Survey on performance analysis of cognitive radio networks

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Abstract

Cognitive radio networks are being studied intensively. The major motivation for this is the heavily underutilized frequency spectrum. The development is being pushed forward by the rapid advances in software defined radio technology which enable a spectrum agile and highly configurable radio transmitter/receiver. We conduct a literature survey on recent major research advances in cognitive radio networks published recently in first-tier journals and conferences. Our viewpoint covers the problems at the MAC layer and above with a special emphasis on traffic performance in the networks.

1 Introduction

The amount of data traffic continues to increase and, moreover, the data is being transmitted increasingly over a wireless medium. To support the increased traffic demands, highly sophisticated MIMO and multi-user detection techniques together with complex radio resource management methods have been developed to push the achievable data rates close to their fundamental limits within the allocated spectrum. However, the spectrum allocation itself is nowadays still very rigid. Majority of the spectrum that could be reasonably utilized for communications is licensed. These licences are allocated over very long periods with very limited possibilities for sharing.

It has been observed that utilization of the licensed spectrum has large temporal variations, see, e.g., [15, 25] and the references therein. Additionally, measurements indicate that the average utilization of the licensed spectrum can be very low. This temporal variation creates so-called spectrum holes or white spaces [15], which refer to time intervals where portions of the total frequency spectrum are unused.

Dynamic Spectrum Access (DSA) refers to communication techniques that exploit the temporal variations of the licensed channels thus providing one approach for relieving the capacity bottlenecks of future wireless networks. The terms Flexible Spectrum Use (FSU) and Opportunistic Spectrum Access (OSA) are also commonly used in this context.

Cognitive radio [18] (CR) can be seen as one possible approach of implementing DSA especially on software defined radio (SDR) platforms. Originally CR referred to software radios extended with a self-awareness about their characteristics and requirements, in order to determine an appropriate radio etiquette to be used. However, since then the research has focused especially on the DSA subproblem of cognitive radio. Indeed, cognitive radio has become a general research term for radio technology where the radios are trying to use the holes of the licensed spectrum. See, e.g, Le et al. [23] for discussion on the semantics of cognitive radio as well as for a brief description of the history of the related research.

This article is a survey on the research on cognitive radio networks. Whereas "the cognitive radio problem" is to detect and utilize the spectrum holes, cognitive radio networks must meet the challenge of many cognitive radios attempting to utilize the spectrum simultaneously. Accordingly, our viewpoint takes us at MAC layer problems and above with the emphasis on traffic performance in the networks. An extensive survey of cognitive radio from a more physical layer view point is given in [12].

From the research literature we observe that a key feature of cognitive radio networks is the division of users into primary and secondary groups. Primary users are the license holders, which represent the current spectrum usage model whereas the secondary users constitute the cognitive part of the network. These secondary users are those who opportunistically attempt to access the channel when primary users are not using it. The important constraint of the setting is that the primary users should experience little or no interference from the secondary users and that the primary users are not required to react in any way to the needs of the secondary users. From a modeling point of view the primary users constitute a priority class.

The problem of secondary users is to detect and share the available spectrum holes. The detection of a primary user signal and available frequencies is often referred to as spectrum sensing. This is a popular topic in signal processing, e.g., applying approaches from machine learning [27, 9]. Spectrum sensing faces many unique challenges such as the errors occurring in fusing the spectrum availability data from different sources [7].

Accessing and sharing of the spectrum opportunities as such bear a close resemblance to the classic medium access problem which has been studied thoroughly. To a certain extent the situation can be seen also as spectrum sharing between multiple networks which has been historically termed coexistence, and it has been part of the network design in, e.g., IEEE 802.11, 802.15 and 802.16 networks [30]. However, interesting new challenges emerge from the variable nature of the resources. The available spectrum varies considerably and depends heavily on how the primary users are expected to tolerate interference on their spectrum. Novel problem settings arise for the secondary users also from the fact that the instantaneous information on the varying resources may be incomplete, or obtaining the information may cause significant delays.

This article is organized as follows. In Section 2 we review the general architecture of cognitive radio networks. In Section 3 we conduct a literature survey on recent major advances published recently in first-tier journals and conferences to provide an overview of the state-of-the-art research on cognitive networks. Finally, we conclude in Section 4.

