+1}\frac{\lambda}{\mu_j}}. \tag{10}$$

Obviously, Inequality (10) always holds if $\lambda/\mu_i \leq 1$. Now consider $\lambda/\mu_i > 1$. Let $P_k = \prod_{i=1}^{k}(\lambda/\mu_i)$. Then Inequality (10) becomes

$$1+P_1+\ldots+P_K \geq \frac{\lambda}{\mu_{K+1}}(1+P_1+\ldots+P_{K-1})$$

which can be rewritten as

$$1+\left(P_1-\frac{\lambda}{\mu_{K+1}}\right)+\left(P_2-P_1\frac{\lambda}{\mu_{K+1}}\right)\ldots+\left(P_K-P_{K-1}\frac{\lambda}{\mu_{K+1}}\right)\geq 0. \tag{11}$$

Since $\mu_{K+1} \geq \max\{\mu_i\}, i \in \{1,\ldots,K\}$, therefore $P_1 \geq \lambda/\mu_{K+1}$ and $P_{k+1} \geq P_k(\lambda/\mu_{K+1})$, $\forall k \in \{1,\ldots,K-1\}$. Hence Inequality (11) holds, and consequently, $\pi_K \geq \hat{\pi}_{K+1}$ holds.

REFERENCES

[1] Y. C. Liang, K. C. Chen, G. Y. Li, and P. Mahönen, "Cognitive radio networking and communications: An overview," *IEEE Trans. Veh. Technol.*, vol. 60, no. 7, pp. 3386–3407, Sep. 2011.

[2] S. Huang, X. Liu, and Z. Ding, "Optimal transmission strategies for dynamic spectrum access in cognitive radio networks," *IEEE Trans. Mobile Comput.*, vol. 8, no. 12, pp. 1636–1684, Nov. 2009.

[3] IEEE Standard for Wireless Regional Area Networks—Part 22: Cognitive Wireless RAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications: Policies and Procedures for Operation in the TV Bands, IEEE Std. 802.22WG, Jul. 2011.

[4] J. Jia, Q. Zhang, and X. Shen, "HC-MAC: A hardware-constrained cognitive MAC for efficient spectrum management," *IEEE J. Select. Areas Commun.*, vol. 26, no. 1, pp. 106–117, Jan. 2008.

[5] H. A. B. Salameh, M. M. Krunz, and O. Younis, "MAC protocol for opportunistic cognitive radio networks with soft guarantees," *IEEE Trans. Mobile Comput.*, vol. 8, no. 10, pp. 1339–1352, Oct. 2009.

[6] L. Jiao, F. Y. Li, and V. Pla, "Modeling and performance analysis of channel assembling in multi-channel cognitive radio networks with spectrum adaptation," *IEEE Trans. Veh. Technol.*, vol. 61, no. 6, 2012

[7] J. Lee and J. So, "Analysis of cognitive radio networks with channel aggregation," in *Proc. IEEE WCNC*, Sydney, Australia, Apr. 2010.

[8] L. Jiao, F. Y. Li, and V. Pla, "Dynamic channel aggregation strategies in cognitive radio networks with spectrum adaptation," in *Proc. IEEE GLOBECOM*, Houston, Texas, USA, Dec. 2011.

[9] C. Politis, "Managing the radio spectrum-the role of cognitive radio in future spectrum use," *Vehicular Technology Magazine*, vol. 4, no. 1, pp. 20–26, Mar. 2009.

[10] Y. Yuan, P. Bahl, R. Chandra, P. A. Chou, J. I. Ferrell, T. Moscibroda, S. Narlanka, and Y. Wu, “KNOWS: Cognitive radio networks over white spaces,” in *Proc. IEEE DySPAN*, Dublin, Ireland, Apr. 2007.

[11] T. Yucek and H. Arslan, “A survey of spectrum sensing algorithms for cognitive radio applications,” *IEEE Commun. Surveys Tuts.*, vol. 11, no. 1, pp. 116–130, First Quarter 2009.

[12] X. R. Zhu, L. F. Shen, and T. S. P. Yum, “Analysis of cognitive radio spectrum access with optimal channel reservation,” *IEEE Commun. Lett.*, vol. 11, no. 4, pp. 304–306, Apr. 2007.

Paper D

Title:	Power Allocation in Multi-channel Cognitive Radio Networks with Channel Assembling
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Power Allocation in Multi-channel Cognitive Radio Networks with Channel Assembling

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Abstract — **Consider power allocation for Secondary User (SU) packet transmissions over multiple channels with variable Primary User (PU) arrival rates in cognitive radio networks. Two problems are studied in this paper: The first one is to minimize the collision probability with PUs and the second one is to maximize the data rate while keeping the collision probability bounded. It is shown that the optimal solution for the first problem is to allocate all power onto the best channel based on a certain criterion. The second problem with a per-channel power budget constraint is proven to be NP-hard and therefore a pseudo-polynomial time solution for the problem is proposed. When a total power budget for all channels is imposed in the second problem, a computationally efficient algorithm is introduced. The proposed algorithms are validated by numerical experiments.**

I. INTRODUCTION

Spectrum access in Cognitive Radio Networks (CRNs) can be implemented in an Opportunistic Spectrum Access (OSA) manner [1], where SUs transmit over a frequency band only if none of the PUs is transmitting in that band. By utilizing spectrum sensing, the SUs can decide to transmit if the sensing result indicates that all PU transmitters are inactive at this band.

In distributed CRNs with OSA approach, Medium Access Control (MAC) protocols usually work in a competing manner whereby the SUs compete for access opportunities, with the winning SU using the available channels while other SUs have

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to wait for the next competition. When multiple available channels exist, channel assembling technique can be utilized by the winner in order to support higher data rate and further improve spectrum utility, as discussed in [2, 3, 4, 5]. Traditionally, waterfilling is adopted for power allocation among multiple channels. However, this approach may lead to high probability of collision between SU and PU activities. If such collision happens, i.e., PUs appear during an SU packet transmission, SUs must release the channel immediately in order to make room for PUs, resulting a possible cost to SUs. Recently, the authors of [6] introduced a risk-return model for SUs in which the cost of this collision in a given band is modeled as a rate loss depending on the power level allocated to this band. Under this model, the optimal power allocation strategy turns out to be similar to the traditional waterfilling. However, in practice, the full impact of such collision is much more than just the wasted transmission power or the associated rate loss. It includes other important ramifications, such as the resulted SU packet loss, the delay and the overhead in the handshake process between SU communication pairs. Hence, modeling this collision just as a rate loss is insufficient.

In this work, we directly minimize or constrain the collision probability. Specifically, we consider two optimal power allocation problems for the case where SUs access the channels in a competing manner and only the winner can utilize the vacant channels for packet transmission after competition. One problem is to minimize the collision probability of an SU packet with PUs. The other one is to maximize the data rate given the upper bound of SU packet collision probability.

The rest of the paper is organized as follows. The system model is given in Sec. 2 while the optimal power allocation problems are described and analyzed in Sec. 3. Then various algorithms are designed to solve the problems in Sec. 4. Numerical results and corresponding discussions are presented in Sec. 5, before the paper is concluded in Sec. 6.

2. SYSTEM MODEL

For notational convenience, we use the notation SU to indicate a secondary user communication pair in the following paragraphs. Assume that there are M channels available to the winner after channel competition and sensing. Suppose a PU service requires only one channel and all of these channels have identical bandwidth B. Due to hardware constraint, an SU can assemble up to N channels for a packet transmission. Those channels can be either neighboring to each other or separated in the spectrum domain. Therefore, considering channel availability and hardware constraint, the SU can utilize up to $\min\{M,N\}$ channels for a packet transmission.

When OFDM is utilized, each of those channels contains further S subchannels corresponding to the subcarriers in the system. The channel state, noise density and the SU's allocated power for the jth subchannel in channel i is denoted by $h_{i,j}$, $n_{i,j}$, and $p_{i,j}$ respectively, where $i \in I$, $I = \{1, \cdots, M\}$ and $j \in J$, $J = \{1, \cdots, S\}$. Each subcarrier has equal bandwidth b, where $Sb = B$. If a transmission scheme other than OFDM is performed where there are no subchannels, $h_{i,j}$, $n_{i,j}$, and $p_{i,j}$ will become h_i, n_i, and p_i respectively.

Assume that the arrival of the PU services follows Poisson process with rate λ_i in channel i, $i \in I$. In a period τ, the probability that there is no PU arrival in channel i is given by $\mathscr{P}_i(\tau) = e^{-\lambda_i \tau}$. Assume further that PU services are independent among different channels. Therefore, the probability that there is no PU arrival in a given channel set C_s during period τ, denoted by $\mathscr{P}_{C_s}(\tau)$, is obtained by

$$\mathscr{P}_{C_s}(\tau) = \prod_{i \in C_s} \mathscr{P}_i(\tau) = e^{-\sum_{i \in C_s} \lambda_i \tau}. \tag{1}$$

If there is no collision with PUs, the time required to transmit an SU packet, denoted as T, is given by

$$T = \frac{L_p}{\sum_{i=1}^{M} \sum_{j=1}^{S} b \log(1 + |h_{i,j}|^2 p_{i,j} / (n_{i,j} b))}, \tag{2}$$

where L_p is the packet length and the denominator is the achieved capacity. Without loss of generality, we merge $n_{i,j}b$ and $|h_{i,j}|^2$ by defining $h'_{i,j} = |h_{i,j}|^2 / (n_{i,j} b)$.

Let us define the channel usage indicator ξ_i, $i \in I$ as

$$\xi_i = \begin{cases} 1, & \sum_j p_{i,j} > 0, \\ 0, & \text{otherwise}, \end{cases} \tag{3}$$

where $\sum_i \xi_i \leq \min\{M, N\}$. ξ_i indicates whether channel i is utilized by an SU packet transmission or not.

It is assumed that the set of assembled channels for an SU packet is fixed during its transmission. Based on Eqs. (1), (2), and (3), the probability that a packet is transmitted without collision with a PU activity can be formulated as

$$\mathscr{P}_r = \exp\left(- \frac{\sum_{i=1}^{M} \lambda_i \xi_i L_p}{\sum_{i=1}^{M} \sum_{j=1}^{S} b \log(1 + h'_{i,j} p_{i,j})} \right). \tag{4}$$

3. OPTIMIZATION PROBLEMS AND ANALYSIS

3.1 Minimizing the Collision Probability

Based on the above system model and for a given power budget, the optimization problem of minimizing the probability that an SU packet will collide with PUs, i.e., minimizing $1-\mathscr{P}_r$, can be derived as

$$\min_{\{p_{i,j}\}_{i\in\mathcal{I},j\in\mathcal{J}}} \frac{\sum_{i=1}^{M}\lambda_i\xi_i L_p}{\sum_{i=1}^{M}\sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j})}, \tag{5}$$

$$\begin{aligned} \text{s.t.}\quad & \xi_i = \begin{cases} 1, & \sum_j p_{i,j} > 0, \\ 0, & \text{otherwise,} \end{cases} \\ & 1 \le \sum_i \xi_i \le \min\{M,N\},\ p_{i,j} \ge 0, \\ & \sum_i\sum_j p_{i,j} \le p_t; \text{or } \sum_j p_{i,j} \le p_t, \forall i \in I, \end{aligned} \tag{6}$$

where p_t is the total power budget. As illustrated in (6), two cases for power constraint are considered, either there is a total power budget or there exists a power constraint for each channel. The condition $\sum_i \xi_i \ge 1$ is introduced so that at least one band is used by the winning SU to send its packet.

For a fixed set of selected channels and the packet length, the probability that an SU packet collides with PUs will be reduced if the data rate[1] increases. Since waterfilling is the optimal power allocation scheme for the total power budget case, once the channels are selected, waterfilling must be utilized. Similarly, in the per-channel power constraint case, the maximum power should be used in each of the selected channels, while among subchannels within a particular channel the power is still allocated in the waterfilling manner.

