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Cognitive Radio: From Theory to Practical Network Engineering

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1.1 Introduction

Under utilization of radio spectrum in traditional wireless communications systems [30], along with the increasing spectrum demand from emerging wireless applications, is driving the development of new spectrum allocation policies for wireless communications. These new spectrum allocation policies, which will allow unlicensed users (i.e., secondary users) to access the radio spectrum when it is not occupied by licensed users (i.e., primary users) will be exploited by the *cognitive radio* (CR) technology. Cognitive radio will improve spectrum utilization in wireless communications systems while accommodating the increasing amount of services and applications in wireless networks. A cognitive radio transceiver is able to adapt to the dynamic radio environment and the network parameters to maximize the utilization of the limited radio resources while providing flexibility in wireless access [45]. The key features of a CR transceiver include awareness of the radio environment (in terms of spectrum usage, power spectral density of transmitted/received signals, wireless protocol signaling) and intelligence. This intelligence is achieved through learning for adaptive tuning of system parameters such as transmit power, carrier frequency, and modulation strategy (at the physical layer), and higher-layer protocol parameters.

Implementation of a cognitive radio will be based on the concept of dynamic spectrum access (DSA). Through DSA, frequency spectrum can be shared among primary users and cognitive radio users (i.e., secondary users) in a dynamically changing radio environment. There are two major flavors of dynamic spectrum access: dynamic licensing (for dynamic exclusive use of radio spectrum) and dynamic sharing (for coexistence) [3, 120]. Dynamic sharing can be of two types: horizontal spectrum sharing and vertical spectrum sharing. In the former case, all users/nodes have equal regulatory status while in the latter case all users/nodes do not have equal regulatory status (i.e., there are primary users and secondary users) and secondary users opportunistically access the spectrum without negatively affecting the primary users' performance.

In this chapter, we focus on vertical spectrum sharing in a cognitive radio network. In particular, we outline the recent information theoretic advances pertaining to the limits of such networks. Information theory provides an ideal framework as well as tools and metrics for analyzing the fundamental limits of communication. The limits obtained provide benchmarks for the operation of cognitive networks, allowing researchers and engineers to gauge the efficiency of any practical network and guide their design. Spectrum sensing is one of the major functions of a cognitive radio the goal of which is to determine the activity of licensed user by periodically observing signals on the target frequency bands. We discuss some theoretical results on the effect of side information (e.g., spatial locations of the users, transmission probability of primary users) on the cognitive sensing performance. Analysis of interference is required to design cognitive radio parameters so that the the impact of interference to the primary users can be minimized. We provide examples of this interference analysis in a cognitive radio system.

To this end, we discuss the practical implementation aspects of vertical spectrum sharing employing either an interference control or an interference avoidance approach and discuss open research challenges. An interference avoidance approach requires spectrum sensing and secondary users are allowed to access a particular spectrum band only if primary users are not detected on that band by certain sensing technique [88, 102]. An interference control approach allows primary and secondary users to transmit simultaneously on the same frequency band. Transmission powers of secondary users, however, should be carefully controlled such that the total interference created by secondary users at each primary receiver be smaller than the maximum tolerable level. In fact, this maximum interference level corresponds to an interference temperature limit which is mandated by FCC and/or primary network operators.

The rest of the chapter is organized as follows. Section 1.2 focuses on the information theoretic limit of communication in a cognitive radio channel shared by a primary transmitter-receiver pair and a secondary transmitter-receiver pair. Section 1.3 describes some specific results on the cognitive sensing performance with side information on the spatial locations of the users. Section 1.4 focuses on the impact of cognitive users on the primary users in terms of interference power. Sections 1.5 and 1.6 describe the modeling and engineering design approaches for the two spectrum access paradigms, namely, the interference control and the interference avoidance paradigms, respectively. In the rest of the chapter, we will use the terms "cognitive user" and "secondary user" interchangeably.

1.2 Information Theoretic Limits of Cognitive Networks

In this section, we emphasize and explore the impact of *cognition*, defined as extra information (or side information) the cognitive radio nodes have about their wireless environment, on the information theoretic limits of communication.

1.2.1 Cognitive Behavior: Interference Avoidance, Control, and Mitigation

Cognitive networks should achieve better performance than standard homogeneous networks[5] as they are able to (1) exploit the nodes' cognitive abilities, i.e. sensing and adapting to their wireless environment, and (2) often (but not necessarily) exploit new policies in secondary spectrum licensing scenarios in which the agile cognitive radios are permitted to share the spectrum with primary users. Naturally, the extent to which the performance of the network can be improved depends on what the cognitive radios know about their spectral environment, and consequently, how they adapt to this. Cognitive behavior, or how the secondary cognitive users employ the primary spectrum, may be grouped into three categories, as also done with slight variations in [22, 26, 28, 39], each of which exploits varying degrees of knowledge of the wireless environment at the secondary user(s):

- **Interference avoidance (spectrum interweave):** The primary and secondary signals may be thought of as being orthogonal to each other: they may access the spectrum in a Time-Division-Multiple-Access (TDMA) fashion, in a Frequency-Division-Multiple-Access (FDMA) fashion, or in any fashion that ensures that the primary and secondary signals do not interfere with each other. The cognition required by the secondary users to accomplish this is knowledge of the spectral gaps (in for example time, frequency) of the primary system. The secondary users may then fill in these spectral gaps.
- **Interference control (spectrum underlay):** The secondary users transmit over the same spectrum as the primary users, but do so in a way that the interference seen by the primary users from the cognitive users is controlled to an acceptable level, captured by primary QoS constraints.[6] The cognition required is knowledge of the "acceptable levels" of interference at primary users in a cognitive user's transmission range as well

[5] Networks is which no nodes are cognitive radios.
[6] What constitutes an acceptable level will be described later and it may vary from system to system.

as knowledge of the effect of the cognitive transmission at the primary receiver. This last assumption boils down, in classical wireless channels, to knowledge of the channel(s) between the cognitive transmitter(s) and the primary receiver(s).

- **Interference mitigation (spectrum overlay):** The secondary users transmit over the same spectrum as the primary users, but in addition to knowledge of the channels between primary and secondary users (nature), the cognitive nodes have additional information about the primary system and its operation. Examples are knowledge of the primary users' codebooks, allowing the secondary users to decode primary users' transmissions, or in certain cases even knowledge of the primary users' message.

We consider a simple channel in which a primary transmitter-receiver pair (white, $\mathcal{PT}_x, \mathcal{PR}_x$) and a cognitive transmitter-receiver pair (grey, $\mathcal{ST}_x, \mathcal{SR}_x$) share the same spectrum, shown in Fig. 1.1. For this simple channel we will derive fundamental limits on the communication possible under each type of cognitive behavior. One information theoretic metric that lends itself well to illustrative purposes and is central to many studies is the capacity region of the channel. Under Gaussian noise, we will illustrate different examples of cognitive behavior and will build up to the right illustration in Fig. 1.1, which corresponds to the rates achieved under different levels of cognition.

The basic and natural conclusion is that, the higher the level of cognition at the cognitive terminals, the higher the achievable rates. However, increased cognition often translates into increased complexity. At what level of cognition future secondary spectrum licensing systems will operate will depend on the available side information and network design constraints.

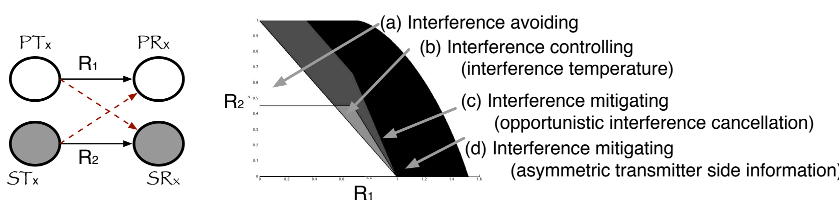

Fig. 1.1. The primary users (white) and secondary users (grey) wish to transmit over the same channel. Solid lines denote desired transmission, dotted lines denote interference. The achievable rate regions under four different cognitive assumptions and transmission schemes are shown on the right. (a) - (d) are in order of increasing cognitive abilities.

1.2.2 Information Theoretic Basics

A communication channel is modeled as a set of conditional probability density functions relating the inputs and outputs of the channel. Given this probabilistic characterization of the channel, the fundamental limits of communication may be expressed in terms of a number of metrics of which *capacity* is one of the most known and powerful. Capacity is defined as the supremum over all rates (expressed in bits/channel use) for which reliable communication may take place. While capacity is central to many information theoretic studies, it is often challenging to determine. Inner bounds, or achievable rates, as well as outer bounds to the capacity may be more readily available. For more precise information theoretic definitions we refer the reader to [18, 19, 114].

The additive white Gaussian noise (AWGN) channel with *quasi-static fading* is the example most used in this section. In the AWGN channel, the output Y is related to the input X according to $Y = hX + N$, where h is a fading coefficient (often modeled as a Gaussian random variable), and N is the noise which is $N \sim \mathcal{N}(0,1)$. Under an average input power constraint $E[|X|^2] \leq P$, the well-known capacity is given by $C = \frac{1}{2}\log_2\left(1+|h|^2P\right) = \frac{1}{2}\log_2\left(1+\text{SINR}\right) := \mathcal{C}(\text{SINR})$, where SINR is the received signal to interference plus noise ratio, and $\mathcal{C}(x) := \frac{1}{2}\log_2(1+x)$.

We now proceed to analyzing three different classes of cognitive behavior.

1.2.3 Interference Avoidance: Spectrum Interweave

Secondary spectrum licensing and cognitive radio was arguably conceived with the goal and intent of implementing the interference-avoiding behavior [45,82]. Cognition in this setting corresponds to the ability to accurately detect the presence of other wireless devices; the cognitive side-information is knowledge of the spatial, temporal and spectral gaps, or *white-spaces* a particular cognitive Tx-Rx pair would experience. Cognitive radios would adjust their transmission to fill in the spectral (or spatial/temporal) void, as illustrated in Fig. 1.2, with the potential to drastically increase the spectral efficiency of wireless systems.