2 Cognitive radio networks

In the following we present a general architecture of cognitive radio networks and a functional framework for them. The presentation here follows [1], which is similar to the the ones in [25, 30].

2.1 Architecture

Network components: The components of the cognitive radio network architecture, as shown in Figure 1, can be classified in two groups: the primary network and the cognitive radio network. The primary network (or licensed network) is referred to as an existing network, where the primary users have a license to operate in a certain spectrum band. If primary networks have an infrastructure, primary user activities are controlled through primary base stations. Due to their priority in spectrum access, the operations of primary users should not be affected by unlicensed users. The cognitive radio network does not have a license to operate in a desired band. Hence, additional functionality is required for cognitive radio users to share the licensed spectrum band. Cognitive radio networks also can be equipped with cognitive radio base stations that provide a single-hop connection to cognitive radio users. Finally, cognitive radio networks may include spectrum brokers that play a role in distributing the spectrum resources among different cognitive radio networks.

Spectrum heterogeneity: Cognitive radio users are capable of accessing both the licensed portions of the spectrum used by primary users and the unlicensed portions of the spectrum through wideband access technology. Consequently, the operation types for cognitive radio networks can be classified as licensed band operation and unlicensed band operation. The licensed band is primarily used by the primary network. Hence, cognitive radio networks are focused mainly on the detection of primary users in this case. In the absence of primary users, cognitive radio users have the same right to access the spectrum. Hence, sophisticated spectrum sharing methods are required for cognitive radio users to compete for the unlicensed band.

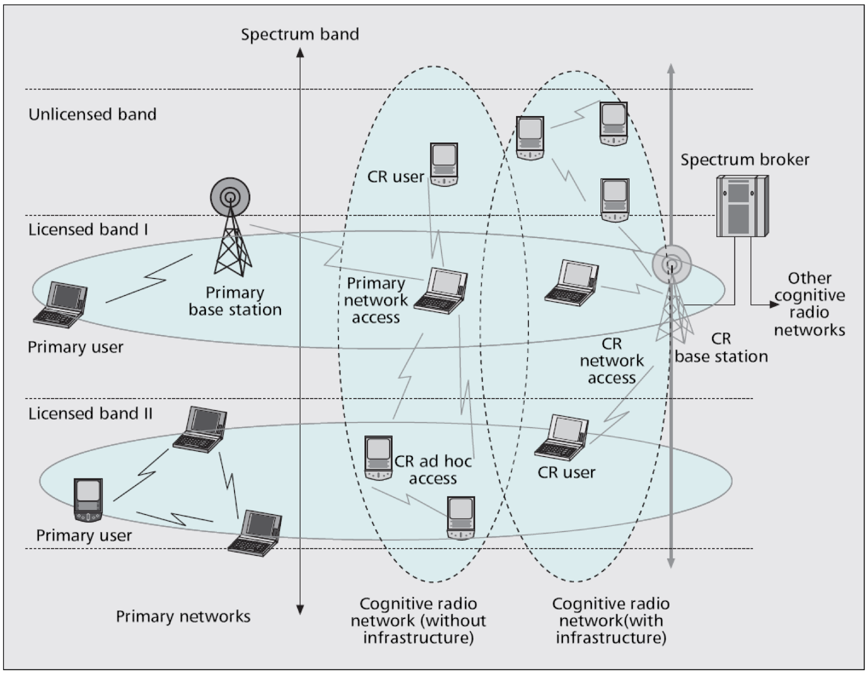

Figure 1: Network architecture for cognitive radio networks

Network heterogeneity: As shown in Figure 1, the cognitive radio users have the opportunity to perform three different access types:

- Cognitive radio network access: Cognitive radio users can access their own cognitive radio base station, on both licensed and unlicensed spectrum bands. Because all interactions occur inside the cognitive radio network, their spectrum sharing policy can be independent of that of the primary network.
- Cognitive radio ad hoc access: cognitive radio users can communicate with other cognitive radio users through an ad hoc connection on both licensed and unlicensed spectrum bands.
- Primary network access: Cognitive radio users can also access the primary base station through the licensed band. Unlike for other access types, cognitive radio users require an adaptive MAC protocol, which enables roaming over multiple primary networks with different access technologies.