Proposition 1 *The optimal solution for problem (5) is to allocate the whole power to only one channel i which gives the minimum value of* $\lambda_i L_p / \sum_{j=1}^{S} b\log(1+h'_{i,j}p^*_{i,j})$*, where* $p^*_{i,j}$ *is the solution of waterfilling for channel i with* p_t*.*

Proof We prove it by contradiction. Assume that $\sum_i \xi_i = \ell \ge 2$, i.e., ℓ channels are utilized as the optimal solution in the total power constraint case. Without loss of generality, we assume that those ℓ channels are sorted from low to high according to their $\lambda_i L_p / \sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j})$ values, where $i \in \{1,\cdots,\ell\}$ and $\sum_i\sum_j p_{i,j} = p_t$.

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[1] The achieved data rate is determined by channel condition, power budget and coding/modulation scheme etc. Modern coding/modulation schemes can achieve a data rate close to the Shannon capacity. In this work, we use data rate and capacity interchangeably.

By dropping channel ℓ, i.e., setting $p_{\ell,j} = 0,\ \forall j$, we have

$$\frac{\sum_{i=1}^{\ell-1} \lambda_i L_p}{\sum_{i=1}^{\ell-1} \sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j})} \tag{7}$$

$$\le \frac{\sum_{i=1}^{\ell} \lambda_i L_p}{\sum_{i=1}^{\ell} \sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j})}, \tag{8}$$

which is a contradiction since it gives us a better optimal point with smaller number of channels[2]. Similar result can be applied to the single channel power constraint case.

3.2 Maximizing the Data Rate with a Collision Probability Constraint

Another formulation is to maximize the data rate while keeping the collision probability below a threshold value. Then the optimization problem becomes

$$\max_{\{p_{i,j}\}_{i\in I, j\in J}} \sum_{i=1}^{M}\sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j}), \tag{9}$$

$$\text{s.t.} \quad \frac{\sum_{i=1}^{M} \lambda_i \xi_i}{\sum_{i=1}^{M} \sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j})} \le \gamma_0, \tag{10}$$

$$\xi_i = \begin{cases} 1, & \sum_j p_{i,j} > 0, \\ 0, & \text{otherwise}, \end{cases}$$

$$\sum_i \xi_i \le \min\{M,N\},\ p_{i,j} \ge 0, \tag{11}$$

$$\sum_i \sum_j p_{i,j} \le p_t; \text{or} \sum_j p_{i,j} \le p_t, \forall i \in I,$$

where $\gamma_0 = -\log(1-\mathscr{P}_{rc0})/L_p$ and $\mathscr{P}_{rc0}$ is the maximum tolerable level of the collision probability.

If we ignore the hardware constraint in (11) and consider only the per-channel power constraint, the problem becomes

$$\max_{\{p_i\}_{i\in I}} \sum_{i=1}^{M}\sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j}), \tag{12}$$

$$\text{s.t.} \quad \frac{\sum_{i=1}^{M} \lambda_i \xi_i}{\sum_{i=1}^{M} \sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j})} \le \gamma_0,$$

$$\xi_i = \begin{cases} 1, & \sum_j p_{i,j} > 0, \\ 0, & \text{otherwise}, \end{cases}$$

$$\sum_j p_{i,j} \le p_t,\ \forall i \in I,\ p_{i,j} \ge 0. \tag{13}$$

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[2] Note that if we do waterfilling again in the new set after dropping that channel, the denominator of Eq. (7) will increase since the portion of the power used for the channel that we dropped can be reused for the remaining channels. Therefore inequality Eq. (7) becomes strict in this case.

Proposition 2 *The optimization problem (*12*)-(*13*) which is a special case of the optimization problem (*9*)-(*11*) is NP-hard.*

Proof Let $p'_{i,j}$ be the solution of (12)-(13) and let us also define $q_i = \sum_{j=1}^{S} p'_{i,j}/p_t$. Since $\sum_{j=1}^{S} p'_{i,j}$ is either zero or p_t, we have $q_i \in \{0,1\}$. Let $v_i = \sum_{j=1}^{S} b\log(1+h'_{i,j}p^*_{i,j})$, where $p^*_{i,j}$ denotes the waterfilling solution in channel i with power budget p_t. Thus, the problem becomes

$$\max_{\{q_i\}_{i\in I}} \quad \sum_i v_i q_i, \tag{14}$$
$$\text{s.t.} \quad \sum_i \lambda_i q_i / \sum_i v_i q_i \leq \gamma_0, \; q_i \in \{0,1\}.$$

For channel i with $\lambda_i - \gamma_0 v_i \leq 0$, we must set $q_i = 1$, because this choice of variable satisfies the constraint and increases the value of objective function. On the other hand, for the channels that satisfy $\lambda_i - \gamma_0 v_i > 0$, we must solve the following optimization problem:

$$\max_{\{q_i\}_{i\in I'}} \quad D + \sum_i v_i q_i, \tag{15}$$
$$\text{s.t.} \quad \sum_i (\lambda_i - \gamma_0 v_i) q_i \leq C, \; q_i \in \{0,1\},$$

where $I' = \{i | \lambda_i - \gamma_0 v_i > 0, i \in I\}$, $C = -\sum_{j\in I''}(\lambda_j - \gamma_0)v_j$, $D = \sum_{j\in I''} v_j q_j$ and $I'' = I - I'$ is the complement of set I'. Clearly, (15) is a knapsack problem. Furthermore, we can start from an instance of a knapsack problem and reduce it to the equivalent power allocation problem (12)-(13) in polynomial time. Hence, the power allocation problem (12)-(13) is NP-hard.

4. ALGORITHMS FOR POWER ALLOCATION

In what follows, we propose two different algorithms for the data rate maximization problem under various power constraints.

4.1 Power Allocation with a Per-Channel Power Constraint

For the per-channel power constraint case, based on our discussion in the proof of Proposition 2, we can re-formulate the problem as

$$\max_{\{q_i\}_{i\in I}} \quad \sum_i v_i q_i, \tag{16}$$
$$\text{s.t.} \quad \sum_i w_i q_i \leq 0, \; \sum_i q_i \leq \min\{M,N\}, \; q_i \in \{0,1\},$$

where $w_i = \lambda_i - \gamma_0 v_i$ denotes the weight of channel i.

Inspired by the dynamic programming algorithm for the knapsack problem, we propose a pseudo-polynomial time algorithm as follows. Define $m(i,x,n)$ to be the maximum value of the objective function that can be attained with weight less than or equal to x, given channels (or *items* in the knapsack problem) selected from set $\{1,2,\ldots,i\}$ with at most n channels. It is easy to see that the following equations hold:

$$m(i,x,0)=\begin{cases}0; & x\geq 0,\\ \text{infeasible}; & \text{otherwise},\end{cases}$$

$$m(0,x,n)=\begin{cases}0; & x\geq 0,\\ \text{infeasible}; & \text{otherwise},\end{cases}$$

$$m(1,x,n)=\begin{cases}v_1; & n\geq 1, x\geq w_1,\\ 0; & n=0, x\geq 0,\\ \text{infeasible}; & x<\min\{0,w_1\},\end{cases}$$

$$m(i,x,n)=\begin{cases}\max\{A,B+v_i\}; & \text{both A and B feasible},\\ A; & \text{A feasible, B infeasible},\\ B+v_i; & \text{B feasible, A infeasible},\\ \text{infeasible}; & \text{both A and B infeasible},\end{cases}$$

where $A=m(i-1,x,n)$ and $B=m(i-1,x-w_i,n-1)$.

Since neither w_i nor v_i are required to be integers, a top-down approach in dynamic programming is utilized. Therefore, the final result, i.e., $m(M,0,\min\{M,N\})$, can be calculated in a recursive manner through dynamic programming.

4.2 Power Allocation with a Total Power Constraint

We now introduce a highly efficient heuristic algorithm for the total power constraint case as illustrated in Algorithm 1. This algorithm is based on the fact that a channel with a smaller $\lambda_i L_p/\sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j})$, $\forall i\in I$ and $\sum_j p_{i,j}=p_t$, may better satisfy the probability constraint.

Define $[R,\mathbf{p}]:=wf(m,n,p)$ as the waterfilling function using from the m-th to the n-th channels with power budget p, where R is the resulted capacity and $\mathbf{p}$ is the resulted power allocation vector. In this algorithm, firstly waterfilling is done for each of channel individually with the total power budget. By doing so, we can check the feasibility of the problem and sort the channels from low to high according to $\lambda_i L_p/\sum_{j=1}^{S} b\log(1+h'_{i,j}p_{i,j})$, $\forall i\in I$ and $\sum_j p_{i,j}=p_t$. Let this new ordered channel set be I_o. Based on the resulted ranking, we form a set with channel index from the first one to the largest possible one, i.e., to make the set have as many channels as possible while keeping the probability and the hardware constraints satisfied. The reason is that with a total power budget, the larger the number of channels we utilize, the higher the capacity it can potentially achieve through waterfilling.

Algorithm 1 : A sub-optimal algorithm

```
for $i := 1$ to $M$ do
    $[R_i, \mathbf{p}] := wf(i, i, p_t)$.
end for
if $\forall\ \lambda_i/R_i > \gamma_0$ then
    Problem infeasible.
else
    Rank channels according to $\lambda_i L_p/R_i$ from low to high.
    if $N \geq M$ then
        Return $[R, \mathbf{p}] := Search(M)$.
    else
        $[Capa, \mathbf{p}^{'}] := Search(N)$.
        if $Search(N) = wf(1, N, p_t)$ then
            for $i := N+1$ to $M$ do
                $[R, \mathbf{p}] := wf(i-N+1, i, p_t)$.
                if the solution is feasible and $R > Capa$ then
                    $Capa := R$ and $\mathbf{p}^{'} := \mathbf{p}$.
                end if
            end for
        end if
        Return $[Capa, \mathbf{p}^{'}]$.
    end if
end if
```

In Algorithm 1, there is a function $[R, \mathbf{p}] := Search(s)$ which is explicitly given in Algorithm 2. This function performs based on the bisection method. Variable s in this function indicates the searching range, i.e., from the first to the sth channel in the new ordered channel set I_o. The returned values $[R, \mathbf{p}]$ are based on the largest feasible subset with elements starting from the first channel consecutively, up to the sth one in the new ordered channel set. Function $[R, \mathbf{p}] := Search(s)$ can always find a feasible solution if it is called, since the feasibility of the problem has been checked and the channels are ranked accordingly in Algorithm 1.

5. NUMERICAL RESULTS

In this section, the performance of the proposed algorithms are evaluated via numerical experiments. In both of the per-channel and the total power budget constraint cases, two scenarios when $N \geq M$ and $N < M$ are investigated. The default parameters are summarized in Table D.1. In order to evaluate the performance of the proposed algorithms, an exhaustive search algorithm is considered as the benchmark. All the illustrated results are the average values of over 100 runs.

Algorithm 2 : *Search*(s)

```
Let $m := 0$, $n := 1$, $f := 1$, $capa := 0$, $\mathbf{p}^{'} := 0$.
repeat
    $m := m + \lceil (1/2)^n s \rfloor f$,  $[R, \mathbf{p}] := wf(1, m, p_t)$.
    if the solution is feasible then
        $f := 1$.
        if $R > capa$ then
            $capa := R$ and $\mathbf{p}^{'} := \mathbf{p}$.
        end if
    else
        $f := -1$.
    end if
    $n := n + 1$.
until $\lceil (1/2)^n s \rfloor = 0$.  Return $[capa, \mathbf{p}^{'}]$.
```

Table D.1: Parameters for performance analysis.

Notations	Values
No. of subchannels (S)	8
Channel state ($h_{i,j}$)	Rayleigh distributed with parameter 1/0.6552
Noise density ($n_{i,j}$)	10^{-10} W/Hz
Power budget (p_t)	8×10^{-3} W
Channel bandwidth (B)	2×10^{6} Hz
PU Poisson arrival rate (λ_i)	Uniformly distributed between 40 to 100 services/s
Packet length (L_p)	8000 bit
Collision prob. ($\mathscr{P}_{rc0}$)	3%

5.1 Per-Channel Power Constraint Case

The pseudo-polynomial time algorithm is compared with the exhaustive search algorithm in two aspects: The achieved data rate and the computational complexity represented by the machine running time. In our numerical experiments, we observed that the pseudo-polynomial time algorithm always finds the optimal solution. Therefore we do not plot these results explicitly. The running time with respect to the number of channels M is plotted in Fig. D.1 when $N \geq M$, i.e., with sufficient hardware on SUs.