This type of behavior requires knowledge of the spectral white spaces. In a realistic system the secondary transmitter would spend some of its time sensing the channel to determine the presence of the primary user. As an illustrative example and idealization, we assume that knowledge of the spectral gaps is perfect: when primary communication is present the cognitive devices are able to precisely determine this presence, instantaneously. While such assumptions may be valid for the purpose of a theoretical study, and provide outer bounds on what can be realistically achieved, practical methods for detecting primary signals have also been of great interest recently. A theoretical framework for determining the limits of communication as a function of the sensed cognitive transmitter and receiver gaps is formulated in [55, 95]. Studies on how detection errors may affect the cognitive and primary systems are found in [92,100,101]. Because current secondary spectrum licensing proposals demand detection guarantees of primary users at extremely low levels in harsh fading environments, a number of works have suggested improving detection capabilities through allowing multiple cognitive radios to collaboratively detect the primary transmissions [20, 32, 37, 81].

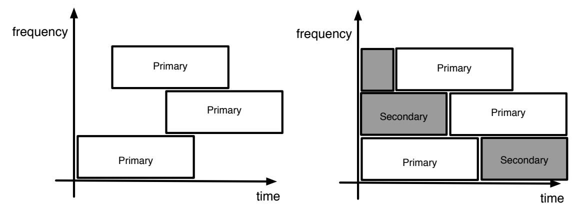

Fig. 1.2. Interference-avoidance: A cognitive user senses the time/frequency "white spaces" and opportunistically transmits over the detected spaces.

Under our idealized assumptions, the rates R_1 of the primary Tx-Rx pair and R_2 of the cognitive Tx-Rx pair achieved through ideal white-space filling are shown as the inner white triangle of Fig. 1.1. When a single user transmits the entire time in an interference-free environment, the intersection points on the axes are attained. The convex hull of these two interference-free points may be achieved by time-sharing (TDMA fashion). Where on this line a system operates depends on how often the primary user occupies the specific band. If the primary and secondary power constraints are P_1 and P_2, respectively, then the white-space filling rate region may be described as:

$$\text{White-space filling region (a)} = \{(R_1, R_2) | 0 \leq R_1 \leq t\mathcal{C}(P_1), 0 \leq R_2 \leq (1-t)\mathcal{C}(P_2), 0 \leq t \leq 1\}.$$

Interference Avoidance through MIMO

In addition to detecting the spectral white-spaces, interference at the primary user may be avoided or controlled if the cognitive user is equipped with multiple antennas, and is able to place its transmit signal in the null space of the primary users receive channel. In this scenario, the channel between the secondary transmit antennas and the primary receive antennas must be known. Studies where the cognitive rates are maximized subject to primary user communication guarantees (such as maximum average interference power constraints) are considered in [53, 54, 115, 117–119]. The scenarios considered in these papers can be considered as an *interference-avoiding* scheme if the tolerable interference at the primary receivers is set to zero, other-wise it falls under the *interference-controlled* paradigm we look at in the following subsection.

1.2.4 Interference Control: Spectrum Underlay

When the interference caused by the secondary users on the primary users is permitted to be below a certain level (according to QoS constraints), the more flexible *interference controlled behavior* emerges. We note that this type of interference controlled behavior covers a large spectrum of cognitive behavior and we highlight only three examples: an example of the resulting achievable rate region in small networks, and throughput scaling laws in two different types of large spectrum underlay networks.

Underlay in Small Networks: Achievable Rates

A cognitive radio may simultaneously transmit with the primary user(s) while using its cognitive abilities to control the amount of harm it inflicts upon them. One common definition of harm involves the notion of *interference temperature*, a term first introduced by the FCC [66] to denote the average level of interference power seen at a primary receiver. In secondary spectrum licensing scenarios, the primary receiver's interference temperature should be kept at a level that will satisfy the primary user's desired quality of service. Provided the cognitive user knows (1) the maximal interference temperature for the surrounding primary receivers, (2) the current interference temperature level, and (3) how its own transmit power will translate to received power at the primary receiver, then the cognitive radio may adjust its own transmission power so as to satisfy any interference temperature constraint the primary user(s) may have. The work in [33, 38, 110, 113] consider the capacity of cognitive systems under various receive-power (or interference-temperature-like) constraints.

As an illustrative example, we consider a very simple interference-temperature based cognitive transmission scheme. Assume in the channel model of Fig. 1.1 that each receiver treats the other user's signal as noise, a lower bound to what may be achieved using more sophisticated decoders [103]. The rate region obtained is shown as the light grey region (b) of Fig. 1.1. This region is obtained as follows: we assume the primary transmitter communicates using a Gaussian codebook of constant average power P_1. We assume the secondary transmitter allows its power to lie in the range $[0, P_2]$ for P_2 some maximal average power constraint. The rate region obtained may be expressed as:

$$\begin{aligned}&\text{Simultaneous-transmission rate region (b)}\\&=\left\{(R_1,R_2)|0\le R_1\le \mathcal{C}\left(\frac{P_1}{h_{21}^2P_2^*+1}\right),\right.\\&\qquad\left.0\le R_2\le \mathcal{C}\left(\frac{P_2^*}{h_{12}^2P_1+1}\right),\ 0\le P_2^*\le P_2\right\}.\end{aligned}$$

The actual value of P_2^* chosen by the cognitive radio depends on the interference-temperature, or received power constraints at the primary receiver.

Underlay in Large Networks: Scaling Laws

Information theoretic limits of interference controlled behavior has also been investigated for large networks, i.e. networks whose number of nodes $n \to \infty$.

We illustrate two types of networks: single hop networks and multi-hop networks. In the former, secondary nodes transmit subject to outage-probability-like constraints on the primary network. In the latter, the multi-hop secondary network is permitted to operate as long as the scaling law of the primary network is kept the same as in the absence of the cognitive network.

Single-hop cognitive networks

In the planar network model considered in [107] multiple primary and secondary users co-exist in a network of radius D (the number of nodes grows to ∞ as $D \to \infty$). Around each receiver, either primary or cognitive, a protected circle of radius $\epsilon_c > 0$ is assumed in which no interfering transmitter may operate. Other than the receiver protected regions, the primary transmitter and receiver locations are arbitrary, subject to a minimum distance D_0 between any two primary transmitters. This scenario corresponds to a broadcast network, such as the TV or the cellular networks, in which the primary transmitters are base-stations. The cognitive transmitters, on the other hand, are uniformly and randomly distributed with constant density λ. We assume that each cognitive receiver is within a $D_{\max}$ distance from its transmitter, the channel gains are path-loss dependent only (no fading or shadowing) and that each user treats unwanted signals from all other users as noise.

The quality of service guarantee of the primary users is of the form Pr[primary user's rate $\leq C_0$] $\leq \beta$. That is, the secondary users must transmit so as to guarantee that the probability that the primary users' rates fall below C_0 is less than a desired amount β. Some of the questions answered in [107] and [105] that relate to this single-hop cognitive network setting may be summarized as:

- **What is the scaling law of the secondary network?** By showing that the average interference to the cognitive users remains bounded due to the finite transmission ranges D_{max} of the cognitive users and D_0 of the primary users, one can show that the lower and upper bounds to each user's average transmission rate are constant and thus the network throughput grows linearly with the number of users [107].
- **How should the network parameters be chosen to guarantee** Pr[**primary user's rate** $\leq C_0$] $\leq \beta$**?** This interesting question is addressed in [48, 105], and is discussed in Section 1.4.2.

Multi-hop cognitive networks

We now consider a cognitive network consisting of multiple primary and multiple cognitive users, where there is no restriction on the maximum cognitive Tx-Rx distance. We assume Tx-Rx pairs are selected randomly, as in a classical [41] stand-alone ad hoc network. Both types of users are ad hoc, randomly distributed according to Poisson point processes with different densities. Here the quality of service guarantee to the primary users states that the scaling law of the primary ad hoc network does not diminish in the presence of the secondary network.

In [57] it is shown that, provided that the cognitive node density is higher than the primary node density, using multi-hop routing, **both** types of users, primary and cognitive, can achieve a throughput scaling as if the other type of users were not present. Specifically, the throughput of the m primary users scales as $\sqrt{m/\log m}$, and that of the n cognitive users as $\sqrt{n/\log n}$.

What is of particular interest in this result is that, to achieve these throughput scalings, the primary network need not change anything in its protocols; it is *oblivious* to the secondary network's presence. The cognitive users, on the other hand, rely on their higher density and a clever routing technique (in the form of *preservation regions* [57]) to avoid interfering with the primary users.

1.2.5 Interference Mitigation: Spectrum Overlay

In interference-mitigating cognitive behavior, the cognitive user transmits over the same spectrum as the primary user, but makes use of this additional cognition to mitigate (1) interference it causes to the primary receiver and (2) interference the cognitive receiver experiences from the primary transmitter. In order to mitigate interference, the cognitive nodes must have the primary system's *codebooks.* This will allow the cognitive transmitter and/or receiver to opportunistically decode the primary users' messages, which in turn may lead to gains for both the primary and secondary users, as we will see. We consider two types of interference-mitigating behavior:

1. **Opportunistic interference cancellation:** The cognitive nodes have the codebooks of the primary users. The cognitive receivers opportunistically decode the primary users' messages which they pull off of their received signal, increasing the secondary channel's transmission rate.
2. **Asymmetrically cooperating cognitive radio channels:** The cognitive nodes have the codebooks of the primary users, and the cognitive transmitter(s) has knowledge of the primary user's message. The cognitive transmitter may use this knowledge to carefully mitigate interference at the cognitive receiver as well as cooperate with the primary in boosting its signal at its receiver.