2.2 Functional framework

Cognitive radio networks impose unique challenges due to their coexistence with primary networks as well as diverse QoS requirements. Thus, new spectrum management functions are required for CR networks with the following critical design challenges: cognitive radio networks should avoid interference with primary networks, QoS awareness to support different traffic types and seamless communication regardless of the appearance of primary users.

To address these challenges, a directory for different functionalities required for spectrum management in CR networks is given below:

- Spectrum sensing: A cognitive radio user can allocate only an unused portion of the spectrum. Therefore, a cognitive radio user should monitor the available spectrum bands, capture their information, and then detect spectrum holes.
- Spectrum decision: Based on the spectrum availability, cognitive radio users can allocate a channel. This allocation not only depends on spectrum availability, but is also determined based on internal (and possibly external) policies.
- Spectrum sharing: Because there may be multiple cognitive radio users trying to access the spectrum, cognitive radio network access should be coordinated to prevent multiple users colliding in overlapping portions of the spectrum.
- Spectrum mobility: Cognitive radio users are regarded as visitors to the spectrum. Hence, if the specific portion of the spectrum in use is required by a primary user, the communication must be continued in another vacant portion of the spectrum.

3 Literature survey

As is clear from the architecture description, above cognitive radio networks correspond to networks where a node needs to sense its surroundings to determine the proper free spectrum, possibly with help from other cognitive nodes, and simultaneously respecting the priority of the primary users. This is a highly dynamic and adaptive network.

The cognitive task of sensing the spectrum is very much related to signal processing. In the functional framework above this is the responsibility of spectrum sensing component.

Traffic performance related questions can be seen in the areas spectrum decision, sharing and mobility. Together all of these functions are responsible for guaranteeing an efficient usage of the wireless medium. To a large extent the performance related questions are similar to those already studied in wireless networking research. A specific feature brought by the cognitive environment is that the network must make the spectrum decision in a dynamic manner while taking into account the needs of the primary users.

The objective of this survey is to characterize the various problem formulations where performance is addressed. To achieve this, we have adopted the following methodological categorization of the related literature: Optimization formulations, Stochastic formulations, Game theory, Scaling laws, and Information theory.

3.1 Optimization formulations

3.1.1 Channel allocation

Papers considered here apply a static optimization formulation for channel allocation subject to special features of a cognitive radio network. The formulations can be considered static with respect to traffic. Commonly the optimization formulations are mixed integer linear programs. These NP-hard problems can then be approximated or heuristic solutions can be developed. Finally, distributed solutions based on the optimization framework have also been developed. All papers consider multihop networks and in spirit they are perhaps closer to DSA rather than a pure cognitive radio network as the channel sensing part is typically overlooked. In some of the papers the interaction between primary/secondary users is explicitly taken into account while in others it is not. Below we classify the papers according to this feature.

With explicit primary/secondary user modeling:

- The concept of a time-spectrum block, introduced in [40], represents the time for which a cognitive radio uses a portion of the spectrum, which is used to define the spectrum allocation problem as the packing of timespectrum blocks in a two dimensional time-frequency space, such that the demands of all nodes are satisfied best possible. The associated optimization problem is NP hard for which an approximation algorithm is given that assumes full knowledge of user demands. The algorithm performs within a small constant factor of the optimum, regardless of network topology. Finally, a distributed solution, b-SMART, is given which only utilizes local information, which is able to achieve high throughput and fairness under various scenarios.

- In [8], an optimization framework is derived for nodes equipped with a single tunable transceiver to monitor the primary channels while continuing operation in the secondary band. The sensing problem is addressed by formulating the task of sensing as a linear programming problem based on received signal strength values on any given channel. For evaluating the impact of using a particular free channel, an analytical model is derived for estimating interference caused at any arbitrary location and frequency. The channel assignment is formulated as an optimization problem that is solved at each user using the empty channels identified through sensing and analytical power estimations.