As observed from Fig. D.1, when the number of total channels grows, the time used by exhaustive search increases dramatically. We have also observed that the pseudo-polynomial time algorithm consumes slightly more time than the exhaustive

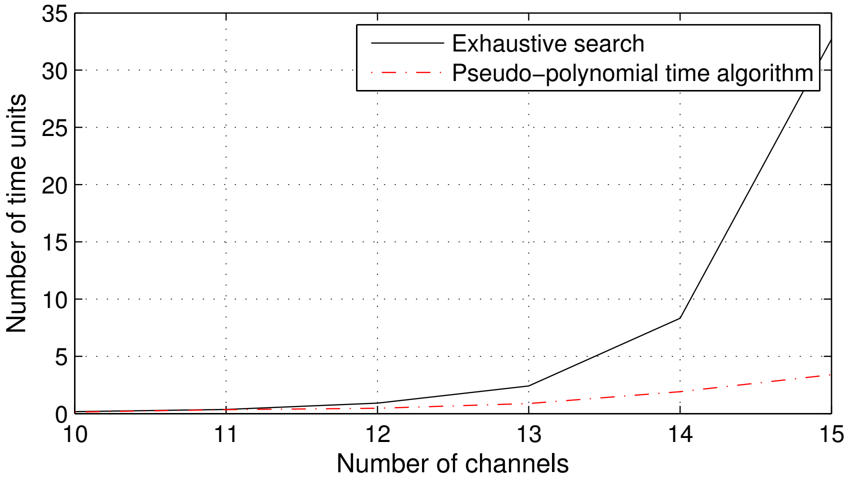

Figure D.1: Time consumption as a function of M when $N \geq M$.

search does when M is small, i.e, $M < 7$ in this example, although not observable in the current plotting. It means that when only a few channels are available, the exhaustive search method is a good option. However for a large M, the pseudo-polynomial time algorithm through dynamic programming is preferable. Similar results have been observed when $N < M$ however not illustrated here due to page limit.

5.2 Total Power Constraint Case

In Fig. D.2, we illustrate the capacity as a function of the mean value of the PU arrival rate among channels in the total power budget case. The total power budget is 8×10^{-2} W, and the PU Poisson arrival rate among different channels, λ_i, is uniformly distributed with the mean value $\bar{\lambda}$ and the variance of 300, while other parameters follow the default values.

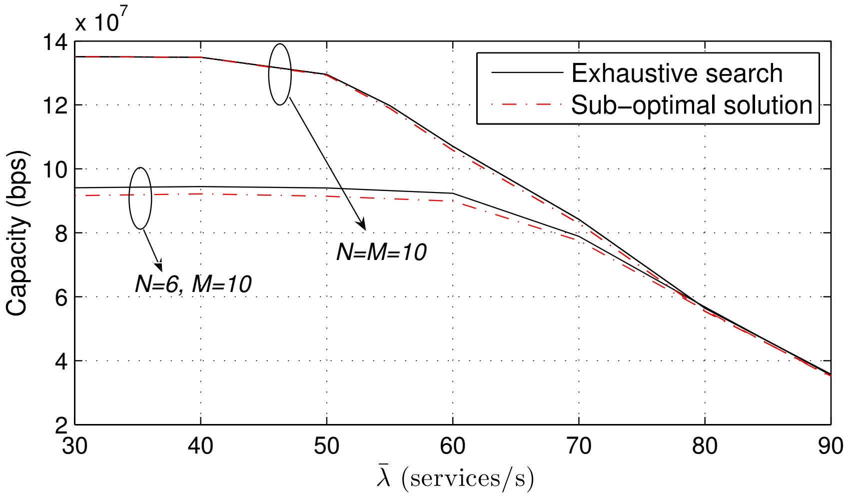

Figure D.2: Capacity as a function of PU arrival rate.

Two cases, $N = M = 10$, and $N = 6$ while $M = 10$, are studied. From Fig. D.2, we can observe that the capacity of the algorithms in both cases is relatively stable initially and decreases as the average PU arrival rate increases. When the mean arrival rate of PU service is small, most of the channels can be utilized for packet transmission while the collision probability constraint is satisfied. When the mean PU arrival rate becomes larger, the number of channels that can make the probability constraint satisfy decreases. Given the same total power budget constraint, with smaller number of assembled channels, i.e., less bandwidth, the capacity will be reduced. Comparing the capacity of the sub-optimal and the exhaustive search algorithms, the capacity of the sub-optimal algorithm is quite close to that of the exhaustive search method.

Furthermore, with respect to computational complexity, the number of times for executing the waterfilling algorithm is only proportional to M using the sub-optimal algorithm while it is exponential to M in the exhaustive search method.

6. CONCLUSIONS

In this paper, power allocation in CRNs is considered from two aspects, minimizing the collision probability with PUs and maximizing the data rate with constraint collision probability. The optimal solution of the first problem is provably to put full energy on the single best channel while the second problem is proven to be NP-hard in the per-channel power constraint case. Therefore a dynamic programming method is proposed for power allocation with a per-channel power constraint. A highly efficient heuristic algorithm is introduced for power allocation with a total power constraint. As expected, the numerical results demonstrate that the dynamic programming achieves the optimized result, and that the heuristic algorithm is capable of achieving a data rate close to the global optimal value at very low computational complexity.

REFERENCES

[1] R. Zhang, Y. C. Liang, and S. Cui, "Dynamic resource allocation in cognitive radio networks: A convex optimization perspective," *IEEE Signal Processing Magazine*, vol. 27, no. 3, pp. 102–114, May 2010.

[2] H. Su and X. Zhang, "Cross-layer based opportunistic MAC protocols for QoS provisionings over cognitive radio mobile wireless networks," *IEEE JSAC*, vol. 26, no. 1, pp. 118-129, Jan. 2008.

[3] J. Jia, Q. Zhang, and X. Shen, "HC-MAC: A hardware-constrained cognitive MAC for efficient spectrum management," *IEEE JSAC,* vol. 26, no. 1, pp. 106-117, Jan. 2008.

[4] H. A. B. Salameh, M. M. Krunz, and O. Younis, "MAC protocol for opportunistic cognitive radio networks with soft guarantees," *IEEE Trans. Mobile Comput.,* vol. 8, no. 10, pp. 1339 - 1352, Oct. 2009.

[5] A. C. Hsu, D. S. L. Wei, and C. -C. J. Kuo, "A cognitive MAC protocol using statistical channel allocation for wireless ad-hoc networks," in *Proc. IEEE WCNC,* Hong Kong, Mar. 2007.

[6] Z. Hasan, E. Hossain, C. Despins, and V. K. Bhargava, "Power allocation for cognitive radios based on primary user activity in an OFDM system", in *Proc. IEEE GLOBECOM*, New Orleans, USA, Nov. 2008.

Paper E

Title: MAC Strategies for Single Rendezvous Multi-hop Cognitive Radio Networks

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MAC Strategies for Single Rendezvous Multi-hop Cognitive Radio Networks

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Abstract — **This paper presents two MAC strategies for multi-hop cognitive radio networks in single radio multi-channel cases. Both strategies use one of the idle multiple channels for communication among secondary users, and the network will leave the current channel and jump to another channel as a group if any primary user appears. The first strategy is based on a pre-defined pattern that will always tune to the next available channel when primary user emerges. The second one is based on the concept of connected dominating set in which a backbone is formed in the network in order to keep the continuity of the communication. The strategies are evaluated in both homogeneous and heterogeneous channels by simulations. Numerical results show that higher throughput has been achieved with the first strategy in homogeneous channels but in heterogeneous channels the latter strategy performs much better.**

I. INTRODUCTION

Cognitive Radio (CR) [1] has become a hot research topic these days. The design of Media Access Control (MAC) protocols is an important issue in the whole protocol stack of Cognitive Radio Networks (CRNs). There are mainly two classes of MAC protocols: centralized MAC like IEEE 802.22 [1] or distributed MAC as described in [2-5,7-9]. Existing distributed MAC protocols can be further classified into two categories: single rendezvous or parallel rendezvous.

Single rendezvous MAC protocols, i.e., OSA-MAC [2], OS-MAC [3], C-MAC [4], KNOWS [7] and the MAC protocols described in [8, 9], have a control channel as the rendezvous channel, and Secondary Users (SUs) can exchange all control information and negotiate channel for data transmission on this channel. Among these protocols, OSA-MAC and C-MAC have a requirement for synchronization, and OS-MAC is based on SU group formation. The information required for forming groups leads to extra overhead and the complexity of this protocol is relatively high. KNOWS is targeted for TV bands. It demands one transceiver and several spectrum sensors, and requires more sophisticated hardware. In [9], there are two radios, one on control channel in charge of control messages exchange and the other one tuned in data channel for data communication. This protocol assumes that SUs are synchronized. Furthermore, it has been demonstrated that parallel rendezvous MAC protocols are more efficient than single rendezvous MAC protocols in multi-channel cases [6]. The MAC described in [5] is such a MAC protocol where the SUs can negotiate transmissions on different channels with less competition with each other. This parallel rendezvous protocol also assumes that the SUs are precisely synchronized.

Most current MAC protocols are focusing on how to take best utilization of multi-channels of Primary Users (PUs). These protocols are complicated and always have an assumption about synchronization among SUs. In these single rendezvous MAC protocols, except C-MAC, the control channel is assumed to be dedicated to SUs. However, in practice, a dedicated control channel does not always exist and a channel could be chosen as the control channel from all these channels. In C-MAC, an idea of how to choose a control channel and keep the multi-hop SUs rendezvous in a not-dedicated control channel is presented but no specific scheme is proposed.

In this paper, we intend to propose two single radio based distributed Carrier Sense Multiple Access With Collision Avoidance (CSMA/CA) MAC strategies suitable for multi-hop cognitive radio networks which work on one of the idle channels. No precise synchronization is required for these strategies. One of the strategies is referred to as Next Available Channel Strategy (NACS) in which all nodes switch to the next available channel when PU starts transmission in the current channel. The other one is a Connected Dominating Set (CDS) based Strategy (CDSS) which introduces a backbone of the network in order to keep the communications within a channel. These MAC strategies may also be used for control channel selection in the multi-channel multi-radio cases such that one radio is always tuned to the scheduled channel when the dedicated control channel for SUs is not there.

The rest of the paper is organized as follows. Section II describes the channel model of PUs and the assumptions. Section III presents the design of these strategies in details. Section IV gives the performance evaluation of the strategies. Finally, the paper is concluded in Section V.

II. CHANNEL MODEL DESCRIPTION AND SYSTEM ASSUMPTIONS

The occupancy of each channel by PUs can be modeled as an ON/OFF activity, where OFF represents that the channel is not used by PUs, thus it is considered as spectral opportunity for SUs. The OFF intervals vary according to PUs' usage pattern. It could last for several hours or even days like emergency police bands, TV bands etc, or only for a few milliseconds like in cellular systems. For long-lasting idle channels, it is easy for SUs to discover and utilize them while for short-lasting idle periods, it is difficult for SUs to detect the existence of these opportunities even before they disappear. In this study, we focus on the cases that the OFF interval is in the scale of several 10 seconds or longer. Another assumption for PUs is that the coverage of the PU transmitter is far more larger than that of SUs' and thus the CRN could be covered by the same set of PUs, like a home network covered by TV broadcast. We consider a system where there are N channels available for SUs. The usage pattern of PUs, in each channel, is assumed to follow i.i.d. ON/OFF exponential-distribution with mean value equal to T_{on} and T_{off}, respectively [10].

In this paper, we consider a case that there is one multi-hop SU group with several SUs inside it. All these SUs use the same channel all the time in order to maintain connectivity. This SU group seeks single channel access opportunity among these N channels. In a more complicated situation, it is possible that several SU groups share up to N channels but this case is beyond the scope of this paper. We also assume that the SUs can distinguish the signals transmitted by PUs and SUs. The topology of the network is static and there is no mobility for SUs.

III. MAC STRATEGIES DESCRIPTION

In order to make the MAC strategies simple and practical, the channel used by these strategies is one of these idle channels selected from all available channels. Operation on a single channel makes the strategies easier to implement and it could be easily extended from existing MAC like 802.11 and 802.15.4.