Opportunistic Interference Cancellation

We assume the cognitive link has the same knowledge as in the interference-temperature case (b) and has some additional information about the primary link's communication: the primary user's *codebook.* Knowledge of primary codebook translates to being able to decode primary transmissions; Next we suggest a scheme which exploits this extra knowledge.

In *opportunistic interference cancellation*, as first outlined in [89] the cognitive receiver opportunistically decodes the primary user's message, which it then subtracts off its received signal. This intuitively cleans up the channel for the cognitive pair's own transmission. The primary user is assumed to be oblivious to the cognitive user's operation, and so continues transmitting at power P_1 and rate R_1. When the rate of the primary user is low enough relative to the primary signal power at the cognitive receiver (or $R_1 \leq \mathcal{C}\left(h_{12}^2 P_1\right)$) to be decoded by $\mathcal{SR}_x$, the channel $(\mathcal{PT}_x, \mathcal{ST}_x \rightarrow \mathcal{SR}_x)$ will form an information theoretic multiple-access channel, whose capacity region is well known [18]. In this case, the cognitive receiver will first decode the primary's message, subtract it off its received signal, and proceed to decode its own. When the cognitive radio cannot decode the primary's message, the latter is treated as noise. The region (c) of Fig. 1.1 illustrates the gains opportunistic decoding may provide over the former two strategies.

Asymmetrically Cooperating Cognitive Radio Channels

We increase the cognition even further and assume the cognitive node(s) has the primary codebooks as well as the message to be transmitted by the primary sender(s). For simplicity of presentation we consider again the two transmitter, two receiver channel shown in Figs. 1.1 and 1.3. This additional knowledge allows for a form of *asymmetric cooperation* between the primary and cognitive transmitters. This asymmetric form of transmitter cooperation, first introduced in [23, 25], can be motivated in a cognitive setting in a number of ways. For example, if $\mathcal{ST}_x$ is geographically close to $\mathcal{PT}_x$ (relative to $\mathcal{PR}_x$), then the wireless channel $(\mathcal{PT}_x \rightarrow \mathcal{ST}_x)$ could be of much higher capacity than the channel $(\mathcal{PT}_x \rightarrow \mathcal{PR}_x)$. Thus, in a fraction of the transmission time, $\mathcal{ST}_x$ could listen to, and obtain the message transmitted by $\mathcal{PT}_x$. Other motivating scenarios may be Automatic Repeat reQuest (ARQ) systems and heterogeneous sensor systems [22, 111].

Background: Exploiting Transmitter Side Information

A key idea behind achieving high data rates in an environment where two senders share a common channel is interference cancellation or mitigation. Costa, in his famous paper "Writing on Dirty Paper" [17] applied the results of Gel'fand-Pinsker [36] to the AWGN channel, where he showed that in a channel with AWGN of power Q, input X, power constraint $E[|X|^2] \leq P$, and additive interference S of arbitrary power known non-causally to the *transmitter* but not the receiver,

$$Y = X + S + N, \quad E[|X|]^2 \leq P, \quad N \sim \mathcal{N}(0, Q)$$

the capacity is that of an interference-free channel, or

$$C = \max_{p(u|s)p(x|u,s)} I(U;Y) - I(U;S) \tag{1.1}$$

$$= \frac{1}{2}\log_2\left(1 + \frac{P}{Q}\right). \tag{1.2}$$

This remarkable and surprising result has found its application in numerous domains including data storage [46, 69], watermarking/steganography [96], and most recently, *dirty-paper coding* has been shown to be the capacity achieving technique in Gaussian MIMO broadcast channels [5, 109]. We now apply dirty-paper coding techniques to the Gaussian cognitive channel.

Bounds on the Capacity of Cognitive Radio Channels

Although in practice the primary message must be obtained causally, as a first step, numerous works have idealized the concept of message knowledge: whenever the cognitive node $\mathcal{ST}_x$ is able to hear and decode the message of the primary node $\mathcal{PT}_x$, it is assumed to have full *a priori* knowledge.[7] The one way double arrow in Fig. 1.3 indicates that $\mathcal{ST}_x$ knows $\mathcal{PT}_x$'s message but not vice versa. This asymmetric transmitter cooperation present in the *cognitive* channel, has elements in common with the *competitive* channel and the *cooperative* channels of Fig. 1.3, which may be explained as follows:

1. **Competitive behavior/channel:** The two transmitters transmit independent messages. There is no cooperation in sending the messages, and thus the two users *compete* for the channel. This is the same channel as the 2 sender, 2 receiver interference channel [7]. The largest to-date known general region for the interference channel is that described in [43] which has been stated more compactly in [12]. Many of the results on the cognitive channel, which contains an interference channel if the non-causal side information is ignored, use a similar rate-splitting approach to derive large rate regions [25, 59, 80].
2. **Cognitive behavior/channel:** Asymmetric cooperation is possible between the transmitters. This asymmetric cooperation is a result of $\mathcal{ST}_x$ knowing $\mathcal{PT}_x$'s message, but not vice-versa.
3. **Cooperative behavior/channel:** The two transmitters know each others' messages (two way double arrows) and can thus fully and symmetrically cooperate in their transmission. The channel pictured in Fig. 1.3 (c) may be thought of as a two antenna sender, two single antenna receivers broadcast channel, where, in Gaussian MIMO channels, *dirty-paper coding* was recently shown to be capacity achieving [5, 109].

Cognitive behavior may be modeled as an interference channel with asymmetric, non-causal transmitter cooperation. This channel was first introduced and studied in [23, 25][8]. Since then, a flurry of results, including capacity results in specific scenarios of this channel have been obtained. When the interference to the primary user is weak ($h_{21} < 1$), rate region (d) has been

[7] This assumption is often called the *genie assumption*, as these messages could have been given to the appropriate transmitters by a genie.

[8] It was first called the *cognitive radio channel*, and is also known as the *interference channel with degraded message sets.*

shown to be the capacity region in Gaussian noise [61] and in related discrete memoryless channels [111]. In channels where interference at both receivers is strong both receivers may decode and cancel out the interference, or where the cognitive decoder wishes to decode both messages, capacity is also known [60, 73, 80]. However, the most general capacity region remains an open question for both the Gaussian noise as well as discrete memoryless channel cases.

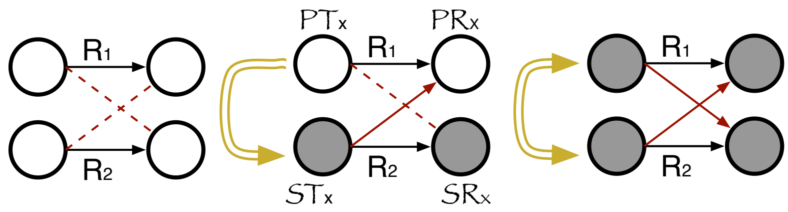

Fig. 1.3. Three types of behavior depending on the amount and type of side-information at the secondary transmitter. (a) Competitive: the secondary terminals have no additional side information. (b) Cognitive: the secondary transmitter has knowledge of the primary user's message and codebook. (c) Cooperative: both transmitters know each others' messages. The double line denotes non-causal message knowledge.

When using an encoding strategy that properly exploits this asymmetric message knowledge at the transmitters, the region (d) of Fig. 1.1 is achievable in AWGN, and in the weak interference regime ($h_{21} < 1$ in AWGN) corresponds to the capacity region of this channel [61, 112]. The encoding strategy used assumes that both transmitters use random Gaussian codebooks. The primary transmitter continues to transmit its message of average power P_1. The secondary transmitter, splits its transmit power P_2 into two portions, $P_2 = \eta P_2 + (1 - \eta)P_2$ for $0 \leq \eta \leq 1$. Part of its power, ηP_2, is spent in a *selfless* manner: on relaying the message of $\mathcal{PT}_x$ to $\mathcal{PR}_x$. The remainder of its power, $(1-\eta)P_2$ is spent in a *selfish* manner on transmitting its own message using the interference-mitigating technique of *dirty-paper coding*. This strategy may be thought of as selfish, as power spent on dirty-paper coding may harm the primary receiver (and is indeed treated as noise at $\mathcal{PR}_x$). The rate region (d) may be expressed as [21, 61]:

$$\text{Asymmetric cooperation rate region (b)} \tag{1.3}$$
$$= \left\{ (R_1, R_2) | 0 \leq R_1 \leq \mathcal{C}\left(\frac{(\sqrt{P_1} + h_{12}\sqrt{\eta P_2})^2}{h_{12}^2(1-\eta)P_2 + 1} \right), \right. \tag{1.4}$$
$$\left. 0 \leq R_2 \leq \mathcal{C}\left((1-\eta)P_2\right),\ 0 \leq \eta \leq 1 \right\}. \tag{1.5}$$

By varying η, we can smoothly interpolate between strictly selfless behavior to strictly selfish behavior. Of particular interest from a secondary spectrum licensing perspective is the fact that the primary user's rate R_1 may be strictly increased with respect to all other three cases (i.e. the x-intercept is now to the right of all other three cases). That is, by having the secondary user possibly relay the primary's message in a selfless manner, the system essentially becomes a 2×1 multiple-input-single-output (MISO) system which sees all the associated capacity gains over non-cooperating transmitters or antennas. This increased gain could serve as a motivation for having the primary share its codebook and message with the secondary user.

While Fig. 1.1 shows the impact of increasing cognition (or side information at the cognitive nodes) on the achievable rate regions corresponding to protocols which make use of this side information, Fig. 1.4 shows the impact of transmitter cooperation. In this figure, the region achieved through asymmetric transmitter cooperation (*cognitive behavior*) is compared to the (1) Gaussian MIMO broadcast channel region (in which the two transmitters may cooperate, *cooperative behavior*, from [5, 109]), (2) the achievable rate region for the interference channel region obtained in [43] (the largest known to date for the Gaussian noise case, *competitive behavior*)[9], and (3) the time-sharing region where the two transmitters take turns using the channel (*interference-avoiding behavior*). We note that the framework for the Gaussian MIMO broadcast channel region may also be used to express an achievable rate region for the Gaussian asymmetrically cooperating channel [21].