- In [29] a graph-theoretic model is developed that describes efficient and fair access by using three different policy-driven utility functions. It is shown that the optimal spectrum allocation problem can be reduced to a variant of the graph coloring problem (NP-hard). Subsequently, a lower bound on the maximal utilization problem where fairness is not considered is proven. Finally, a vertex labeling mechanism is described that can be used to construct both centralized and distributed approximation algorithms.

No primary/secondary user modeling:

- In [3], the idea is to use a central server for performing proactive planning periodically to regulate the long-term spectrum demand of the APs, while admitted APs coordinate among themselves in a distributed manner to adapt to instantaneous spectrum allocation. The long-term spectrum demand uses an interference-aware statistical admission control algorithm (based on similar concepts as effective bandwidth). Adaptation to instantaneous spectrum allocation due to varying traffic demands is based on a heuristic distributed solution to a utilization maximization problem. The APs coordinate and perform local actions to optimize the global spectrum allocation. While the optimization problem is NP-hard, the proposed algorithm has polynomial complexity and is still able to provide good performance.

- In [16], an optimization problem is formulated with the objective of minimizing the required network-wide radio spectrum resource for a set of source-destination pair rate requirements. Special attention is given to modeling of spectrum sharing and unequal (non-uniform) sub-band division, scheduling and interference modeling, and multipath routing. The resulting formulation is a mixed-integer non-linear program (NP-hard). For this novel lower and upper bound approximation schemes are derived, which yield an accurate characterization of the optimum.

- In [31] an optimization formulation is derived for maximizing data rates for a set of user communication sessions by jointly considering power control, scheduling, and routing. The problem results in a mixed integer nonlinear programming formulation for which an accurate upper bound is derived. Finally, a distributed optimization algorithm is developed that iteratively increases data rates for user communication sessions, which is able to achieve a near-optimal performance.

- In [36] a graph-theoretic optimization formulation is derived for the channel allocation problem and a heuristic distributed algorithm is proposed for solving it. However, no bounds or approximations are derived.

- Another channel allocation formulation is given in [24]. However, no bounds/approximations or distributed solutions are considered.

3.1.2 Channel probing

Optimal channel sensing/probing strategies for opportunistic spectrum access are analyzed in [4]. In the considered setting a transmitter seeks to maximize its achievable data rate by opportunistically transmitting over a select subset of a potentially large number of channels. Due to constraints on time, energy, and other resources, a transmitter may only be able to probe a limited number of channels. Methods from competitive analysis have been applied to design strategies that perform well in the worst case. For this a class, optimal randomized strategies are derived. The analysis uses probabilistic techniques characterizing the random nature of the wireless environment. However, there are no stochastic components in the analysis. Also, an algorithm that constructs a strategy belonging to this optimal class is derived. The interaction between primary and secondary users is not modeled. The article [4] is essentially a continuation of [5] by the same authors. Finally, note that channel probing was also considered partly in [8].

3.2 Stochastic models

Stochastic models refer to the dynamic models where the state of the channel (especially, due to primary user reservation) varies randomly in time. Within these models the research aims generally at maximizing the total throughput or utility of the secondary users under some constraints that make the problem interesting. Typical constraints include constrained sensing ability, limited channel availability information and delays in channel sensing. Constraints can also take a more abstract form. For instance, in [2] the authors consider a random (c, f) assignment in which channel switching is constrained so that each node is assigned a random f-subset of channels from the c available channels. Stochastic considerations are commonly associated with MAC protocol development for the secondary users.

Constrained sensing in cognitive networks becomes a MAC-layer issue. In [34] Su and Zhang study a distributed spectrum sensing based MAC scheme where every secondary user observes only one licensed channel and reports the availability data to other secondary users. This way all secondary users have a good idea which channels are available and they can coordinate the access rights among themselves. Channel availability is modeled using a two-state (ON/OFF) Markov chain and the secondary user performance is analysed using Markovian and $M/G^Y/1$ models. In [41] the authors model the channel occupancy as a Markov process for which transition probabilities are known but the state (i.e., which channels are occupied) can be observed only partially. Which channels to sense (it is assumed that nodes sense only subsets of channels) and which channels to access constitute a partially observable Markov decision process (POMDP) for which the authors are able to derive various performance results. The framework allows also accounting for sensing errors and collision probabilities. The state space of the Markov chain grows exponentially with respect to the number of channels and suboptimal strategies are developed based on the assumption that the channels are independent ON/OFF Markov processes. Whereas many MAC protocols developed for cognitive radio address primarily the dynamic/opportunistic spectrum allocation problem, [41] can be considered to be truly "cognitive" as the opportunistic user makes optimal decisions for sensing and access based on the belief vector that summarizes the knowledge of the network state based on all past decisions and observations. Without problems in sensing the MAC protocol development is simplified considerably and can be approached also from pure protocol development point of view, as in [14], where common control channel is used for contention on the surplus channels between the secondary users.