Briefly, the MAC strategies work as follows. SUs operate in a CSMA/CA fashion in the selected channel not occupied by any PUs. Once a PU in that channel emerges, SUs tune to another available channel. The difference between the traditional 802.11 MAC and the proposed strategies is that the proposed strategies need to deal with several new problems in CRN scenarios, like how to protect the communication of PUs, which channel to choose from all these available channels, how to keep the network within a channel etc. In what follows, we discuss channel sensing used in our strategies and the initial stage of the network that makes the network rendezvous for the first time before the proposed two strategies are presented.

A. Channel Sensing Strategy

Channel sensing strategy can be classified into two methods: in-band sensing and out-of-band sensing [1]. In-band sensing means to sense within the channel that the SUs are using. Correspondingly, out-of-band sensing means to sense the channel that the SUs are not currently using. The target of in-band sensing is to detect the appearance of a PU on the channel being used. Out-of-band sensing is used to acquire channel state information and this information is needed for channel selection and switching later on. For in-band sensing, the process is carried out as part of the carrier sensing in MAC protocols for SUs. For out-of-band sensing, an SU could tune to other channels to acquire such information and broadcast the sensing results to the current channel after this sensing. The frequency of out-of-band sensing depends on PUs' activity and the number of channels. Taking TV bands as an example, the ON period taken by PUs is usually long, and the sensing frequency is therefore set as once in half an hour [7].

B. Initial Stage

The initial stage is a transient period from first network deployment to routing convergence. In order to make the nodes rendezvous for the first time, all nodes always tune to the first free channel according to channel ID. Always here means that in order to keep in pace with other nodes, a node periodically searches the channel that has smaller ID than the current channel and tunes into it if it is idle. Because we assume that SUs have no mobility, proactive routing is used. When routing is converged, the network is established and the network could tune into other channels as a group according to the proposed strategies.

C. Next Available Channel Strategy

The strategy for NACS works as follows. The network stays in the selected channel for communication until any PUs appear. In this strategy, since the channel selection method is fixed, it is not necessary to do the out-of-band sensing. When the current working channel becomes occupied by a PU, the SUs just sense next channels one by one until an idle channel is found, and all SUs switch to this new channel as a group.

When SUs have tuned to an idle channel, they firstly send Hello messages to discover their neighbors and try to check whether anyone is lost. An SU that wants to leave the network should send a message that indicates its departure. Since we assume that the network is covered by the same set of PUs, the case that nodes tune to different channels is less likely to happen except the following three cases. The first case happens due to the differences of tuning time. When a PU arrives, the idle SUs can sense it immediately and start searching the next channel but the ongoing SUs communication pairs cannot do this before they finish their transmissions. The maximum time difference T_d could be a data packet transmission time plus its corresponding control packets time. After the idle SUs leave a particular channel which is sensed busy at this moment, the channel could be idle again when the rest ongoing SUs come and sense it because of this time difference. Then, the SUs may tune in different channels. The second case may happen due to false alarm in channel sensing. False alarm means there is no PU transmission but SU nodes sense that there is a PU. The third case is caused by failed detection in channel sensing which means that there is a PU transmission but SU nodes did not detect it.

The first two problems could be solved as follows. When SUs sense the presence of PUs, they will discover their neighbors after T_d when they tune to the next idle channel. If any neighbors are lost, they will broadcast a message to let the connected nodes search the channel from the original channel to the current channel again. If there is an idle channel, all nodes will join it. For the third problem, once failed detection happens, the in-band sensing mechanism to detect whether the channel is occupied by PU is still working. Thus even if the node cannot sense the existence of PU in the first place, it will sense it successfully at a later time instant and tune to an available channel. In this way, the SUs could rendezvous again.

In this strategy, the channel sensing and selection are controlled by the MAC layer CSMA and fixed channel selection regulations. The advantage of this strategy is easy to implement, but obviously, it is not adaptive to the cases when channels have different data rates.

D. CDS Based Strategy

A Dominating Set (DS) is a subset of a network such that every node is either a member of this set or one hop away from this set. When all nodes in a DS are connected, it becomes a CDS. CDS nodes form a backbone of the network. The key idea of the CDSS design is that if the backbone of the network is still connected after channel switching, it is easier for recovering the network because other nodes are all within one hop range of this backbone, and an adaptive channel switching selection mechanism could be implemented. In the following paragraphs, we will explain step by step the procedure of this strategy.

1) Channel Sensing and Notification:

In this strategy, CDS nodes just perform in-band sensing and out-of-band sensing is done by idle non-CDS nodes. This is because that SUs should avoid communications after the appearance of any PUs on the same channel in order to protect the PU transmissions. Therefore, whenever the network needs to vacate a channel because of the presence of PUs, all nodes could choose the channel by simply checking their local information. So the information obtained and stored in CDS nodes should be CDS-range-wide synchronized. If one of them performs out-of-band sensing, the ongoing broadcast messages may be delayed or even fail during this period, which may result in CDS nodes in different channels after channel switching.

The out-of-band sensing strategy works as the follows. An idle non-CDS node randomly chooses one channel for sensing, and reports the result by broadcasting to all other nodes inside the same network. Other non-CDS SUs which hear this message will randomly choose another channel and start sensing. In order to make the CDS nodes have the same information at a particular time, the broadcast sensing result is validated after such a period that guarantees the total dissemination of this message. In this broadcast message, there is a field indicating the time for validation of this information. This validation time should be longer than the dissemination period of the broadcast information, which means that out-of-band sensing result will be synchronized among all CDS nodes after the dissemination period. Therefore, if a PU comes before the information is fully disseminated among CDS nodes, the information is not regarded as valid. The dissemination period of the broadcast information could be estimated by Ping messages. For the validation time field, we adopt a count-down mechanism. In this way, nodes use the field indicating the remaining time before the information is validated, and network-wide time synchronization is not required.

In order to make this broadcast information delivered successfully, the priority is given to this information superior to other packets. Furthermore, ACK and retransmission schemes are required to these broadcast messages in the CDS nodes thus these messages are reliably delivered among CDS nodes. In order to avoid stale information after validation, an expiration time, T_v, is adopted.

2) Channel Selection and Switching Mechanisms:

Channel switching happens when PUs show up or a channel with better condition becomes available. The first case is passive switching and the other one is active switching.

For passive switching, when a PU transmission starts, SUs buffer all transmissions and search from their channel status database for information about other possible idle channels. If there is only one idle channel indicated in the database, it just tunes to that channel and verify again whether the channel is still idle after the switching time. If idle, communication will be re-initiated when other SUs join this channel. If there are several idle channels, it chooses the best one. If the channel chosen by an SU according to its database is not idle, the SU will start the next round of channel selection.

For active switching, the target is to tune to a better channel for data transmission. In a particular system, if the network wants to choose a channel that is suitable, it should get enough information about these channels. The information of other channels is obtained from out-of-band sensing. Since channel switching has time penalties, the network will tune to a new channel only if the channel bandwidth is good enough for a higher data rate in this design. The channel switching is determined by nodes in the network separately. If nodes receive out-of-band sensing information indicating that a channel condition meets the requirement for channel switching, they will transfer to the new channel when the validation time of this information expires. If several broadcast messages have the same validated time, SUs will use the one with lowest ID.

Since the CDS nodes are less likely scattered in different channels than other nodes, the backbone of the network is protected and the recovery of the network after channel switching is easier. For the non-CDS nodes, since they are one hop away from CDS nodes, they will search the CDS nodes if they cannot find them after channel switching. If, in any case, a CDS node cannot find a neighbor CDS node, they will broadcast a switch message to other CDS nodes that it connects to tune to the first idle channel from the original one.

V. SIMULATIONS AND NUMERICAL RESULTS

As shown in Fig. E.1, a small-scale network with 13 nodes is deployed in an area of $1600m \times 250m$. There is one data flow from node A to B. The CDS nodes in this topology is the nodes between A and B with 2 circles. Other nodes are idle nodes in this case and can perform out-of-band sensing in CDSS. The distance between CDS nodes is 250 meters.

NS2 is adopted for simulation and the two proposed MAC strategies are implemented based on 802.11. The carrier sense and transmission ranges are 550 meters and 250 meters respectively. The packet length is 1500 Bytes. For CDSS, the interval for idle non-CDS SUs performing out-of-band sensing is 1.5 s and the expiration time is set as $T_v = 5$ s. Each channel switching consumes 40 ms [11]. In the following paragraphs, we will present the simulation results of these strategies according to two different channel conditions, i.e. in homogeneous channels and heterogeneous channels.

A. Homogeneous Channels

Homogeneous channels mean that a set of channels that have the same bandwidth and the coding scheme is the same in all these channels, i.e. identical data

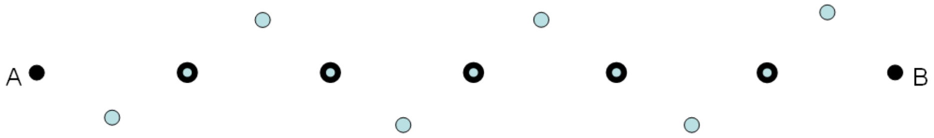

Figure E.1: Simulation topology for SUs.

rate for all channels. We discuss the results in two cases: when there is a PU activity in every channel and there is a channel that is always vacant.

1) Every Channel Has a PU Transmission:

In this case, we assume that the average ON and OFF periods of channels are 30 seconds and 70 seconds respectively thus P_{on} is 30% and P_{off} is 70%. The data rate in each channel is the same as 11 $Mbps$. We do not consider interference between adjacent channels. The traffic load injected makes the network saturated.

Define the throughput when the channel is dedicated to the SU network based on 802.11 as ideal throughput η_i for one channel. The theoretical throughput of the network as a function of the number of channels is obtained as follows:

$$\eta_p = \eta_i \times (1 - P_{on}^N), \tag{1}$$

where P_{on} is the probability that the channel is occupied by a PU and N is the number of channels. This value could be a theoretic upper bound in both of the two strategies in a statistical sense.

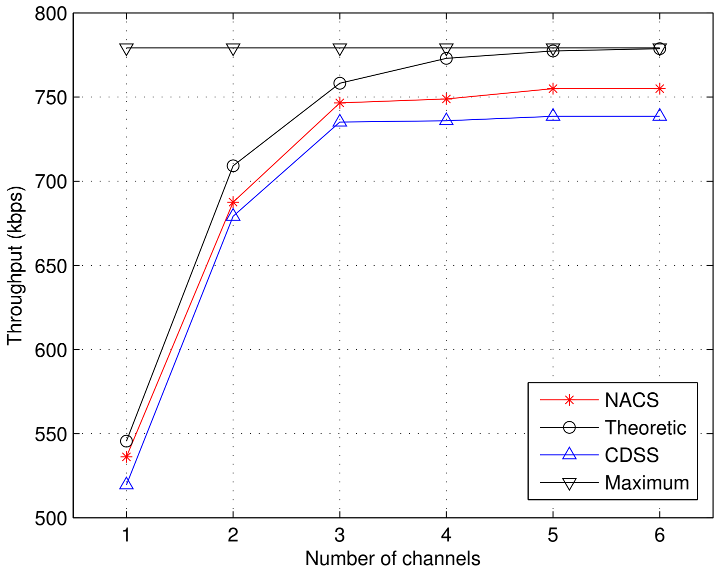

Figure E.2: Throughput of different MAC strategies in homogeneous channels.

The simulation results of homogeneous channels are shown in Fig. E.2. The value *Maximum* is the ideal throughput of the network based on 802.11 in a channel without PUs and it is drawn there as a reference. The *Theoretic* curve is the numerical result of Eq. (1). It is calculated based on the *Maximum* value without considering switching penalty and channel sensing overheads. In real life, however, since we cannot avoid overhead for out-of-band sensing in CDSS and the switching penalty between channels, the throughput of CRN MAC could only approach but not meet this *Theoretic* curve. *NACS* and *CDSS* in Fig. E.2 indicate the simulation results of these two strategies. Both of them have the same trend as the *Theoretic* value. With the increasing number of channels, the throughputs of NACS, CDSS and *Theoretic* curve are approaching the *Maximum* value. The reason is that since all channels follows the ON/OFF process, at a given time instant, the probability of all these channels occupied by PUs would be lower with the growing number of channels. In other words, the chance that a channel is available for SUs would be higher with the increasing of the channel number. As a result, the throughput is higher when the number of channels becomes larger. From Fig. E.2, we can see that the throughput of CDSS and NACS is close to the *Theoretic* curve but they are not as good as it. The reason for the lower throughput of NACS than *Theoretic* is its switching penalties. Compared with NACS, the throughput of CDSS is lower because it needs overhead for broadcasting the out-of-band sensing results.

