Cognitive Radio
Report1

By
Li ZHU Zheng LI
Caoxie ZHANG Yun LI

Part I

Introduction

0.1 Cognitive Radio:A Extension of Software Radio

Cognitive radio(CR) refers to a paradigm in which either a network or a wireless node changes its transmission or reception parameters to communicate efficiently avoiding interference with licensed or unlicensed users. This intelligent radio is also viewed also as novel approach for improving the utilization of the radio electromagnetic spectrum. Before we delve into the content of CR, a glimpse of the origin of CR is presented here in order that a clear roadmap on how CR develops from previous technology which lays the foundation for it can be made. The key technology, which CR is based on, is Software-defined radio, sometimes shortened to software radio(SR). Joseph Mitola, who is internationally recognized as the "Godfather" of the software radio, coined the term in 1991 and he then promoted the term cognitive radio in 1998. SR is generally a multiband multimode radio that supports multiple air interfaces and protocols and is reconfigurable through software run on DSP or general-purpose microprocessors[1], which provides an ideal platform for the realization of cognitive radio. Build on SR, the goal of CR is to develop software agents that have such a high level of competence in radio domains that they may accurately be call "cognitive". In general, "cognitive radio is a particular extension of software radio that employs model-based reasoning about users, multimedia content, and communications context".[3]

0.2 Dynamic Spectrum Access in a Opportunistic Manner

While cognitive radio represents a much broader paradigm where many aspects of communication systems can be improved via cognition, in this report we mainly focus on a important application of CR – dynamic spectrum access.
textnormalThe idea of dynamic spectrum access is promoted in response to the limited available spectrum and inefficiency in spectrum usage now. According to Federal Communications Commission(FCC)[6], a large portion of the assigned spectrum is used sporadically and geographical variations in the utilization of assigned spectrum ranges from 15% to 85% with high variance in time. To deal with the underutilization of spectrum caused by a fixed spectrum policy, engineers, economists, and regulation communities are taking actions in searching for better spectrum management and techniques. In contrast to the current static spectrum management policy, the term dynamic spectrum access has broad connotations that encompass various approaches to spectrum reform. The diverse ideas presented at the first IEEE Symposium on New Frontiers in Dynamic Spectrum Access Networks(DySPAN) suggest the extent of this term and a discussion about the categorization of the dynamic spectrum access can be found in [5].

textnormalIn this report, we focus on the overlay approach under the hierarchical access model. The opportunistic manner will be adopted throughout. Since most of the spectrum is already assigned, the most important challenge is to share the licensed spectrum without interfering with the transmission of other licensed users.The cognitive radio enables the usage of temporally unused spectrum, which is referred to as itspectrum hole or itwhite space[18]. If this band is further used by a licensed user, the cognitive radio moves to another spectrum hole or stays in the same band, altering its transmission power level or modulation scheme to avoid interference.

0.3 A New Networking Paradigm

As mentioned above, the spectrum scarcity and inefficiency in its usage necessitates a new communication paradigm to exploit wireless spectrum opportunistically. From a networking perspective, this new model is referred to as NeXt Generation (xG) Networks as well as Dynamic Spectrum Access (DSA) and cognitive radio networks.[4]
textnormalThe concept of xG networks is actually bound up with the technology of cognitive radio and dynamic spectrum access. "Cognitive radio techniques provide the capability to use or share the spectrum in an opportunistic manner. Dynamic spectrum access techniques allow the cognitive radio to operate in the best available channel. More specifically, the cognitive radio technology will enable the users to (1) determine which portions of the spectrum is available and detect the presence of licensed users when a user operates in a licensed band (spectrum sensing), (2) select the best available channel (spectrum management), (3) coordinate access to this channel with other users (spectrum sharing), and (4) vacate the channel when a licensed user is detected (spectrum mobility)."[4]
In summary, the main functions for cognitive radios in cognitive networks can be summarized as follows:[4]

- Spectrum sensing: Detecting unused spectrum and sharing the spectrum without harmful interference with other users.
- Spectrum management: Capturing the best available spectrum to meet user communication requirements.
- Spectrum mobility: Maintaining seamless communication requirements during the transition to better spectrum.
- Spectrum sharing: Providing the fair spectrum scheduling method among coexisting cognitive network users.