By introducing non-negligible delay in the sensing process, one obtains somewhat different problem settings. Kim and Shin [22] study MAC-layer spectrum sensing where sensing and transmission are carried out with a single antenna. Each sensing operation on a channels has a small time delay and they study how to maximize the spectrum opportunities and minimize the delay in finding an available channel. Channel availability is modeled using an ON/OFF process to reflect the primary users usage pattern. A related research by Chaporkar and Proutière [6] studies also the trade-off in efficiency of channel allocation with the delay of gathering channel information. Their joint-optimal probing and scheduling framework primarily addresses the case of variable channel states due to noise and interference, but can also be directly applied in the dynamic spectrum access context.

If the spectrum sensing or channel access is random, interesting variants of the classic random access results emerge. In [17] the authors consider the performance of three random access (with sensing) methods in terms of primary user protection. The channel model has exponential idle times and general busy periods (busy periods of an M/G/1 queue). Two phase random access model was considered in [33]: The primary users access the channel randomly and the vacant slots are available to secondary users who resolve the transmissions using similar random access in the available time slots. The authors extend the study also to the case where sensing can be imperfect or certain amount of interference can be tolerated in primary class. In case of perfect sensing the maximum sum throughput is achieved when the average rate of the secondary users equals the average number of unoccupied channels.

Research has also addressed the Erlang model variants in the context of cognitive networks. Ishibashi et al. [19] present a classic call based traffic model for both primary and secondary users in an environment which has multiple operators. Their premise is that each licensed operator has a number of channels available. Classic traffic utilizes channels only in its home network whereas cognitive traffic can borrow unused resources also from other licensed users, but will be dropped to make room for classic traffic if necessary. They also introduce the concept of virtual wireless network which refers to an operator/traffic that has no home network capacity at all but relies completely on the surplus capacity of others to show that it is feasible. The authors carry out standard blocking probability analysis and argue that additional traffic can be indeed allowed without deteriorating performance in the licensed traffic.

In addition to the Markov models, stochastic control is one approach for modeling the cognitive access. Although this direction is somewhat less explored, Urgaonkar and Neely [37] present Lyapunov optimization techniques to maximize the throughput utilities of dynamic secondary users under the collision constraints of the static primary users. In addition to centralized computation a distributed (heuristic) implementation is proposed.

3.3 Game theory

Challenges of cognitive networks have been addressed also from the game theoretic viewpoint, where spectrum sharing is seen as a competition. The game theoretic objective is to reach the Nash Equilibrium where no user can get utility benefit by changing its own allocation strategy alone.

In [28] the authors discuss cognitive networks and game theory in general. They identify conditions that have to be met when game theoretic analysis can be applied and identify potential games in the cases where the radios can adjust their power levels and signature waveforms.

Another general overview of the approach is provided n the thesis by Thomas [35]. Three critical design decisions that affect the performance of the cognitive network are identified: the selfishness of the cognitive elements, their degree of ignorance, and the amount of control they have over the network. Potential and quasi-concave games are investigated in the cognitive network context. Cognitive networks are also applied to maximizing multicast route lifetime in wireless networks and to minimize the transmission power and spectral impact of a wireless network topology.

Practical resource allocation in the game theory context has also received considerable attention. In [13] the authors consider a model where communicating pairs of nodes share a single collision domain. In their model each node has a number of radio devices which it can allocate to a set of channels. Multiple devices can be assigned to the same channel but the total rate of the channel can decrease as more devices access it. The authors show that despite the non-cooperative nature of the users (each trying to maximize its own rate) the solution converges to a load balancing solution. Algorithms are also provided for achieving this solution under different sets of available information.