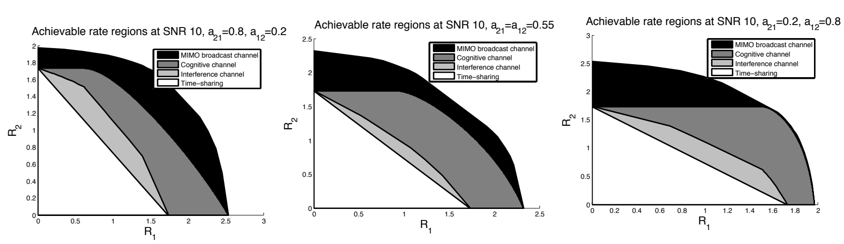

Fig. 1.4. Capacity region of the Gaussian 2×1 MIMO two receiver broadcast channel (outer), cognitive channel (middle), achievable region of the interference channel (second smallest) and time-sharing (innermost) region for Gaussian noise powers $N_1 = N_2 = 1$, power constraints $P_1 = P_2 = 10$ at the two transmitters, and three different channel parameters h_{12}, h_{21}.

While the above channel assumes non-causal message knowledge, a variety of two-phase half-duplex causal schemes have been presented in [25, 67], while

[9] The achievable rate region of [43] used in these figures (as the "interference channel" achievable region) assumes the same Gaussian input distribution as in [25] and is omitted for brevity.

a full-duplex rate region was studied in [4]. Many achievable rate regions are derived by having the primary transmitter exploit knowledge of the *exact* interference seen at the receivers (e.g. dirty-paper coding in AWGN channels). The performance of dirty-paper coding when this assumption breaks down has been studied in the context of a compound channel in [83] and in a channel in which the interference is partially known [40].

Cognitive channels have also been explored in the context of multiple nodes and/or antennas. Extensions to channels in which both the primary and secondary networks form classical multiple-access channels have been considered in [11, 24]. Cognitive versions of the X channel [78] have been considered in [27, 56], while cognitive transmissions using multiple-antennas, without asymmetric transmitter cooperation have been considered in [119].

1.3 Cognitive Sensing with Side-information

Sensing is an inherent problem in a cognitive network that requires non-overlapping primary and secondary operations. Spectrum sensing has been pursued by a great number of researchers. We mention here only a specific result about the effect of side-information on cognitive sensing performance [47]. This side information can consist of spatial locations of the primary and cognitive receivers and *a priori* primary transmission probability. For sensing algorithms based on Bayesian energy detection, such side information affects the detection threshold and the resulting performance. Specifically, information on spatial locations can help stabilize the performance for a wide range of the primary activity factor. Highly skewed *a priori* primary-transmission probability further helps improve the performance significantly.

In particular, consider a circular network with a single primary Tx-Rx pair and a single secondary Tx-Rx pair, as shown in Fig. 1.5. The primary receiver is at the center of the network, while both the primary and secondary transmitters are randomly and uniformly located within the disc. To the secondary transmitter, knowledge of the locations of the primary receiver (S_{tx}) and the secondary (its own) receiver (S_{rx}) are considered as side information.

For sensing based on Bayesian energy detection, the sensing threshold is chosen to minimize a total cost consisting of the interference caused from the secondary transmitters when the spectrum is in-use and the transmission opportunity loss experienced by the secondary users not operating when the spectrum is idle. Fig. 1.6 shows the sensing performance with various combinations of side information on the spatial locations. Comparisons with the standard *Constant False Alarm Detector* (CFAR) [63] with $P_{FA} = 0.001$ and 0.01, without any side information, are also included. Spatial location information can improve the performance between 1.5 to 3 times, depending on the primary activity factor and the combination of information available. Fig. 1.7[10] shows the performance with additional information on the primary

[10] The authors would like to thank Dr. Seung-Chul Hong for providing this figure.

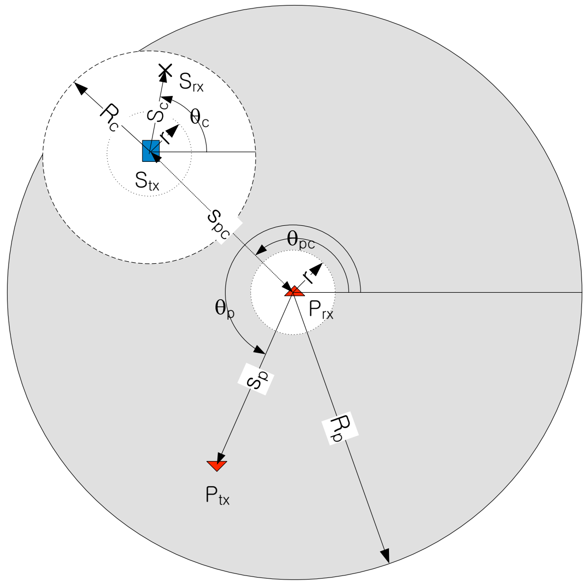

Fig. 1.5. Network configuration.

a priori transmission probability ρ. When ρ is skewed ($\rho \neq 0.5$), then the knowledge of ρ further improves the detector performance dramatically.

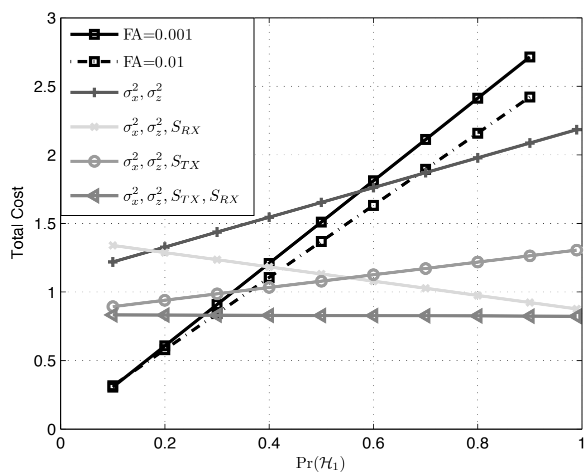

Fig. 1.6. Total cost comparisons without knowledge of ρ.

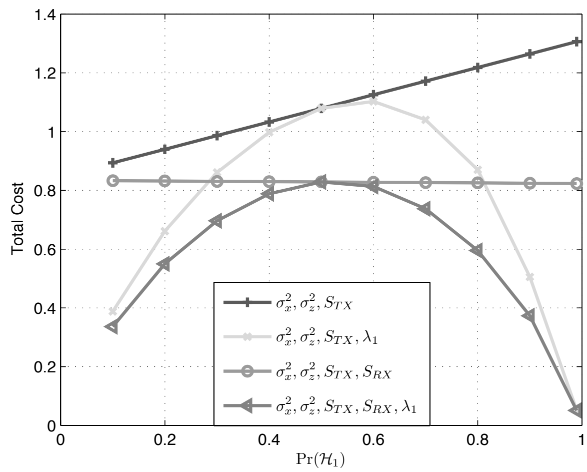

Fig. 1.7. Total cost comparisons with knowledge of ρ.

While spectrum sensing is fundamental to the design of a cognitive radio network based on the interference avoidance approach, interference analysis is a fundamental part of cognitive radio design based on the interference control and mitigation paradigms. The next section deals with interference analysis in a cognitive radio network.

1.4 Interference Analysis

Interference analysis has been studied by a number of authors (see for example [15, 33, 66, 110, 113]). The results can be used to design various network parameters to guarantee a certain performance to the primary users. Our objective here is to provide only an example of this interference analysis and its application in two different network settings: a network with beacons and a network with exclusive regions for the primary users.

Consider an extended, circular network in which the cognitive users are uniformly distributed with constant density λ. The network radius D increases with the number of cognitive users n. The interference generated by these cognitive users depends on their locations, which are random, and on the random channel fading. This leads to random interference. The average interference power to the worst-case primary users, which may be shown to be at the center of the circular network, can be computed as [106]

$$E[I_n] = \frac{2\pi\lambda P}{(\alpha-2)}\left(\frac{1}{\epsilon^{\alpha-2}} - \frac{1}{D^{\alpha-2}}\right) \tag{1.6}$$

where α is the path-loss exponent, ϵ is a receiver-protected radius, and P is the cognitive transmit power. Provided that the path-loss exponent $\alpha > 2$, then the average interference is bounded, even with an infinite number of cognitive users ($n \to \infty$ or $D \to \infty$).

The average interference can be used to either limit the transmit power of the cognitive users, or to design certain network parameters to limit the impact of interference on the primary users. Next, we discuss two examples of how the interference analysis can be applied to design network parameters.

1.4.1 A Network with Beacons

In a network with beacons, the primary users transmit a beacon before each transmission. This beacon is received by all users in the network. The cognitive users, upon detecting this beacon, will abstain from transmitting for the next duration. Such a mechanism is designed to avoid interference from the cognitive users to the primary users. In practice, however, because of channel fading, the cognitive users may sometime mis-detect the beacon. They can then transmit concurrently with the primary users, creating interference. This interference depends on certain parameters, such as the beacon detection threshold, the distance between the primary transmitter and receiver and the receiver protected radius. By designing network parameters, such as the beacon detection threshold, one can control this interference to limit its impact on the primary users' performance.

Using a simple power detection threshold, the missing beacon probability can be shown to be

$$q = 1 - e^{-\gamma d^{\alpha}} \tag{1.7}$$

where again α is the path-loss exponent, γ denotes the ratio between power threshold and beacon transmit power (or the beacon detection threshold), and d is the distance from the cognitive user to the primary transmitter (the beacon transmitter). Given a certain activity factor of the cognitive users when missing the beacon, the generated interference can then be computed analytically [106]. Bounds on the interference can then help in the design of network parameters.