The main focus of this report is on the algorithm optimization of spectrum sharing, which is detailed in the following.

0.4 Spectrum Sharing

In cognitive networks, one of the main challenges in open spectrum usage is the spectrum sharing. In some respects, spectrum sharing can be regarded to be similar to generic medium access control (MAC) problems in existing systems. However, substantially different challenges exist for spectrum sharing in cognitive networks. "The coexistence with licensed users and the wide range of available spectrum are two of the main reasons for these unique challenges."[4]
Here we outline the discussion on spectrum sharing in [4]. We first enumerate the steps in spectrum sharing in cognitive networks. The spectrum sharing process consists of five major steps:[4]

1. Spectrum sensing: An cognitive network user can only allocate a portion of the spectrum if that portion is not used by an unlicensed user. Accordingly, when an cognitive network node aims to transmit packets, it first needs to be aware of the spectrum usage around its vicinity.

2. Spectrum allocation: Based on the spectrum availability, the node can then allocate a channel. This allocation not only depends on spectrum availability, but it is also determined based on internal (and possibly external) policies. Hence, the design of a spectrum allocation policy to improve the performance of a node is an important research topic.

3. Spectrum access: In this step, another major problem of spectrum sharing comes into picture. Since there may be multiple cognitive network nodes trying to access the spectrum, this access should also be coordinated in order to prevent multiple users colliding in overlapping portions of the spectrum.

4. Transmitter-receiver handshake: Once a portion of the spectrum is determined for communication, the receiver of this communication should also be indicated about the selected spectrum. Hence, a transmitter-receiver handshake protocol is essential for efficient communication in cognitive networks. Note that the term ithandshake by no means restricts this protocol between the transmitter and the receiver. A third party such as a centralized station can also be involved.

5. Spectrum mobility: cognitive network nodes are regarded as "visitors" to the spectrum they allocate. Hence, if the specific portion of the spectrum in use is required by a

licensed user, the communication needs to be continued in another vacant portion. As a result, spectrum mobility is also important for successful communication between cognitive network nodes.

In addition, a classification of spectrum sharing techniques and the fundamental results about these techniques is given in [5]. Considering the tradeoff between system complexity and performance, hybrid techniques may be considered for the spectrum technique. In this report, we discuss a algorithm that is distributed, cooperative and overlay, namely in opportunistic manner.