2) With Always-Vacant Channel(s):

In this case, it is very easy to conclude that the throughput of NACS is almost the same as the *Maximum* value because once the network tunes to this always-vacant channel, it can communicate with each other without switching again. The throughputs of CDSS is close to the *Maximum* value but has overhead because of out-of-band sensing result dissemination.

B. Heterogeneous Channels

By heterogeneous channel, it is meant that a set of channels that have different bandwidth among them, so the data rates that could be used in these channels are different, like DAB and TV channels. Again, we present the results according to the following two cases: when there is a PU activity on every channel and there is a channel that is always vacant.

1) Every Channel Has a PU Transmission:

In this case, the average ON and OFF periods of channels are 30 seconds and 70 seconds respectively. We consider two data rates in these channels: 11 $Mbps$ and 5.5 $Mbps$. The probability of each channel that has the data rate of 11 $Mbps$ or 5.5 $Mbps$ is equal, i.e. 50% for each rate. Define the throughput that the channel is dedicated to a network in high data rate channel as η_h, and the channel is dedicated to a network in low data rate as η_l. The theoretical throughput of CDSS can be calculated by the following equation:

$$\eta_p = \sum_{j=0}^{N} P_j(\eta_h(1-P_{h,on}^{j}) + \eta_l(1-P_{l,on}^{(N-j)})P_{h,on}^{j}), \tag{2}$$

where $P_j = C_N^j P^j(1-P)^{(N-j)}$, P is the probability that a channel belongs to the high data rate channels thus P_j is the probability that there are j out of N channels are in higher data rate category, $P_{h,on}$ is the probability that a high data rate channel is occupied by PU and $P_{l,on}$ is the probability that a low data rate channel is occupied by PU.

The simulation results for heterogeneous channels are shown in Fig. E.3. The value *Maximum* means that the throughput of the network based on 802.11 in a high data rate channel without PU activities. The *Theoretic* curve of CDSS is the numerical result from Eq. (2). *NACS* and *CDSS* are the simulation results of these two strategies. From Fig.3, we can observe that the *Theoretic* curve and the simulation results of CDSS are quite close. Due to overhead and switching penalties, the simulated throughput is lower than the *Theoretical* curve. The difference between these two values becomes larger with the increasing of the number of channels. The reason is that with an increasing number of channels, the chance of switching between channels is higher thus the SUs suffer more switching penalties. Compared with NACS, the throughput of CDSS is much higher. That is because that CDSS always chooses to tune to the channels with higher data rate when they are not occupied by PUs while the NACS does not.

2) With Always-Vacant Channel(s):

The case in heterogeneous channels is more complex than that in homogeneous channels. In NACS, no matter how many always-vacant channels there are and what data rate channels they have, the network will be stuck in the first always-vacant channel that it tunes in. The throughput will be close to the *Maximum* throughput that a network can get in that particular type of channel. In CDSS, if the always-vacant channel has a higher data rate, the network will keep communicating in that channel and the throughput is close to the *Maximum* throughput in higher data rate channel. If the always-vacant channel has low data rate, it will only be a back-up channel for the higher data rate channels. The advantage is that the network will always have a channel to tune in if all high data rate channels are not available and the throughput is higher than in the case without the always-vacant channel.

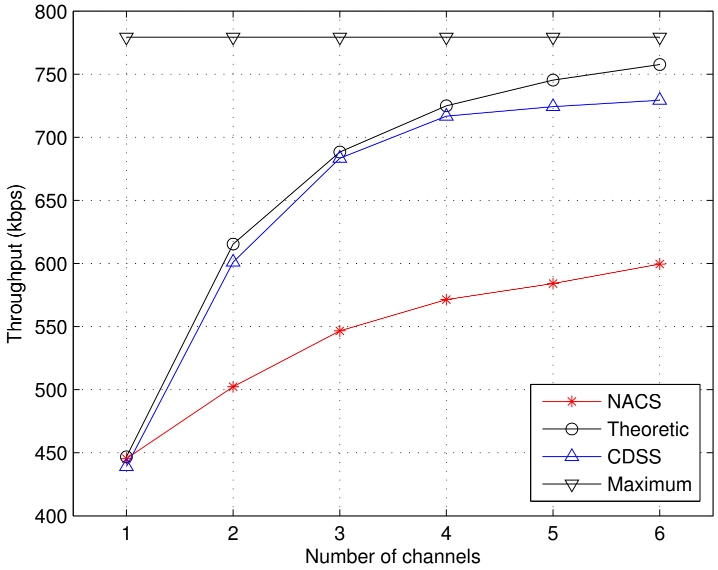

Figure E.3: Throughput of different MAC strategies in heterogeneous channels.

C. Further Discussions

From the above results, we can observe that in homogeneous channel conditions, both strategies are close to the *Theoretical* curve and the performance of NACS is better because it has no out-of-band sensing result broadcast overhead. In heterogeneous channel conditions, the performance of CDSS is much better than that of NACS because it can always tune into the channel that has higher data rate whenever there is a chance and out-of-band sensing nodes discover it. To further improve system performance, one could introduce a dynamic strategy selecting method combining these two strategies: in the beginning, CDSS is used until the out-of-band sensing covers all these channels. If channels are homogeneous, NACS is adopted; otherwise, CDSS will be employed.

In this paper, we only considered one CRN in these channels and it is always better for CDSS to choose the channel with higher data rate. If we consider several networks sharing these channels, it may lead to congestion in higher data rate channels because all the networks will jump into the channel with higher data rate. In this case, a more sophisticated channel selection method is expected.

VI. CONCLUSION

In this paper, two MAC strategies, NACS and CDSS, for multi-hop cognitive radio networks have been proposed. These strategies are aimed at rendezvousing multi-hop secondary users together within a channel in multi-channel cases. Simulation results show that NACS has better performance in homogeneous channels since out-of-band sensing overhead is avoided, while in heterogeneous channels, CDSS is much more efficient than NACS because a better data rate channel is preferably selected if it is available.

REFERENCES

[1] I. F. Akyildiz, W. Y. Lee, and K. Chowdhury, “CRAHNs: Cognitive radio ad hoc networks,” *Ad Hoc Networks*, vol. 7, no. 5, pp. 810–836, Jul. 2009.

[2] L. Long and E. Hossain, “OSA-MAC: A MAC protocol for opportunistic spectrum access in cognitive radio networks,” in *Proc. IEEE WCNC*, Las Vegas, USA, Mar. 2008.

[3] B. Hamdaoui and K. G. Shin, “OS-MAC: An efficient MAC protocol for spectrum-agile wireless networks,” *IEEE Trans. Mobile Comput.*, vol. 7, no. 8, pp. 915-930, Aug. 2008.

[4] C. Cordeiro and K. Challapali, “C-MAC: A cognitive MAC protocol for multi-channel wireless networks,” in *Proc. IEEE DySPAN*, Dublin, Ireland, Apr. 2007.

[5] H. Su and X. Zhang, “Channel-hopping based single transceiver MAC for cognitive radio networks,” in *Proc. IEEE CISS*, Princeton, USA, Mar. 2008.

[6] J. Mo, H. -S. W. So and J. Walrand, “Comparison of multichannel MAC protocols,” *IEEE Trans. Mobile Comput.*, vol.7, no.1, pp.50-65, Jan. 2008.

[7] Y. Yuan, P. Bahl, R. Chandra, P. A Chou, J. I Ferrell, T. Moscibroda, S. Narlanka and Y. N. Wu, “KNOWS: Cognitive radio networks over white spaces,” in *Proc. IEEE DySPAN*, Dublin, Ireland, Apr. 2007.

[8] Q. Zhao, L. Tong, A. Swami and Y. X. Chen,“Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework,” *IEEE JSAC*, vol.25, no.3, pp.589 - 600, Apr. 2007.

[9] H. Su and X. Zhang, “Cross-layer based opportunistic MAC protocols for QoS provisionings over cognitive radio mobile wireless networks,” *IEEE JSAC*, vol.26, no.1, pp.118-129, Jan. 2008.

[10] C. T. Chou, S. Shankar N, H. Kim, and K. G. Shin, “What and how much to gain by spectrum agility?” *IEEE JSAC*, vol. 25, no. 3, pp. 576-588, Apr. 2007.

[11] P. N. Anggraeni, N. H. Mahmood, J. Berthod, N. Chaussonniere, L. My, and H. Yomo, “Dynamic channel selection for cognitive radios with heterogeneous primary bands,” *Wireless Personal Communications*, vol. 45, issue 3, pp. 369 - 384, May, 2008.

Paper F

Title:	A Distributed Routing Protocol Integrated with Channel Allocation in Multi-channel Multi-hop Wireless Ad Hoc Networks
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A Distributed Routing Protocol Integrated with Channel Allocation in Multi-channel Multi-hop Wireless Ad Hoc Networks

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Abstract —**In this paper, we propose a novel routing protocol which is integrated with channel assignment for multi-channel multi-hop wireless ad hoc networks. In this design, each node is equipped with three transceivers. One is always tuned on a control channel which is in charge of control and broadcast messages, and the other two perform as a transmitter and a receiver respectively for traffic flow transmissions on different data channels. In our protocol, a path discovery and a channel allocation strategy are designed to mitigate two types of interference, i.e., inter-path interference and intra-path interference. The routing protocol works in an on-demand manner, and the proposed route discovery process selects path to potentially traverse nodes with lighter traffic load and lower number of ongoing flows. With a given number of orthogonal channels, the optimal solution of the channel allocation for multiple flows is shown to be in general NP-hard. Therefore, a heuristic algorithm for channel allocation based on the information acquired along a flow path is adopted. NS2 based simulation experiments are conducted to evaluate the performance of the proposed protocol.**

I. INTRODUCTION

The end-to-end saturated throughput of a multi-hop ad hoc network with single channel will decrease dramatically as the number of hops increases. This is mainly due to the limited access opportunities among nodes in a shared channel. However, if multiple channels exist and multiple radios are equipped on each node, mutual

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interference will be avoided since different channels can be utilized in a neighborhood. Multiple channels are indeed supported by many existing MAC protocols. For example, interfaces that support IEEE 802.11a and 802.11b/g can utilize up to 12 and 3 non-overlapping channels respectively. Those multiple channels can be exploited by the network to reduce interference among neighboring nodes therefore achieving higher throughput.

Consider two kinds of interference for a flow in multi-hop wireless networks, intra-path interference and inter-path interference. The intra-path interference means the co-channel interference caused from the same traffic flow which is transmitted on *another hop along the path* or from other flows which have a *common path* over several hops. The inter-path interference, on the other hand, is the co-channel interference caused by *other* traffic flows being transmitted *in the neighborhood*, excluding intra-path interference. There are different approaches that can diminish interference and improve throughput in a multi-hop network, like exploring orthogonal channels with multiple interfaces, scheduling for transmission, utilizing directional antenna and beamforming. Among those approaches, we believe that equipping multiple interfaces to a node on different channels is likely the most straightforward way to improve network throughput, since no hardware and MAC protocol modifications are required based on cheap hardware interfaces, like 802.11 cards.