For example, the interference bound versus the beacon detection threshold can be plotted as in Fig. 1.8. This graph provides a specific rate at which the intereference increases as the beacon threshold increases. The rate depends on other parameters such as α, D, ϵ, and P. The case when the cognitive transmitters are always transmitting (a beacon-less system) corresponds to $\gamma = \infty$.

1.4.2 A Network with Primary Exclusive Regions

Another way of limiting the impact of cognitive users on primary users is to impose a certain distance from the primary user, within which the cognitive

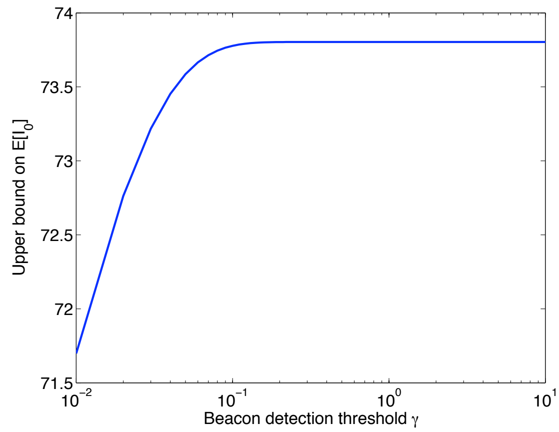

Fig. 1.8. An upper bound on the average interference versus the beacon threshold level.

users cannot transmit. This configuration appears suitable to a broadcast network in which there is one primary transmitter communicating with multiple primary receivers. Examples include the TV network or the downlink in the cellular network. In such networks, primary receivers may be passive devices and therefore are hard to be detected by cognitive users, in contrast to the primary transmitter whose location can be easily inferred. Thus it may be reasonable to place an exclusive radius D_0 around the primary transmitter, within which no cognitive transmissions are allowed. Such a primary-exclusive region (PER) has been proposed for the upcoming spectrum sharing of the TV band [48, 79]. The cognitive transmitters are randomly and uniformly distributed outside the PER, within a network radius D from the primary transmitter. As the number of cognitive users increases, D increases. The network model is shown in Fig. 1.9[11].

Of interest is how to design the exclusive radius D_0, given other network parameters, to guarantee an outage performance to the primary users. This outage performance guarantees a certain data rate for a certain percentage of time for all primary receivers within the PER. The 'worst case' receiver is at the edge of the PER in a network with an infinite number of cognitive users ($D \to \infty$).

Using the interference power analysis (1.6), coupled with the outage constraint, an explicit relation between D_0 and other parameters, including the protected radius ϵ, the transmit power of the primary user P_0 and cognitive users P, can be established [105]. For example, the relation between D_0 and the primary transmiter power P_0 is shown in Fig. 1.10. The fourth-order increase in power here is inline with the path-loss exponent $\alpha = 4$. The figure

[11] We would like to thank Dr. Seung-Chul Hong for providing us with this figure.

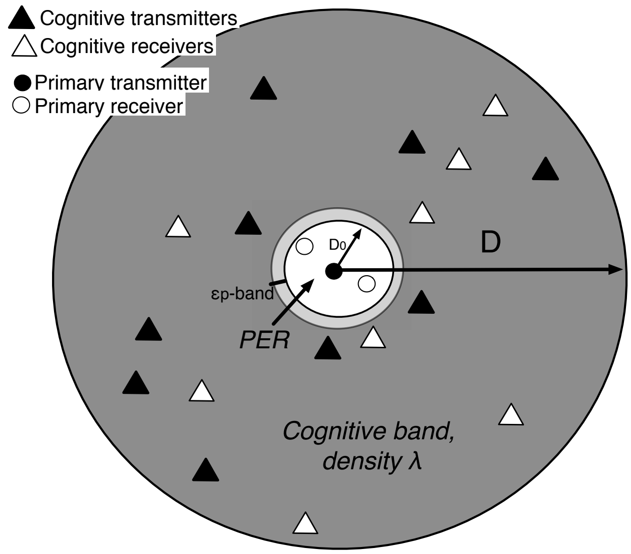

Fig. 1.9. A cognitive network consists of a single primary transmitter at the center of a *primary exclusive region* (PER) with radius D_0, which contains its intended receiver. Surrounding the PER is a protected band of width $\epsilon > 0$. Outside the PER and the protected bands, n cognitive transmitters are distributed randomly and uniformly with density λ.

shows that a small increase in the receiver-protected radius ϵ can lead to a large reduction in the required primary transmit power P_0 to reach a receiver at a given radius D_0 while satisfying the given outage constraint.

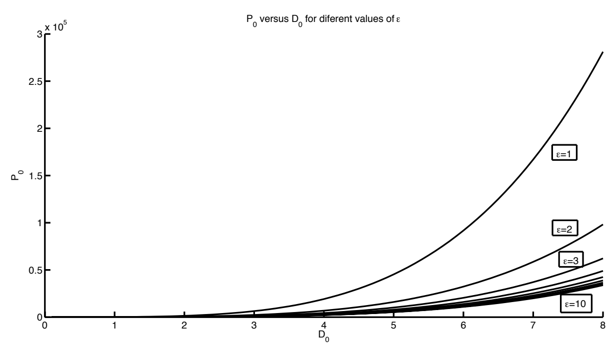

Fig. 1.10. Relationship between the primary transmit power P_0 and the exclusive region radius D_0.

1.5 Practical Cognitive Network Engineering: Interference Control Approach

Interference control based spectrum sharing allows simultaneous transmissions of primary and secondary users given the total interference constraints at primary receivers. These interference power constraints, in essence, require a sophisticated power control scheme for secondary transmitters. In order to meet interference constraints and QoS requirements for secondary users, channel gains among secondary users and from secondary users to primary receivers is usually required for proper power allocation. While collecting the channel gain information among secondary users are possible in many cases, obtaining channel gains from secondary transmitters to primary receivers is usually not trivial because primary networks may not assist secondary networks in measuring/estimating the channel gains. Hence, although in theory the interference control approach can be used in both centralized or distributed wireless networks, this spectrum access paradigm would be more applicable for networks with infrastructure such as cellular networks where channel state information can be readily obtained.

One typical example where the interference control approach can be employed for cellular-type networks is shown in Fig. 1.11. In this example, base stations (BSs) in the secondary network transmit in the downlink direction exploiting the licensed frequency bands used by primary users in the uplink direction. For this particular network setting, channel gains from secondary transmitters (i.e., secondary BS) to primary receivers (i.e., primary BS) can be estimated by the secondary networks using pilot signals transmitted from the primary BSs. Similar network setting was considered in [71], [65] where secondary users (i.e., cognitive radios) use an ad hoc mode for communication. In this section, we describe a typical spectrum sharing model with QoS and fairness constraints for secondary users and interference constraints for primary users. For ease of exposition, we refer to the network setting in Fig. 1.11 in the model description where single-hop traffic flows are considered. We will discuss the scenario with multi-hop traffic flows later on.

1.5.1 Single-Antenna Case

Engineering of wireless networks is in general much more challenging than engineering of the wireline counterpart. This is due to inherent transmission characteristics of a wireless channel with fading and shadowing. As a result, users who are assigned the same quantity of radio resources would achieve different throughput performances. Therefore, wireless network engineering should maintain certain fairness among different users such that users with unfavorable channel conditions still have satisfactory performance. In addition, most wireless applications have certain QoS requirements which can be usually described by different performance measures such as throughput, delay, delay jitter, etc. These QoS requirements usually correspond to certain minimum transmission rates or signal to noise ratio for wireless users.

The problem of optimal spectrum sharing among secondary users can be formulated as an optimization problem with a suitable objective function and a set of constraints which capture user fairness, QoS constraints for secondary users, and interference constraints for primary users. Suppose there are n secondary users and m primary receivers. For the sake of brevity, the term secondary user here refers to a pair of secondary users who communicate with each other in an ad hoc mode or a secondary user communicates with the BS in a cellular setting.

Let R_i denote an achievable rate for secondary user i which depends on the amount of allocated power, bandwidth, noise and interference it receives from other primary and secondary users. To engineer the cognitive radio network, we would choose a suitable objective function for the underlying spectrum sharing optimization problem which could balance good overall network performance as well as fairness for the secondary users. In [85], one such objective function, which is parameterized by a parameter κ, was proposed as follows:

$$U(R_1, R_2, \cdots, R_n) = \sum_{i=1}^{n} f_\kappa\left(R_i\right) \tag{1.8}$$

where $f_\kappa\left(x\right)$ is the utility function for one user which can be written as

$$f_\kappa\left(x\right) = \begin{cases} \ln(x), \text{ if } \kappa = 1 \\ \frac{x^{1-\kappa}}{1-\kappa}, \text{ otherwise.} \end{cases} \tag{1.9}$$

This general objective function can achieve different types of fairness depending on parameter κ. Specifically, for $\kappa = 0$ the total throughput is maximized, while $\kappa = 1$ achieves the proportional fairness for different users [64], $\kappa = 2$ achieves harmonic mean fairness, and $\kappa \to \infty$ provides max-min fairness. In general, the higher the value of κ the fairer the solution of the underlying optimization problem. Let h_{ij} denote the channel gain from the transmitter of secondary user j to primary receiver i, P_i denote transmission power of secondary transmitter i, and I_j denote the maximum tolerable interference level at primary receiver j. Suppose each secondary user i has a minimum QoS requirement described in terms of minimum rate B_i. The spectrum sharing problem for secondary users under QoS and interference constraints can be formulated as follows:

$$\begin{aligned} &\text{maximize} \quad U(R_1, R_2, \cdots, R_n) \\ &\text{subject to} \\ &\qquad R_i \geq B_i, \quad i = 1, 2, \cdots, n \\ &\qquad \mu_j = \sum_{i=1}^{n} h_{j,i} P_i \leq I_j, \quad j = 1, 2, \cdots, m \end{aligned}$$

where μ_j is the total interference created by secondary users at primary receiver j.