Part II

Related Work

0.5 Opportunistic Spectrum Access(OSA)

Motivated by the conflict between finite spectrum resources and increasing number of wireless devices, open spectrum policy is employed which enables secondary users to share under-utilized spectrums with primary users (legacy users) opportunistically [7],[8],[9],[10].
[7], [8] focus on the algorithm design in Opportunistic Spectrum Access (OSA) assuming that each secondary users have full knowledge of the availability of all channels. In the context of open spectrum, the primary goal is to maximize utilization and provide fairness among different devices [7], [8] and the main problem lies in dealing with the fluctuation in spectrum availability (spectrum heterogeneity) and avoiding interference with primary users, which calls for coordination between users. Considering the case where the collection of spectrums forms a spectrum pool, algorithms can be designed to find an appropriate distribution among secondary users while minimizing interference. In a slow varying scenario where user location topology and available spectrum remains unchanged during the allocation, by modeling with graph theory and describing three utility functions, the spectrum allocation problem is reduced to a graph-coloring problem and proved to be PN-hard. As the centralized algorithm requires a central allocation server which is almost impossible to implement, a distributed version of the algorithm is built to fulfill the approximation. [7] While, in a mobile environment where numerous users keeps changing in position, this topology-optimized allocation algorithm requires huge amount of computation because the network has to perform global reassignment after any change in topology in order to maintain spectrum utilization and fairness among users. Actually, prior information can be obtained from previous spectrum assignment and used in distributed algorithms which further reduce the workload to adapt to topology change. A local bargain framework is introduced by [8] where users make self-organization into bargain groups and these groups make spectrum assignment independently to reach an approximation of optimal solution. Simulation validates this approach in maximizing the fairness-based spectrum utilization but with less complexity. [9], [10] focus on the physical layer and media access control layer (MAC) of OSA technology. Typically, OSA includes spectrum sensor at physical layer, sensing policy at MAC layer and access policy at MAC layer. [10] Considering the power-consuming nature of full spectrum sensing, it is unrealistic for battery-powered wireless nodes to perform full spectrum sensing. So we could only optimize our design based on the assumption that every secondary user only has access to a subset of the full spectrum. Keeping the interference perceived by primary users under a certain threshold, [9] proposes an analytical framework for OSA based on the theory of partially observed Markov decision process (POMDP). The solution to optimal POMPDA has exponential complexity, so a suboptimal greedy approach to POMDP is then proposed as a tradeoff to reduce complexity to linear level. It is proved

that the design of spectrum sensor and access policy can be decoupled from that of sensing policy without losing optimality. [10] Based on this, the joint OSA design can be formulated as an unconstraint POMDP which leads to insight of the best tradeoff between false alarm and miss detection.

0.6 Power allocation

In [13],Michael J. Neely developed a dynamic control strategy for minimizing energy expenditure in a time varying wireless network with adaptive transmission rates. The algorithm operates without knowledge of traffic rates or channel statistics, and yields average power that is arbitrarily close to the minimum possible value achieved by an algorithm optimized with complete knowledge of future events. Proximity to this optimal solution is shown to be inversely proportional to network delay. Neely then presented a similar algorithm that solves the related problem of maximizing network throughput subject to peak and average power constraints. The techniques used by Neely are novel and establish a foundation for stochastic network optimization. And in [11], Neely and Modiano made the formulation of a general power control problem for time-varying wireless networks, the characterization of the network layer capacity region, and the development of capacity achieving routing and power allocation algorithms that offer delay guarantees and consider the full effects of queueing.

0.7 Utility optimization

Modern data networks consist of a variety of heterogeneous components, and continue to grow as new applications are developed and new technologies are integrated into the existing communication infrastructure. While network resources are expanding, the demand for these resources is also expanding, and it is often the case that data links are loaded with more traffic than they were designed to handle. In order to provide high speed connectivity for future personal computers, hardware devices, wireless units, and sensor systems, it is essential to develop fair networking techniques that take full advantage of all resources and system capabilities. Michael J. Neely, Eytan Modiano and Chih-Ping Li designed a set of decoupled algorithms for resource allocation, routing, and flow control for general networks with both wireless and wireline data links and time varying channels in [12]. And they have presented a fundamental approach to stochastic network control for heterogeneous data networks. Simple strategies were developed that perform arbitrarily close to the optimally fair throughput point, with a corresponding tradeoff in end-to-end network delay. The strategies involve resource allocation and routing decisions that are decoupled over the independent portions of the network, and flow control algorithms that decoupled over dependent control valves at every node. Such theory-driven networking strategies will impact the design and operation of future data networks.

0.8 Application of Maximum Weighted Matching (MWM)

The resource allocation problem can be reduced to Maximum Weighted Matching (MWM) if secondary users transmit on the channel without interference on other channels, which is the case of orthogonal channels for secondary users[14]. A matching is to link two groups of nodes and no two links share the same node. A weigh of a matching is the sum of all the weight of the links belonging to the matching. MWM is to find the maximal weigh of a matching, with an $O(N^3)$ complexity algorithm found in presence[15]. Recent works [16],[17] have investigated Greedy Maximal Match Scheduling(GMS) to achieve near optimal results in a much simpler implementation. GMS firstly try to find the largest weight in the available links and remove all the links that have same nodes as in the first link. It then starts to find the largest weight of link in the remaining links. Same procedure is continued until no link is left. GMS algorithm has an O (LlogL) complexity with low overhead and the total weight is at least 1/2 of the weight of the MWM [16].