Existing work on multi-channel multi-hop networks can be roughly sorted into three categories. The first one targets at wireless mesh networks (WMNs) [1, 2, 3, 4, 5, 6]. In this category, the network usually has one or several gateways through which it is connected to the Internet. Those gateways are usually the source of incoming traffic and the destination of outgoing traffic from the perspective of mesh routers. Therefore, the logical topology of WMNs can be generated based on a spanning tree, where the gateways usually perform as roots. Although different strategies are proposed for WMNs [5, 4], they are not quite suitable for ad hoc networks with flexible traffic where the source and the destination of traffic flows can be any nodes in the network. Many other studies in WMNs target at routing algorithm design [1, 2, 3, 6] rather than protocol design. The second category focuses on multi-channel multi-hop networks however with a single transceiver[7, 8, 9]. Although it has an advantage that no extra hardware is required, the single channel leads to unavoidably low throughput due to the intra-path interference. The third category talks about scheduling [10, 11]. Although it is an efficient technique to improve throughput, it is not easy to be implemented in purely distributed networks. In addition to the above mentioned techniques, a scheme that handles channel selection and interface assignment is proposed in [12]. However, a new layer is to be added in between of the second layer and the third layer in order to support that approach. In [13], a link-state routing protocol is proposed for multi-channel multi-hop wireless networks. However, the link-state information propagation may become quite costly in a large-scale network.

Based on the above observations, an on-demand routing protocol together with channel allocation is designed in this work for multi-channel multi-interface ad hoc networks. Our protocol applies to a distributed network where the source and the destination can be any nodes in the network, and the network-wide information sharing is not required. Instead of only developing an algorithm for path selection and channel allocation, the detailed signaling process is also designed and the overall protocol is evaluated through NS2 simulations.

The rest of the paper is organized as follows. Sec. II presents the system model. In Sec. III, the detailed routing protocol design and the channel allocation algorithm are described. Sec. IV illustrates the simulation results of the protocol before the paper is concluded in Sec. V.

II. SYSTEM MODEL

We consider a multi-hop wireless ad hoc network in which all nodes are stationary. Assume that there are $N \geq 2$ data channels and one control channel (CC), and that each node in the network is equipped with three transceivers: one is always tuned on the CC in order to transmit and receive control messages while the other two, denoted by TX and RX respectively, are responsible for transmitting and receiving data packets at two distinct channels. The structure of a node in the network is shown in Fig. F.1. To allow an interface access multiple channels, the transceivers need to switch among different channels at a cost of a switching delay. In other words, at a particular time instant, if a node will transmit a packet to its neighbor, the TX will switch to the channel on which the neighbor's RX is tuned and then communicate. Although not ignorable, the switching penalty can be made as short as 80 μs [14] with modern hardware.

Despite the cost for a network to have a CC dedicated for control message exchange, it brings us benefits in our design. The first advantage is that the connectivity of the network is easily maintained. It is obvious that the neighboring nodes cannot hear from one another if their interfaces are not tuned on the same channel. With a CC and its dedicated interface that perform as a *highway* among nodes, the connectivity of the network is easily maintained. Furthermore, if the neighboring nodes do not operate on the same channel, the sender of a broadcast message needs

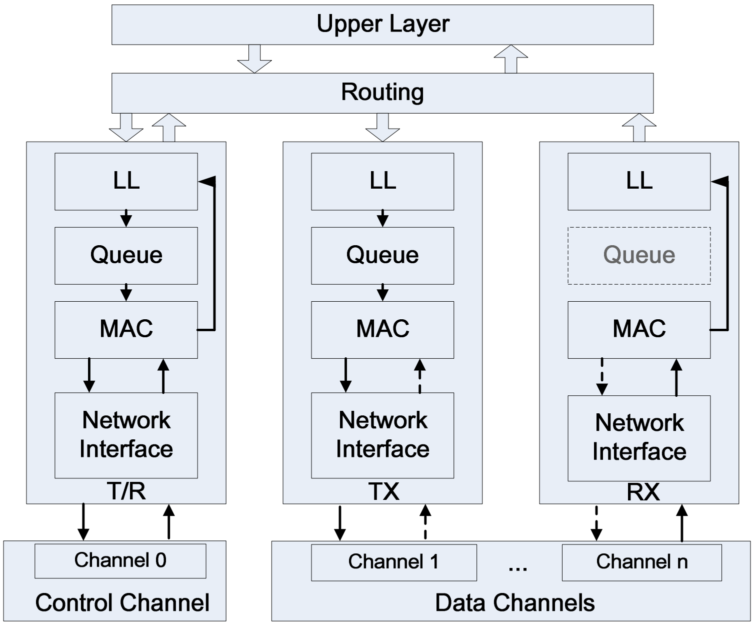

Figure F.1: The structure of the nodes in the multi-channel network: three interfaces for each node.

to send it several times on different channels. With a control channel, broadcast becomes easier. Another benefit is that we can expect that the broadcast packets from a node can be received by its neighbors at approximately the same time [15]. This property will be utilized in the route discovery process. Another consideration is the convenience for the potential extension of this protocol to multi-channel multi-hop cognitive radio networks in the future, in which a CC becomes more important as a *highway* for signaling [16].

III. ROUTING PROTOCOL DESIGN

As concluded in [6], the joint optimization of channel allocation and path selection is in general NP-hard. Therefore, we do not expect to design a routing protocol with channel allocation which can always achieve global optimization. Instead, we deal with routing and channel allocation separately, and aim at designing a plug-and-play distributed routing protocol which is expedient. For path discovery, we try to avoid selecting nodes with heavy traffic load, while for channel allocation, both the inter-path and the intra-path interference is to be mitigated based on an efficient heuristic scheme.

The designed routing protocol works in four steps, summarized as follows. The first step is local channel condition estimation. In order to calculate the interference and channel utilization in the neighborhood of a node, we propose a hopping sequence and probing message based scheme. When there is no traffic load at a node, the RX of a node will hop among different channels according to a pre-defined sequence. This RX hopping sequence of a node is broadcast on CC periodically. Therefore, the hopping sequence of a particular node can be known by all its neighbors. Then the TX of a node will tune on different data channels according to its neighbors' sequences and send probing HELLO messages to its neighbors. Based on the received HELLO messages at the RX side, the channel conditions can be estimated. The second step of this protocol is route discovery. When a route request is triggered from the upper layer, a path from the source to the destination needs to be discovered by sending a route request (RREQ) on CC. Nodes with lower traffic load is preferred in the path discovery process and a back-off scheme of RREQ forwarding is designed for this purpose.

When the RREQ arrives at the destination, the third step, i.e., channel allocation and route establishment, will be performed. According to the channel condition information that the RREQ gathered from each node along the path, the destination node will derive channel allocation along the path considering both the inter-path and the intra-path interference in the network. For intra-path interference avoidance, we can allocate various channels along a path of a flow. To avoid inter-path interference, our algorithm relies on the above mentioned channel condition information. When channel allocation along a path is decided, a routing reply (RREP) with the channel allocation information is generated and the RXs of nodes along the path will be tuned on to the allocated channels for the lifetime of the flow instead of hopping among multiple channels. The last step includes route maintenance in case of link failure. In the following, we will explain the design of the integrated routing protocol and channel allocation in detail.

A. Local Interference and Channel Utilization Estimation

As mentioned above, each node has its own pseudo-random hopping sequence among channels. If there is no ongoing flow at a node, the RX of that node will jump periodically on to different channels according to a pre-defined channel hopping sequence. The visiting probability for each channel is equal for all those channels and the sojourn time, denoted as T_s, in all those channels is identical. A beacon message, denoted by BEACON, is utilized to broadcast the hopping sequence of a node on CC with period T_b. In this way, all nodes will have knowledge about the hopping sequences of their neighbors. The time to live (TTL) of BEACON is set to be one.

Define a parameter, namely, average transmission data rate (ATR), to describe the interference and channel usage information between a communication pair. The $\text{ATR}_{i,j,k}$ value is a parameter indicating the condition of channel k from a neighboring node j to the concerned node i. Between a particular transmitter and receiver pair, the ATR value tells the preference of channels on which the packets will be *received*. The higher the ATR value, the better the channel condition. In order to calculate ATR, a channel probing procedure is carried out over period T_h. More specifically, within every T_h, the TX of a node will tune on to a randomly selected channel to which at least one of its neighbors is listening according to the hopping sequences of the neighbors' RXs. Then the TX will *consecutively* broadcast M HELLO messages with sequence No. i, $i \in [1, M]$ at a time. M is known by all nodes and each HELLO message has a field indicating its sequence number, and the TTL of each HELLO message is one.

In order to calculate an ATR value, it is important to define a start and an end of a round of channel probing procedure from a particular neighbor on a specific channel at an RX side. A round of channel probing starts when the *first* HELLO message is received by the RX if the previous round from the same neighbor on the same channel has finished. The *first* HELLO message is not necessarily the HELLO message with sequence No. 1, since the HELLO message with sequence No. 1 may be dropped due to collision. In other words, if a HELLO message with sequence No. 2 (or even a larger number) is received firstly, the procedure is also considered as started.

After a channel probing procedure starts, if a HELLO with sequence No. M is received from the same transmitter on the same channel, this round of channel probing is finished. In order to avoid the possible deadlock if the HELLO message with sequence No. M is dropped, we define T_{max} as the maximum time duration of a round of channel probing. It means that after T_{max} when a new round starts, the round of channel probing is finished, no matter the HELLO message with sequence No. M is received or not. After that, we can calculate the corresponding ATR value.

Let t_f and t_l be the time instants of the reception of the first and the last HELLO messages respectively in a round of channel probing, and the number of the received packets be M_r. Then the $\mathrm{ATR}_{i,j,k}$ value of channel k from a neighboring node j to the RX on node i is

$$\mathrm{ATR}_{i,j,k} = \frac{L_p(M_r - 1)}{(t_l - t_f)} \left(\frac{M_r - 1}{M - 1}\right)^w, \ \forall M_r > 1, \qquad (1)$$

where L_p is the length of the HELLO message and w is a non-negative integer. Eq. (1) has two parts, where $\frac{L_p(M_r-1)}{(t_l-t_f)}$ is the average data rate of these probing HELLO messages while the remaining part represents the impact of packet drop. Note that $M_r \leq M$. Therefore, the larger the w, the higher the penalty of the packet drop and the smaller the overall ATR. When $M_r = 1$, we set $\text{ATR}_{i,j,k} = 0$, meaning that the channel condition is very poor because $M - 1$ HELLO messages are dropped. The ATR value gives us an estimate of the data rate on the channel that the HELLO messages are received from a particular node, and it will be utilized in the channel allocation algorithm later on.

To make the ATR value precisely estimated, $T_s >> T_{max}$ must be satisfied. This is used to avoid the cases that RXs jump to another channel before ATR values are estimated.

B. Route Discovery

The route discovery process is triggered whenever a packet from upper layer is to be transmitted but there is no established route in the routing table. An RREQ is transmitted on the CC and the following information must be added in the RREQ message at each hop: the working channel of the RX in a node if its RX has already been fixed on a channel for ongoing flows; the ATR value from the upstream node to the downstream node in each channel for each hop.

In the route discovery process, on the one hand, one should avoid selecting a node whose TX potentially needs to switch among different channels due to the existence of ongoing flows across that node. On the other hand, we should avoid a node with heavy traffic load. Due to those considerations, a back-off timer which is proportional to the number of packets and the number of destinations in the TX queue is introduced to the RREQ forwarding. More specifically, if a node that has no packets buffered in the TX queue receives an RREQ, it will forward it immediately. Otherwise, it will wait for a period which is proportional to the number of destinations in the queue multiplied by the total queue length in terms of number of packets before the RREQ is forwarded. Represent the delay by $T_d = N_{dq}T_c$, where N_{dq} is the number of destinations multiplied by the queue length in a node, and T_c is the unit time delay of RREQ forwarding pre-defined in the system. In this case, the node that has lighter traffic load with fewer number of destinations will forward the RREQ faster therefore the path that goes through preferred nodes may arrive at destination earlier. In our protocol, we consider only the first arrived RREQ. To make an equal play, the simultaneous transmission of a broadcast RREQ from a node is required. Therefore, as mentioned earlier, CC makes it easier for implementation.

In the RREQ forwarding, the reverse route will be established. However, channel allocation is not made along the reverse path since it is not known whether the path is to be selected or not for data transmission. Therefore, the reverse route is not used for data packet forwarding. Nevertheless, the reverse route is still made available for RREP messages and TCP ACK messages transmitted on the CC.