The optimization problem formulated above can be solved efficiently in cases where it is convex. For scenarios where the formulated problem is non-convex, a fast and suboptimal algorithm may be required. It is noted that the formulated optimization problem may not be feasible when its constraints are too stringent and/or the network load is too high. If this is the case, an admission control mechanism needs to be invoked to limit the number of admitted secondary users. Then, power allocation for the set of admitted secondary users can be performed. Using this framework, in [71], a solution approach was proposed for the joint admission control and power allocation problem for secondary users assuming code-division multiple access (CDMA) technology at the physical layer.

In order to obtain power allocation solutions for the aforementioned spectrum sharing problems, channel gains among secondary users and from secondary transmitters to primary receivers should be estimated frequently. Unfortunately, instantaneous channel gains from the secondary transmitters to primary receivers may be not readily obtained. The secondary network, however, can estimate the corresponding channel gains in the reverse direction by exploiting pilot signals transmitted by primary receivers (i.e., primary BSs). Due to the reciprocal characteristic of the wireless channel, the secondary network can obtain required mean channel gains averaged over short-term fading. Let $\bar{h}_{ij}$ be the average channel gain from secondary transmitter j to primary receiver i which is estimated by exploiting the pilot signal. The interference constraints at primary receiver j can be written as

$$\bar{\mu}_j = \sum_{i=1}^{n} \bar{h}_{j,i} P_i \leq \theta I_j, \quad j = 1, 2, \ldots, m \tag{1.10}$$

where $\theta < 1$ is a conservative factor which should be chosen to make the interference constraints be violated with a small probability. Mathematically, we should have

$$\Pr\left[\, \mu_j > I_j \,|\, \bar{\mu}_j \leq \theta I_j \right] \leq \Gamma_0, \qquad j = 1, 2, \ldots, m \tag{1.11}$$

where Γ_0 is the desired interference constraint violation probability. Given information about fading channel statistics, the interference constraint violation probability written in (1.11) can be calculated. Hence, the power allocation solution can be obtained by determining the factor θ and the corresponding transmission powers for secondary transmitters [65]. In [74], a related spectrum sharing problem was solved which maximizes throughput of secondary networks while sufficiently protecting primary users by maintaining a sufficiently high probability of detection. This paper, however, did not consider fairness among secondary users but tried to quantify the throughput and sensing tradeoff by finding an optimal sensing time.

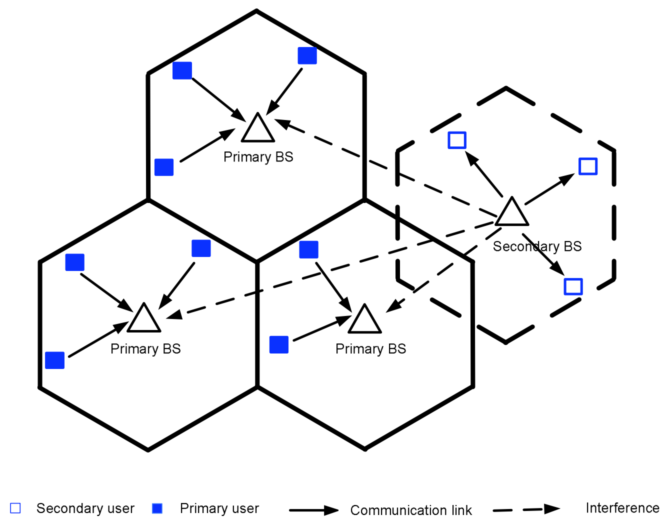

Fig. 1.11. Typical example of spectrum access using interference control paradigm.

1.5.2 Multiple Antenna Case

In scenarios where multiple antennas are available at secondary users and/or primary receivers, more care should be taken in performing power allocation for secondary users [74,116,119]. In general, the availability of multiple antennas at secondary transmitters and/or receivers provides potential multiplexing and diversity gains which would enhance performance of a cognitive radio network. In addition, if each primary receiver has multiple antennas, there are two different ways to impose interference constraints, namely, one total interference-power constraint over all receive antennas or a set of interference-power constraints applied to each individual receive antenna. Also, if each primary transmitter has multiple antennas, power allocation among transmit antennas under total transmit power constraints and interference-power constraints at primary receivers should be jointly considered.

In [116], joint beamforming and power allocation for a single-input multiple-output (SIMO) MAC of a cognitive radio network with multiple secondary transmitters and primary receivers each with one antenna was investigated. In this paper, solutions for sum-rate maximization problems with or without minimum SINR requirements for secondary users were proposed. In [119], power allocation for capacity maximization of a single pair of secondary users using MIMO was considered. Both the cases with one and multiple channels were investigated. Under this MIMO setting, optimal transmit power over transmit antennas was performed. It was shown that by exploiting multiple antennas, secondary users can balance between spatial multiplexing for their transmission while limiting interference to primary receivers. Note that these initial works on cognitive radio networks using multiple antennas consider either a MIMO setting for a single pair of secondary users or SIMO setting for multiple secondary users. Because sum-rate maximization usually favors users in good conditions, tradeoff between throughput and fairness should be considered by maximizing a suitable utility function such as that in (1.8). Solving a spectrum sharing problem with fairness consideration for secondary users and interference constraints for primary receivers in a multi-user MIMO cognitive radio network is still an open problem.

1.6 Practical Cognitive Network Engineering: Interference Avoidance Approach

In an interference avoidance approach, secondary users need to sense a frequency band of interest and transmit only if primary users are not detected on the chosen band. The interference avoidance approach is, therefore, more conservative than the interference control approach. However, no strict power control is required for this spectrum access paradigm. In this section, we discuss both scheduling and random access based medium access control (MAC) techniques for this spectrum access approach. Both single-hop and multi-hop transmission scenarios are considered. Since the spectrum of interest to a secondary network is usually very broad, fast wideband spectrum sensing is very challenging. To solve this problem, the spectrum of interest can be divided into multiple narrow frequency bands where spectrum sensing can be done by cheap radio devices. For this reason, we only describe multi-channel MAC issues in the following.

1.6.1 Single-hop Case

Scheduling-Based MAC

The scheduling-based MAC for single-hop flows would be mostly applicable for a point-to-multi-point network. This would be the case when multiple secondary users communicate with a base station (BS) or an access point (AP) using available licensed frequency bands [75, 76]. Given spectrum sensing results, a scheduler at a BS or an AP has full information about availability of all channels to make scheduling decisions. The scheduler can also opportunistically exploit fluctuations in channel quality of available channels due to fading to enhance throughput performance [75, 104]. As in a traditional scheduling problem, fairness among users should be taken into account in designing a scheduling algorithm. The key difference in a cognitive scheduling problem is that some channels may not be available for secondary users at some particular time. Therefore, statistical information regarding channel availability should be considered to maintain good long-term throughput and fairness performance for secondary users. Note that opportunistic scheduling considering multiple channels has been investigated in some recent works (e.g., in [68], [76]).

Random Access-Based MAC

A random access based MAC protocol is needed when there is no network controller to coordinate spectrum allocation for multiple users. A typical application for the random access-based MAC is in ad hoc networks where a node can establish data connections with one or several neighboring nodes. In this case, a MAC protocol should perform the following functions:

- *Channel contention and reservation*: Each user with data to transmit needs to choose one or several available channels. The chosen channels should be available at both transmitter and receiver sides to avoid collision with primary users. Channel reservations should be informed to other neighboring users to avoid possible transmission collisions among secondary users.
- *Spectrum sensing*: Due to the presence of primary users, some channels may not be available for secondary users. Therefore, secondary users should sense their chosen channels to avoid collision with primary users.

In the following, we present some key design aspects and engineering approaches for a random access-based cognitive MAC protocol in single and multi-user scenarios.

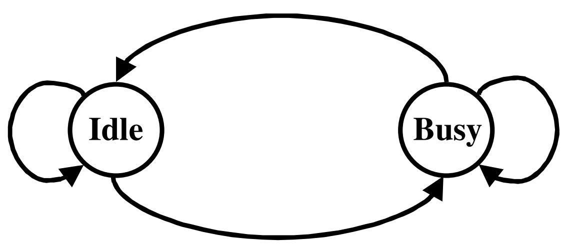

Fig. 1.12. Two-state Markov channel describing the availability of each channel.

1. *Optimal MAC design for a single-cognitive-user scenario*: If there is a single pair of secondary users communicating with each other, there is no need to perform channel reservation and contention resolution. The key design problem for this setting is to exploit spectrum holes in all channels to optimize the secondary network performance. It is obvious that if the secondary user can sense all the channels quickly then it would simply find available channels and transmit data using these channels. In practice, sensing time is usually non-negligible and a user can only

sense one or a small number of channels at once. Therefore, an optimal sensing and access strategy plays an important role in obtaining good network performance [8–10]. Such an optimal sensing and access strategy depends strongly on statistical properties of channel availability. In the following, we describe design approaches under two different assumptions about channel availability.