Bibliography

[1] J. Mitola. Software radios: wireless architecture for the 21st century. John Wiley & Sons Inc, 2000.

[2] J. Mitola et al., Cognitive radio: Making software radios more personal, IEEE Pers. Commun., vol. 6, no. 4, pp. 13C18, Aug. 1999.

[3] J. Mitola III, Cognitive radio for flexible mobile multimedia communication, in: Proc. IEEE International Workshop on Mobile Multimedia Communications (MoMuC) 1999, November 1999, pp. 3C10.

[4] I. F. Akyildiz, W-Y Lee, M. C. Vuran and S. Mohanty. NeXt generation/ dynamic spectrum access/cognitive radio wireless networks: a survey. Computer Networks Journal (Elsevier), vol. 50, pp. 2127-2159, Sept. 2006.

[5] Q. Zhao and B.M. Sadler. A survey of dynamic spectrum access: signal processing, networking, and regulatory policy. IEEE Signal Processing Magazine, vol. 24, no. 3, pp. 79-89, May, 2007.

[6] FCC, ET Docket No 03-222 Notice of proposed rule making and order, December 2003.

[7] C. Peng, H. Zheng, and B.Y. Zhao. Utilization and fairness in spectrum assignment for opportunistic spectrum access. ACM/Springer MONET, vol. 11, issue 4, Aug. 2006.

[8] L. Cao, H. Zheng. Distributed spectrum allocation via local bargaining. Proc. IEEE SECON, Sept. 2005.

[9] Q. Zhao, L. Tong, A. Swami, and Y. Chen. Decentralized cognitive MAC for opportunistic spectrum access in ad hoc networks: A POMDP framework. IEEE Journal on Selected Areas in Communications (JSAC): Special Issue on Adaptive, Spectrum Agile and Cognitive Wireles Networks, vol. 25, no. 3, pp. 589-600, April, 2007.

[10] Y. Chen, Q. Zhao, and A. Swami. Joint design and separation principle for opportunistic spectrum access. under submission to IEEE Transactions on Information Theory

[11] M. J. Neely, E.Modiano, and C. E Rohrs. Dynamic power allocation and routing for time varying wireless networks. IEEE Journal on Selected Areas in Communications, vol. 23, no. 1, pp. 89-103, Jan 2005.

[12] M. J.Neely, E. Modiano, and C. Li. Fairness and optimal stochastic control for heterogeneous networks. Proc. IEEE INFOCOM, March 2005.

[13] M. J. Neely. Energy optimal control for time varying wireless networks. IEEE Transactions on Information Theory, vol. 52, no. 7, July 2006.

[14] Urgaonkar, Michael J. Neely: Opportunistic Scheduling with Reliability Guarantees in Cognitive Radio Networks. PROC. IEEE INFOCOM, PHOENIX, AZ, APRIL 2008

[15] C. H. Papadimitriou and K. Steiglitz, Combinatorial Optimization: Algorithms and Complexity. Englewood Cli, New Jersey: Prentice-Hall, 1982.

[16] X. Lin and N. B. Shroff. The impact of imperfect scheduling on crosslayer rate control in wireless networks. Proc. IEEE INFOCOM, March 2005.

[17] P. Chaporkar, K. Kar, and S. Sarkar. Throughput guarantees through maximal scheduling in wireless networks. Proc. of 43rd Allerton Conference, Sept. 2005.

[18] S. Haykin, Cognitive radio: brain-empowered wireless communications, IEEE Journal on Selected Areas in Communications 23 (2) (2005) 201C220.