When the RREQ arrives at the destination or an intermediate node which has a route for data packets to the destination, it will form an RREP to reply to the source. Before the RREP is sent, channel allocate algorithm is called in order to determine the working channel for the RXs along the path from the current node all the way back to the node closest to the source.

C. Channel Allocation and Route Establishment

Instead of performing joint routing and channel allocation, we will only consider channel allocation along the current path since the path is already selected. Then the question becomes how to minimize or eliminate interference along the path of a flow or among paths of various flows by allocating different channels to RXs at different nodes, given N data channels. In what follows, we will firstly analyze the complexity of the channel allocation problem in different cases and then propose an algorithm for channel allocation.

Consider the case that multiple flows co-exist in the network and different flows have various sources and destinations. Furthermore, it is assumed that there are no intersection nodes existing among the paths of different flows in the network. In this case, for a communication pair within a path of a flow, after selecting a channel at the RX side of a node, the working channel of the TX in the previous hop is also determined. To support simultaneous transmissions without interference, nodes which either get interference from this communication pair or generate interference to this communication pair cannot use the same channel. The interference among nodes from the same flow and among different flows is determined by the geometric location of nodes, interference range etc. Based on the potential interference, a *conflict graph* is established, in which nodes are connected if the same channel cannot be allocated to their RXs due to interference. If this conflict graph is N-colorable, the interference can be eliminated by using N channels. Clearly, it is a graph coloring problem. Moreover, we can start from an instance of a graph coloring problem and build an equivalent channel allocation scheme. It is well known that it is NP-hard to decide whether a graph is N-colorable except $N = 1$ and 2.

Let us take a look at a special case, i.e., the chain topology with a single flow as an example. The network topology and its conflict graph are illustrated in Fig. F.2. In this example, we assume that the maximum value of the carrier sensing range and the interference range is larger than two-hop distance and less than three-hop distance. We also assume that this network is built on 802.11 and that RTS/CTS is enabled. A UDP flow starts from node 0 to node 6. In this case, since node 0 is the source, on which channel its RX tunes is not important. However, the RX at node

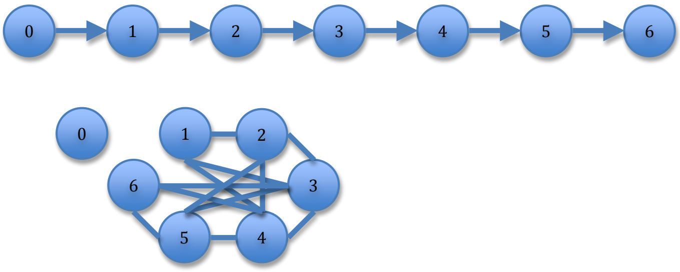

Figure F.2: Network with chain topology and its conflict graph.

1 cannot use the same channel as the RX on nodes 2, 3, and 4. Therefore, there is a line drawn in between of them in the conflict graph shown at the lower part of Fig. F.2. Similar analysis can be applied to other nodes.

Observing the conflict graph based on the chain topology, one can notice that all nodes connected to a particular node are its consecutive multiple-hop neighbors. Therefore, the graph is an *Interval graph* because it follows the consecutive ones property [17]. The chromatic number of an interval graph is simply the node number in its maximum clique. Although in general finding the maximum clique in a graph is NP-hard, it is not difficult to find it in an interval graph in polynomial time since the number of cliques in it is polynomially bounded [18]. More generally, if it is true that all nodes connected to a particular node in the corresponding conflict graph are among its consecutive multiple-hop neighbors along the path of a flow, we can get similar conclusion. When the chromatic number is found and it is less than or equal to N, the interference can be eliminated. Otherwise, mutual interference or channel sharing cannot be avoided by channel allocation.

Based on the above analysis, we conclude that it is currently infeasible to obtain a generally valid solution for optimal channel allocation in polynomial time even if perfect flow-path information is known by all nodes. Therefore, we consider a heuristic solution based on available information, i.e., the ATR value. From the information that is carried in RREQ, the nodes which already have flows will be found out, and the working channels of RXs in those nodes should not be changed since it may destroy the allocated channels for existing flows. The working channel for other RXs along the path will be allocated according to the algorithm described in Alg. 1. The basic idea of this algorithm is *to separate the allocated channels along the path as much as possible and to utilize channels with higher ATR values*. The algorithm works in a recursive manner. In each round of iteration, we firstly check if there is only one or even no channel which is not utilized by its one-hop neighbors along the path. If there is no channel left, we select the one with the maximum ATR value. If there is only one, just use this channel. Otherwise, it is meant that at least two channels are not utilized by its one-hop neighbors and we have more freedom to select. Then, we eliminate the channels with small ATR values in each node. Thirdly, the nodes which have the minimum number of remaining channels will get channel assigned since they have the lowest freedom in channel selection.

Before presenting the algorithms, the parameters utilized in Alg. 1 are summarized. Let $|\phi|$ be the number of elements in the set ϕ, where ϕ is a node or a channel set in general. It is denoted by α the set of nodes with channel already allocated along the path, and let $\bar{\alpha}$ represent the set of nodes out of α along the path. For a particular node, let the set of channels that are not occupied by its neighbors within i hops along the path be ξ_i. For example, for a particular node, ξ_2 denotes the set of channels that are not utilized by its one-hop or two-hop neighbors along the path. Let β be the set of nodes with the minimum $|\xi_1|$ in $\bar{\alpha}$. For a particular node in the selected path, denote the number of hops from the node to the source by r_s. Similarly, denote the number of hops from the node to the destination or the intermediate node with a route to the destination by r_d. Let $r = \max(r_s, r_d)$.

Once the channels are determined along the path for each node according to the above algorithm, the channel allocation information will be added in the RREP and it will be sent back to the source on CC. When an intermediate node receives an RREP, it will add in its routing table a new entry with the information about the destination, the next hop node, and the RX's working channel in the next hop. At the same time, its own RX will tune on to the allocated channel instead of jumping according to the pre-defined sequence during the route lifetime. This hopping sequence information adjustment will also be updated by BEACON in CC to its neighbors. If the data packets are queued up in the transmission queue, the TX of a node will stop the HELLO message probing in order to make more opportunities for data packet transmission. When a data packet is forwarded according to the route entry, the lifetime for the route is extended to the current time plus T_o, where T_o is the timeout value of an active route. If no data packet is sent during T_o, the route is discarded.

D. Route Maintenance

When a link break in an active route is detected, a route error (RERR) message is generated to notify other upstream nodes. Upon the reception of an RERR in an intermediate node back to the source, it marks its route to the destination as invalid by setting distance to the destination as infinity in the route table. Furthermore, if there is no valid route entries on a node, its RX will start hopping among different channels again in order to estimate the ATR values. When a source node receives an RERR, it can re-initiate the route discovery as presented in the previous subsection.

Algorithm 1 : channel allocation algorithm

```
repeat
    repeat
        Update $\alpha$.
        for each node in $\bar{\alpha}$, from destination to source do
            if $|\xi_1| == 1$ then
                Select this channel in $\xi_1$.
            else if $|\xi_1| == 0$ then
                Select the channel with the maximum ATR[1].
            end if
        end for
    until $|\xi_1|$ does not change for each node.
    for each node in $\bar{\alpha}$ do
        Find the channel with the maximum ATR, $\mathrm{ATR}_{max}$, in $\xi_1$.
        for each channel do
            if its ATR value is less than $\mathrm{ATR}_{max}/2$ then
                Remove this channel from $\xi_1$.
            end if
        end for
    end for
    Update $\beta$.
    for each node in $\beta$, from destination to source do
        for ($i = \min(r,N)$; $i \geq 1$; $i--$) do
            if $|\xi_i| == 0$ then
                Continue.
            else if $|\xi_i| == 1$ then
                Select the channel, and break.
            else
                Select the channel with the maximum ATR in $\xi_i$, and break.
            end if
        end for
    end for
until $\bar{\alpha} == \emptyset$
```

IV. SIMULATIONS AND NUMERICAL RESULTS

The proposed routing protocol is implemented based on an overall revision of an extended NS2 simulator [19]. The parameters in our simulations can be found in Table F.1. In what follows, we consider two topologies to evaluate the performance of the proposed routing protocol.

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[1] Note that the ATR values in this algorithm refer to the ones measured from the upstream node to the current node along the path.

A. Chain Topology with a Single Flow

The first scenario studied is a chain topology with distance 240 m between two neighboring nodes. The injected traffic is a UDP flow with packet size 500 bytes and it can make the network saturated. In the 802.11 MAC layer, we utilize the basic rate as 1 Mbps and the data rate as 11 Mbps with RTS/CTS enabled[2]. The transmission range is 250 m while the carrier sensing range is 550 m.

Table F.1: Parameters in simulations.

Parameter	T_{max}	T_c	T_s	T_b	T_h	T_o	M	W
Value	50 ms	2 ms	1 s	5 s	0.5 s	4 s	3	2

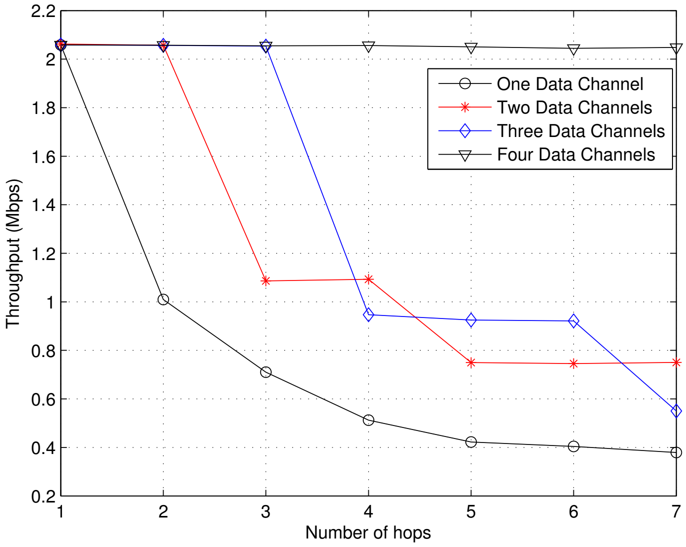

Figure F.3: Throughput as a function of number of hops in the chain topology.

The MAC layer throughput as a function of the number of hops is illustrated in Fig. F.3. As can be observed, the throughput curve with a single channel coincides with the results reported in [20]. However, with four channels, the network can have an approximately constant throughput independent of the number of hops. It is because that the conflict graph of the network under this set of configuration is four-colorable, and the output of the channel allocation algorithm can also find such allocation with precise ATR estimates. We also examine the case with more than four channels and similar results as the four channel case are observed. However, when only two or three channels are available, the throughput still decrease as the

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[2] To verify our protocol in the single-channel case with the well-known results in [20], we still follow the old-fashioned 802.11b parameters. Although there are only three non-overlapping channels in 802.11b, we adopt the same setting when more than three channels are utilized in order to keep coherence.

number of hops increases because channel sharing cannot be avoided totally. Interestingly, at hop number four, the three channel case has lower throughput than the two channel case. The reason is that in the two channel case, the collision probability is quite low since the RTS/CTS can be decoded by the interfaces on the same channel in the neighboring nodes. However, in the three channel case, the RTS/CTS messages can be sensed but not decoded by the interfaces that share the same channel based on the output of the channel allocation algorithm. Hence, the collision probability of the three channel case is higher than the two channel case, and this has been confirmed from the trace file analyses.

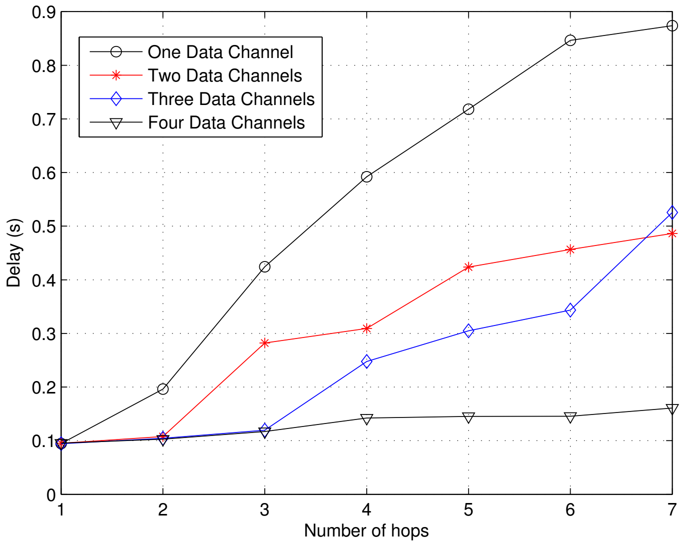

Figure F.4: End-to-end delay as a function of number of hops in the chain topology.