- *Markovian assumption*: When data transmission of primary users shows correlation, availability of the channels can be modeled as a Markov chain [35], [121]. If the availability of one channel is independent of other channels, a two-state Markov chain can be used to model evolution between idle and busy states (i.e., available and not available for secondary users' transmission, respectively) of each channel.
  Fig. 1.12 shows a transition diagram of a two-state Markov chain for one particular channel. Suppose there are L channels and time is divided into equal-sized time slots. Also, assume that a secondary user can sense L_1 channels at the beginning of each time slot and transmit data on available channels in the remaining interval of a time slot based on sensing outcomes. In the following, we will discuss the typical optimal spectrum and access problem where a secondary user wishes to find an optimal set of channels to sense in each time slot to achieve maximum long-term throughput performance.
  Specifically, the secondary user makes the decision in choosing the set of channels to sense in one particular time slot based on its decisions and sensing outcomes in all previous time slots. In [121], it has been shown that this problem can be solved using the theory of Partially Observable Markov Decision Process (POMDP) [93]. This is because by sensing only a subset of channels in each time slot, the secondary user can obtain only partial information about availability of all the channels. According to the POMDP theory, knowledge of the system state can be summarized in a belief vector [93].
  Let $V = 2^L$ denote the number of system states each of which represents idle/busy status on all L channels. Then, the belief vector can be denoted as $\Omega(t) = [\omega_1(t), \omega_2(t), \cdots, \omega_V(t)]$ where $\omega_i(t)$ is the conditional probability (given the decision and observation history) that the network is in state i at the beginning of time slot t. In addition, the belief vector is the sufficient statistic for the optimal sensing policy. In [93], it has been shown that the optimal solution of the POMDP problem can be found using a linear programming approach. Given the optimal solution, the secondary user can find a set of channels to sense in each time slot. It then updates the belief vector based on the sensing outcomes which are used to find a solution for the next time slot. Although the optimal solution for this opportunistic spectrum access problem can be calculated, the computational complexity grows exponentially with the number of channels. Therefore, a good and suboptimal spectrum sensing policy is usually preferred [121].

- *Independence assumption*: In this case, the availability of each channel is assumed to be independent of time. Assume that each channel is either available or busy in each time slot and its transmission rate is chosen from a finite set of rates. Let T_s be the time slot interval, T_m be sensing and channel probing time. Here, sensing is used to verify availability of a particular channel and probing is used to find a current feasible rate on a channel. If a secondary user senses k channels, the normalized remaining time for data transmission is

$$c_k = 1 - k\frac{T_m}{T_s}. \tag{1.12}$$

We are interested in the optimal spectrum access problem where the secondary user wishes to maximize its total transmission rate by adopting an optimal sensing/probing strategy. Here, the more channels the secondary user senses, the more likely it finds available channels with a cost of reducing the data transmission time. Let p_i denote the probability that channel i is available for the secondary user. If the secondary user knows p_i, it would sense channels in the order of decreasing p_i. Otherwise, it can simply sense channels in a random order. Without loss of generality, we number the channels in the order they are sensed by the secondary user. Assume that there are K possible transmission rates on any channel each of which corresponds to one particular modulation and coding scheme. Also, assume that the probability that rate k is chosen on any channel is s_k. We further assume that the secondary user has to make a decision after each sensing/probing regarding transmitting on the current channel (if it is available) or continue sensing/probing other channels. The operation of this optimal spectrum sensing/probing problem is shown in Fig. 1.13. Note that the problem discussed here generalizes the opportunistic multi-band access problem in [90] to the cognitive radio context.

Let r_k be the transmission rate of channel k, η_k be the achieved throughput after sensing/probing channel k, and Λ_k be the average throughput accumulated from the k-th sensing/probing. Using optimal stopping theory [13], we have

$$\eta_k = \begin{cases} c_k\varphi_k r_k \text{ if } c_k\varphi_k r_k > \Lambda_{k+1} \\ \Lambda_{k+1}, \quad \text{otherwise} \end{cases} \tag{1.13}$$

where $\varphi_k = 1, 0$ represents the event that channel k is available or busy, respectively. Equation (1.13) can be interpreted as follows. If the obtained throughput due to the k-th sensing/probing is larger than the expected throughput that would be achieved if the secondary user keeps sensing/probing further channels (i.e., $c_k\varphi_k r_k > \Lambda_{k+1}$), the secondary user would stop sensing/probing and transmit on the current channel. Note that the optimal sensing strategy is completely determined by Λ_k. We have

$$\Lambda_L = c_L \mathbf{E}[\varphi_L r_L] = c_L p_L \mathbf{E}[r_L] = c_L p_L \sum_{l=1}^{K} s_l r_l. \tag{1.14}$$

Other values of Λ_k ($k < L$) can be calculated using backward induction. Specifically, let us define $\Psi_k = \{l : c_k r_l > \Lambda_{k+1}\}$ and let $\bar{\Psi}_k$ be the complement of Ψ_k. Then, we have

$$\Lambda_k = c_k p_k \sum_{l \in \Psi_k} s_l r_l + \Lambda_{k+1} \left[(1 - p_k) + p_k \sum_{l \in \bar{\Psi}_k} s_l \right]. \tag{1.15}$$

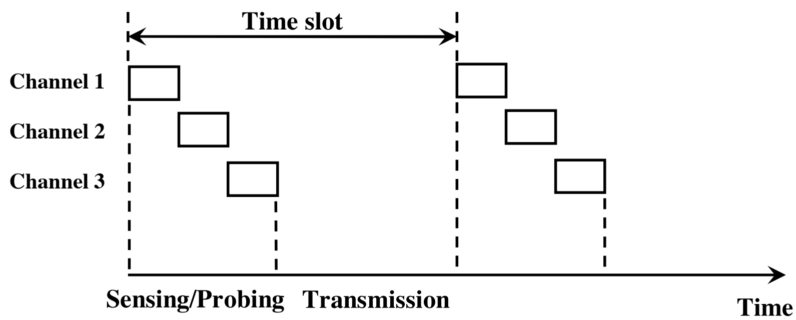

Fig. 1.13. Timing diagram for spectrum sensing/probing and access.

The aforementioned optimal sensing/probing strategies are applied to scenarios with a single cognitive user. However, they can be used to develop a multi-user MAC protocol by taking a winner-take-all approach which can be described as follows. Secondary users who are currently backlogged perform contention on a control channel. The secondary user that wins the contention employs an optimal sensing/probing strategy to find good available channels for data transmission as being discussed above. These contention and access operations are repeated in each fixed-size time slot. This method has been employed in [58], [98] to develop multi-channel MAC protocols for cognitive radio networks. This design approach, however, has several limitations. On the one hand, for the discussed optimal control strategies a winning secondary user explores spectrum opportunities only in a subset of channels to limit the sensing/probing overhead. Therefore, spectrum holes in unexplored channels are wasted. On the other hand, a secondary user may find several available channels among explored channels as in the POMDP-based control strategy; however, its queue backlog may be smaller than the transmission capacity offered by these available channels. As a result of this, some valuable radio resources are wasted because user backlogs are not taken into consideration. Therefore, it is desired that a cognitive MAC protocol should exploit transmission opportunities on all channels and avoid over-allocating capacity for secondary users considering users' queue backlogs.

2. *MAC protocol design for a multiple-cognitive-user scenario*: Design of a multi-channel MAC protocol is challenging due to the following reasons. First, as in a single-channel CSMA-based MAC protocol, the well-known hidden and exposed terminal problems still exist in a corresponding multi-channel MAC protocol. It is known that employment of RTS/CTS could not completely solve these problems. Although a dual busy tone approach, which employs two separate tones transmitted by a transmitter and a receiver in two narrow bands to protect RTS transmission and data reception, could remove the hidden terminal problem, this approach requires extra bandwidth and one more transceiver per user [44]. Second, different approaches for channel contention and reservations should be adopted depending on radio capabilities of cognitive devices. Therefore, there would be no universal MAC protocol that works well in all different scenarios. In general, users are expected to hear channel reservations made by other users to prevent possible collisions. Therefore, if each secondary user has only one transceiver, a user transmitting on one particular channel may not hear channel reservation negotiated on other channels. This problem is referred as a multi-channel hidden terminal problem [94]. Third, it is necessary to balance traffic load on different channels to reduce excessive contention overhead. Finally, a MAC protocol should provide fairness among different users.

   Design of a multichannel MAC protocol in general and for a cognitive network in particular strongly depends on radio capabilities of wireless/cognitive users, i.e., the number of radios each user has [84]. In the cognitive radio context, it also depends on dynamics of primary users and evacuation time requirements in case primary users return to a previously-available channel. These aspects determine how fast secondary users can update a "spectrum map" and how frequent spectrum sensing/evacuation should be performed. There are some recent works on MAC protocol design for multichannel and/or multiuser cognitive radio networks [16, 42, 49, 52, 58, 70, 77, 97, 98]. In the following, we discuss some important design principles and point out open research issues.

   In general, there are two popular approaches to designing a multi-channel MAC protocol, namely, common control channel and channel-hopping based approaches [84]. In a common control channel approach, one chosen channel is used to exchange control information which determines data channels for contending users. This design approach usually works well under low traffic load but may have degraded performance under high traffic load due to congestion of the common control channel. In the channel-hopping based approach, users hop through all channels by following a common or different hopping patterns. Two users who wish to communicate with each other must meet on one particular channel to perform channel reservations for data transmission. This design approach can resolve the congestion problem of the common control channel approach; however, its implementation is more complicated. In the following, we describe typical designs for scenarios where each cognitive user has two or one transceiver.

- *Each cognitive user has two transceivers*: We describe a typical MAC protocol design based on the common control channel approach for this setting here. For this design, each cognitive user employs one transceiver for channel contention and reservation and employs the other transceiver to transmit data on a chosen channel. Specifically, the control transceiver of any user is always tuned to a chosen control channel to transmit control messages and listen to channel reservations made by other users. With the dedicated control transceiver, each cognitive user always has up-to-date information about traffic load on each channel to make its own channel reservation. In addition to making channel reservations, each cognitive user should perform spectrum sensing frequently to have an up-to-date spectrum map. To avoid confusion between primary and secondary transmissions, spectrum sensing can be performed in pre-determined quiet periods during which secondary users shut off their transmissions to perform spectrum sensing.