Wang et al. [39] take a more information theoretical approach to resource sharing. They model explicitly SINR dependent transmission rates and power allocation of non-cooperative rate-maximizing users over multiple channels. They show that the solution converges to a Nash equilibrium in a price-based iterative water-filling algorithm, which can also be used in a distributed fashion. The authors also present a protocol to implement their scheme.

3.4 Scaling laws

Scaling laws for the performance of cognitive networks have been derived in [38], [26] and [11]. The considered settings are very different from the commonly cited results on the scaling laws of multihop wireless networks. In fact, in the research only single-hop connectivity has been assumed and the focus is on characterizing the scaling behavior of the interference of the secondary users on the primary users.

In [38] the authors consider a cognitive network consisting of n randomly located pairs of cognitive transmitters and receivers communicating simultaneously in the presence of multiple primary users. Assuming single-hop transmission it is shown that, with path loss exponent larger than 2, the cognitive network throughput scales linearly with the number of cognitive users. Additionally, bounds are obtained on the required radius for a primary user so that within this radius no cognitive user may be active in order to achieve a given outage probability for the primary user. Similar scaling results are also obtained in a more recent article [11].

The analysis in [26] assumes that interference from the secondary users is solely due to fading and path loss is not taken into account. The secondary network is defined to be useful if at least one node could transmit while maintaining its interference to the primary users below a given threshold. The results characterize the limiting behavior between the threshold, outage probability and the number of secondary users.

3.5 Information theory

An information theoretic approach is applied in [10, 21, 20, 32]. The objective in these studies is to characterize the achievable rates in a cognitive radio network under various assumptions on how the secondary users interfere with the primary users (which depends on the underlying properties of the used communication methods). The papers provide fundamental understanding on the capacity of the system. However, as is usual in information theoretic studies, the analysis does not address the impact of the stochastic nature of different traffic types. However, the information theoretic approach provides a very useful foundation for analyzing the traffic performance of cognitive systems.

The article [32] provides an overview of the different approaches for the primary/secondary data transmission and their impact on the achievable performance. The approaches can be categorized as *underlay, overlay* and *interweave.* Of these the underlay and overlay approaches in fact allow concurrent primary and secondary transmissions. However, there are subtle differences in the approaches depending on the use of so-called side information and specific coding methods. On the other hand, the interweave method refers to the idea of complete interference avoidance from the secondary users to primary users. Thus, it is clear that concurrent primary and secondary transmissions in the overlay technique can potentially provide higher secondary throughputs than the conservative interweave approach. A simple comparison between the achievable rates using the overlay and the interweave approaches are given in [32]. The mathematical models of the overlay approaches are in [10] and [21]. The models corresponding to the interweave approach can be found in [20]

4 Conclusions

Cognitive radio networks are being studied intensively. The major motivation for this is the currently heavily underutilized frequency spectrum. The development is being pushed forward by the rapid advances in SDR technology enabling a spectrum agile and highly configurable radio transmitter/receiver. A fundamental property of the cognitive radio networks is the highly dynamic relationship between the primary users having an exclusive priority to their respective licensed spectrum and the secondary users representing the cognitive network devices. This creates new challenges for the network design which have been addressed applying varies approaches as has been discussed in the previous sections.

The fundamental problems in detecting the spectrum holes are naturally mostly related to signal processing at the physical layer. From the traffic point of view careful attention must be paid in order to guarantee an efficient usage of the wireless medium while simultaneously providing fairness between competing users and respecting the priority of the primary users.

Methods from information theory provide useful tools for performance analysis by characterizing the achievable rates of the wireless channel in a cognitive environment. Stochastic analysis is needed to characterize traffic performance in such systems under, e.g., fairness criteria. The analysis needs to be further complemented with optimal strategies for dealing with the dynamics between primary/secondary users, and also the tradeoffs in channel probing provide an interesting opportunities for modeling. The above areas are far from being thoroughly understood. In summary, the cognitive radio network provides a rich field of study with many fundamental and challenging problem settings for future research.

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