The average end-to-end delay is shown in Fig. F.4 with the same configuration as above. The results are the average value of more than 100 packets. In the first hop, the delay is around 100 ms and the queuing delay is the dominating part because of the heavily injected traffic load. The delay increases as the number of hops grows. Comparing the curves of delay with the throughput performance, these two sets of curves match with one another. Note that in the fourth hop, although low throughput is achieved in the three channel case because of the collisions, the end-to-end average packet delay is still lower since the packets without collision have lower delay, making the overall delay shorter than the two channels case. However, at the seventh hop, it suffers a higher delay than the two channels case since more collisions happened.

B. Hyperbolic Topology with Multiple Flows

To examine the performance of the routing protocol when multiple flows exist, we consider the topology as shown in Fig. F.5. We still adopt the same parameter configuration as in the previous scenario in the MAC layer. In this topology, Node 2 and Node 8 are within the carrier sensing range of each other. Similar configuration applies to Node 3 and Node 9. Therefore, if they utilize the same channel, the resource will be shared. We consider two UDP flows with saturated injected traffic and packet size 500 bytes. One flow is from Node 0 to Node 5, and the other one is from Node 6 to Node 11. The UDP flow between Node 0 and Node 5 is injected in the beginning of the simulation while the flow from Node 6 to Node 11 starts from approximately 20 s. Fig. F.6 illustrates the total throughput of the network based on our routing protocol given different number of data channels. The throughput labeled as optimal corresponds to the throughput when at least four data channels are available. With this topology and the injected flows, the chromatic number of the conflict graph of the network is four. Therefore, at least four data channels are required in order to make those flows separated. With at least four data channels, our routing protocol can achieve the optimal throughput in this topology given precisely estimated ATR values. From the simulation results, we can observe that when the number of data channels equals to one or three, the throughput of the network is lower than the optimal throughput, since channel sharing cannot be avoided. However, since the interference among two flows are avoided in the optimal case, the throughput of the network is doubled when the second flow is injected.

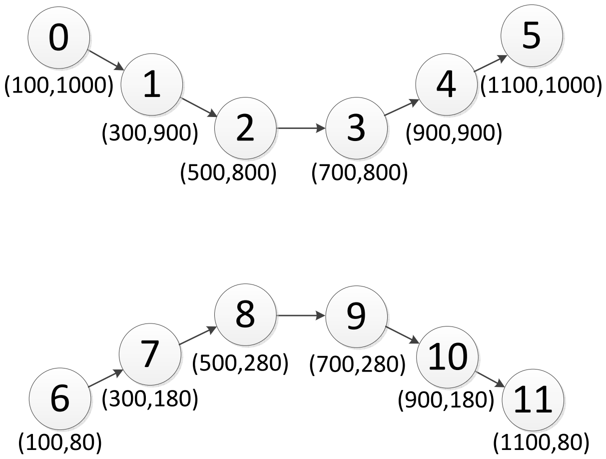

Figure F.5: Topology for a multi-flow scenario

To study the performance of the routing protocol with TCP flows, we inject two TCP flows into the above network instead of UDP. The packet size of the TCP flow is set to be 1000 bytes. Fig. F.7 plots the throughput of each flow when at least four data channels are available. As can be observed from this figure, when the second flow is injected at around 20.5s, both of the TCP flows have almost the same throughput, due to the properly separated TCP flows among different data channels. We have observed that if channels are not properly allocated, one TCP flow will capture the whole network while the other one becomes starved. With our routing protocol and channel allocation strategy, the unfairness in various TCP flows can be efficiently avoided since different TCP flows can be separated by using various channels. Interestingly, the throughput of both TCP flows becomes slightly lower after the new TCP flow arrives. The main reason is that the TCP ACK messages for different flows are transmitted in CC, which may become the bottleneck of the network.

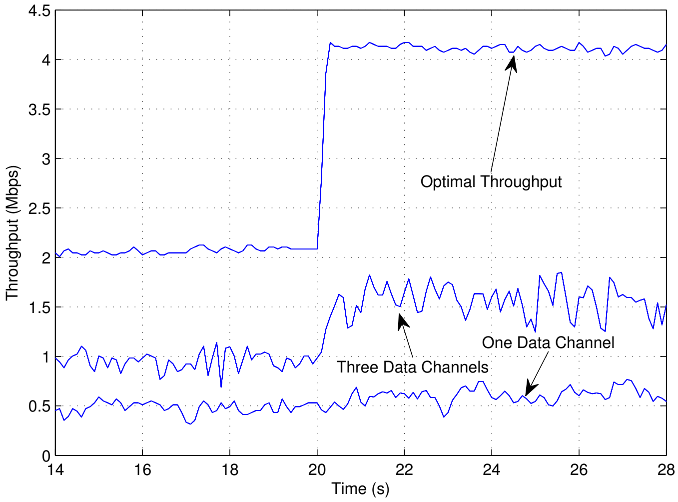

Figure F.6: Throughput of UDP flows.

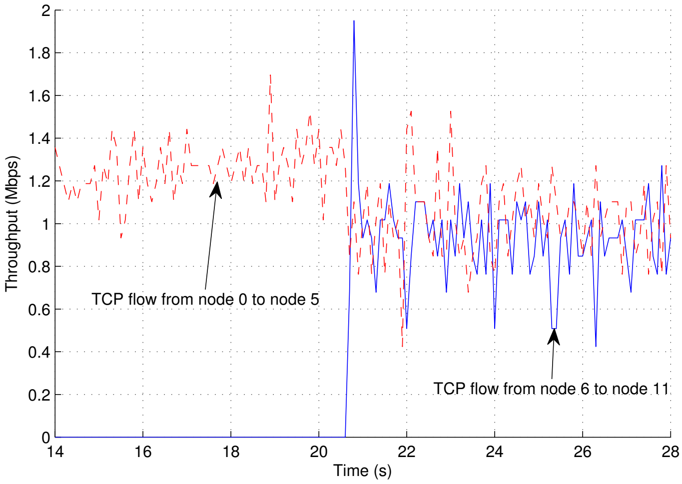

Figure F.7: Throughput of TCP flows.

C. Further Discussions

From the above simulation results, we demonstrate that the proposed routing protocol can efficiently explore the benefits of multiple channels and multiple interfaces, and mitigate both intra-path and inter-path interference over multiple hops. Admittedly, based on the proposed channel allocation algorithm and the information gathered along the path, there is *no* guarantee that the optimal throughput can *always* be achieved by this protocol for *arbitrary* topology even if more channels than the chromatic number exist. It is mainly because that the algorithm is heuristic-based while the channel allocation problem is in general NP-hard. Moreover, the ATR values may not always be accurately estimated[3]. In fact, non-optimal results, even though observed seldom in our simulations, are likely caused by imprecise ATR estimation. However, through extensive simulations, we experience that optimal throughput is achieved in approximately 96% or 84% cases of all simulation runs given five data channels for the chain or hyperbolic topology respectively.

V. CONCLUSIONS

In this paper, a novel on-demand routing protocol is proposed for multi-channel multi-hop ad hoc networks. The routing protocol utilizes probing messages to evaluate the channel conditions and mitigates the inter-path and the intra-path interference by allocating various channels along the flow path. Through extensive simulations, we demonstrate that the proposed routing protocol can efficiently explore the advantages of the existing multiple channels in multi-hop scenarios. The properly allocated channels lead to not only high network throughput for UDP traffic type, but also fairness among multiple TCP flows.

REFERENCES

[1] A. H. Mohsenian-Rad and V. W. S. Wong, “Joint logical topology design, interface assignment, channel allocation, and routing for multi-channel wireless mesh networks,” *IEEE Trans. Wireless Commun.*, vol. 6, no. 12, pp. 4432–4440, Dec. 2007.

[2] A. K. Das, R. Vijayakumar, and S. Roy, “Static channel assignment in multi-radio multi-channel 802.11 wireless mesh networks: Issues, metrics and algorithms,” in *Proc. IEEE GLOBECOM*, San Francisco, CA, USA, Nov. 2006.

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[3] For example, it is possible that a consecutive number of M HELLO messages pass through a highly congested link smoothly, resulting in unexpected high ATR values.

[3] A. Raniwala, K. Gopalan, and T. C. Chiueh, "Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks," *ACM Mobile Computing and Communications Review*, vol. 8, no. 2, pp. 50–65, 2004.

[4] A. Raniwala and T. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in *Proc. IEEE INFOCOM*, Miami, FL, USA, Mar. 2005.

[5] H. S. Chiu, B. Wu, K. L. Yeung, and K. S. Lui, "Widest spanning tree for multi-channel multi-interface wireless mesh networks," in *Proc. IEEE WCNC*, Las Vegas, NV, USA, Mar. 2008.

[6] M. Alicherry, R. Bhatia, and L. Li, "Joint channel assignment and routing for throughput optimization in multiradio wireless mesh networks," *IEEE JSAC*, vol. 24, no. 11, pp. 1960–1971, Nov. 2006.

[7] C. A. Jackson and H. B. Russell, "Channel-access and routing protocols to utilize multiple heterogeneous channels for ad hoc networks," in *Proc. IEEE MILCOM*, San Jose, CA, USA, Oct. 2010.

[8] J. So and N. H. Vaidya, "A routing protocol for utilizing multiple channels in multi-hop wireless networks with a single transceiver," in *Technical Report*, Univ. of Illinois at Urbana-Champaign, Oct. 2004.

[9] A. Zubow, M. Kurth, and J. Redlich, "Multi-channel opportunistic routing in multi-hop wireless networks," in *Technical Report*, Humboldt University Berlin, 2006.

[10] K. Jain, J. Padhye, V. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," in *Proc. ACM MOBICOM*, San Diego, CA, USA, Sep. 2003.

[11] X. Meng, K. Tan, and Q. Zhang, "Joint routing and channel assignment in multi-radio wireless mesh networks," in *Proc. IEEE ICC*, Istanbul, Turkey, Jun. 2006.

[12] H. Wu, F. Yang, K. Tan, J. Chen, Q. Zhang, and Z. Zhang, "Distributed channel assignment and routing in multiradio multichannel multihop wireless networks," *IEEE JSAC*, vol. 24, no. 11, pp. 1972–1983, Nov. 2006.

[13] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," in *Proc. ACM MOBICOM*, Philadelphia, PA, USA, Sep. 2004.

[14] V. Bahl, R. Chandra, and J. Dunagan, "SSCH: Slotted seeded channel hopping for capacity improvement in ad hoc networks," in *Proc. ACM MOBICOM*, Philadelphia, USA, Sep. 2004.

[15] P. Kyasanur and N. Vaidya, "Routing and interface assignment in multi-channel multi-interface wireless networks," in *Proc. IEEE WCNC*, New Orleans, LA, USA, Mar. 2005.

[16] I. F. Akyildiz, W. Y. Lee, and K. Chowdhury, "CRAHNs: Cognitive radio ad hoc networks," *Ad Hoc Networks*, vol. 7, no. 5, pp. 810–836, Jul. 2009.

[17] J. Meidanis, O. Porto, and G. P. Telles, "On the consecutive ones property," *Discrete Applied Mathematics*, vol. 88, pp. 325–354, 1998.

[18] B. Rosgen and L. Stewart, "Complexity results on graphs with few cliques," *Discrete Mathematics and Theoretical Computer Science*, vol. 9, no. 1, pp. 127–136, 2007.

[19] J. Zhong and J. Li, "Cognitive radio cognitive network simulator," http://stuweb.ee.mtu.edu/ ljialian/.

[20] J. Li, C. Blake, D. S. J. D. Couto, H. I. Lee, and R. Morris, "Capacity of ad hoc wireless networkss," in *Proc. ACM MOBICOM*, Rome, Italy, Jul. 2001.