  If the spectrum map changes slowly, cognitive users would have correct information about spectrum opportunities on all channels. When a cognitive user wants to transmit data to its neighbors, it transmits a CRTS message which contains a list of preferred channels to its intended receiver. The list of preferred channels consists of available channels learned from spectrum sensing with low secondary traffic load. The receiver upon receiving CRTS chooses one "best" channel in the received channel list and sends the chosen channel in a CCTS message to the transmitter. The transmitter upon receiving CCTS switches to the chosen channel for data transmission.

  Here, two different channel negotiation strategies can be adopted in designing a cognitive MAC protocol. In the first strategy, each available channel is only allocated for a single pair of cognitive users. Therefore, after a particular available channel is chosen by a pair of cognitive users, other cognitive users in their neighborhood should remove this channel from their available channel lists. A pair of secondary users should release their chosen channel after successfully transmitting a packet, i.e., they have to perform new channel negotiation/reservation through exchanging CRTS/CCTS messages before transmitting another packet. This channel negotiation strategy, however, creates a large amount of overhead due to CRTS/CCTS messages when the number of cognitive users is large. In the second channel negotiation strategy, multiple pairs of secondary users can choose the same channel. Hence, after exchanging CRTS/CCTS messages, cognitive users need to perform contention with other cognitive users choosing the same channel. Operation of this MAC protocol is illustrated in Fig. 1.14. Users reside on their chosen channels until they detect the presence of primary users or a pre-determined period T_{max} has been expired. T_{max} can be chosen to be equal to the required channel evacuation time (e.g., this value is 2s in 802.22 standard). This design could alleviate congestion on the control channel and reduce overhead. This is due to the reason that the traffic load on each channel is much lower than the total traffic load of all cognitive users, and cognitive users contend on the control channel less frequently.

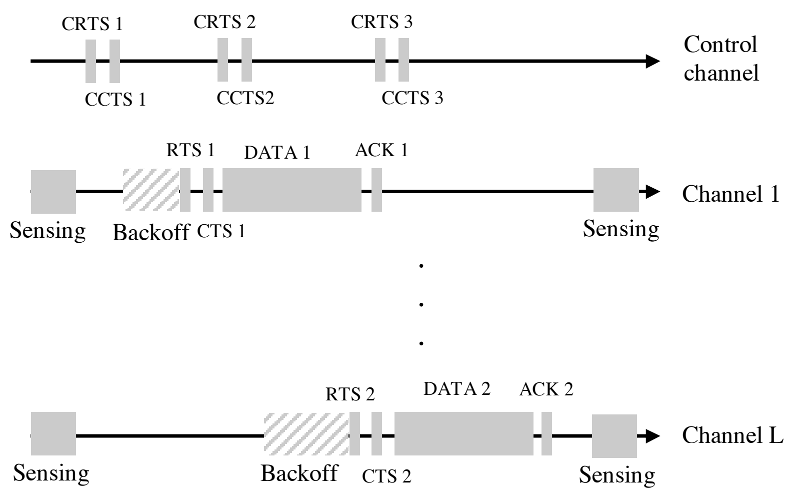

Fig. 1.14. MAC protocol with two transceivers per cognitive user.

- *Each cognitive user has one transceiver*: In this case, the transceiver is used to exchange control information as well as transmit/receive data. To resolve the multi-channel hidden terminal problem mentioned above, a synchronous MAC protocol can be employed as proposed in [94]. Specifically, time is divided into periodic beacon intervals as illustrated in Fig. 1.15. Periodic beacon transmissions are used to synchronize all users. Cognitive users choose their channels by exchanging CRTS/CCTS messages during a channel reservation phase. If multiple cognitive users are allowed to choose the same channel, contention on each channel is resolved through exchanging RTS/CTS messages by the corresponding cognitive users. This design can potentially improve channel utilization when the beacon interval is large and several packets from different users can be transmitted in a data transmission phase. Moreover, sensing should be performed to find available channels by each cognitive user. In Fig. 1.15, sensing is performed at the beginning of each beacon interval based on which cognitive users reserve channels for a data transmission phase. In the case where a beacon interval is longer than a channel evacuation time, one or more sensing periods should be placed in the data transmission phase to protect primary users.

In the above MAC protocol, the control channel may be congested when the number of cognitive users is large. In addition, transmission time on all channels other than the control channel is wasted during the channel reservation phase. These problems can be resolved by channel-hopping based MAC protocols [84], [2] where cognitive users hop through the channels by following a common or different hopping patterns. Cognitive users who want to communicate with each other wait until their partners hop to the same channel to exchange control information. For the case where users following different hopping sequences, each user learns hopping patterns of their neighbors by listening to corresponding broadcast seeds. When a user wants to communicate with its neighbor, it follows the intended neighbor's hopping pattern to exchange control information and negotiates data channels. In addition, sensing can be performed during pre-determined quiet periods to detect available channels.

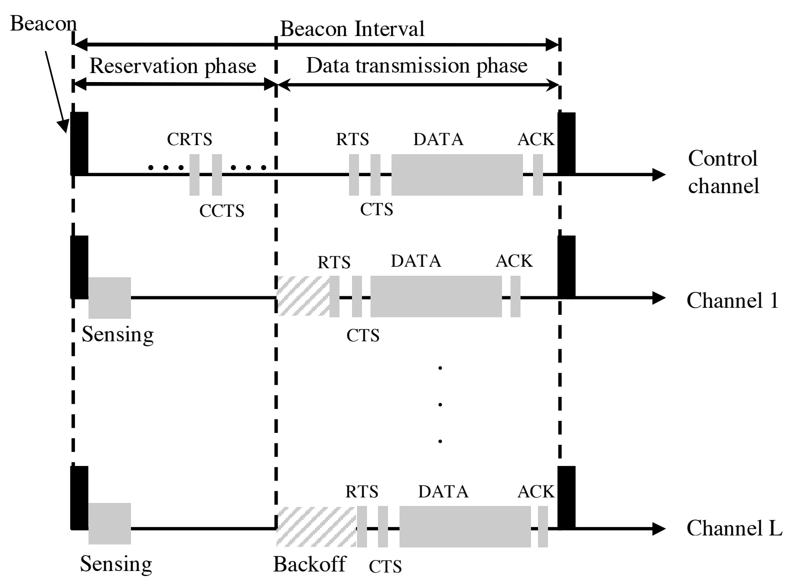

Fig. 1.15. MAC protocol with one transceiver per cognitive user.

Although some recent works have compared different multi-channel MAC protocols based on simple analysis and simulation [84], an accurate analytical model to quantify performance of multi-channel MAC protocols in wireless networks in general and in cognitive radio networks in particular is still an open problem. In addition, optimal control design for spectrum sensing and access was only done for a single-user scenario [8–10]. Developing an optimal MAC protocol for the multi-user scenario is an open and challenging problem. This is because throughput analysis needs to be performed for optimal design of a MAC protocol. Unfortunately, this is a complicated problem by itself. In fact, calculating throughput performance usually requires tracking detailed protocol evolutions which capture complicated relationships among many protocol parameters. Given the fact that a closed form equation to calculate network throughput is usually difficult to obtain, finding an optimal design for channel sensing and negotiation operations of a MAC protocol is a very difficult task.

1.6.2 Multi-hop Case

In a multihop setting, cognitive users establish multihop transmissions with its peers where traffic is transmitted from sources to destinations through multiple communication links. Engineering multihop cognitive networks requires more care due to possible existence of different sets of primary users with different channel activity. Either an interference control or an interference avoidance approach can be employed to protect active primary users in the multihop setting. Employment of the interference control approach is, however, challenging because network-wide estimation of channel gains from secondary users to primary receivers may not be easy. Using the interference avoidance approach, if primary users are present on some channels, secondary users are simply prohibited to use these busy channels for their transmissions [91]. Detection of primary users using a certain spectrum sensing technique can be performed by each cognitive users to construct its local spectrum map.

In general, multihop communications can be established by scheduling or random access-based transmissions. It has been known that CSMA/CA based MAC protocols are quite inefficient for a multihop wireless network [72]. This is due to the hidden terminal problem and suboptimality of the backoff mechanism. Although implementation of a dual tone approach could remove the hidden terminal problem, more control bands and transceivers per user are required [44]. The scheduling-based approach could potentially achieve better throughput performance; however, a scheduling-based MAC usually requires centralized implementation where information about source-destination pairs, network topology, link conflict relationship or channel gains needs to be gathered at a central control point to calculate optimal network configuration [1,6,62,91]. A scheduling-based MAC is, therefore, more suitable to stationary wireless networks (e.g., wireless mesh networks) with slowly-changing source-destination demands (e.g., in networks with aggregated traffic flows [62]).

The scheduling-based MAC design strongly depends on an interference model. In particular, the interference model determines sets of wireless links which can be activated simultaneously. There are two popular interference model models, namely protocol model and physical model [41]. In the protocol model, interference relationship among wireless links is binary where wireless links outside interference range of one another can be transmitted simultaneously. Therefore, any two wireless links can be either conflicting with each other or can be activated simultaneously. This interference relationship is usually captured in a conflict graph to find an optimal network configuration [1] (e.g., optimal rate control, routing and scheduling for wireless networks). The physical model determines a set of active links by a corresponding set of constraints on minimum signal to noise plus interference ratio (SINR). In essence, a minimum SINR requirement for each wireless link is imposed to guarantee the desired bit error rate performance. Under the physical model, transmit power and channel gains among wireless links need to be gathered to determine sets of active links and corresponding optimal network configuration [62]. The physical model is more accurate but it is also more complicated than the protocol model. In general, the scheduling sub-problem in a cross-layer design problem is a bottleneck where sets of simultaneously-activated wireless links must be determined such that desired end-to-end performance for all multihop flows can be achieved.

Conclusion

Results on the achievable rate of a cognitive radio link have been summarized for three different types of cognitive behavior, namely, interference avoidance, interference control, and interference mitigation. In a spectrum underlay scenario with the interference controlled behavior of the cognitive radio nodes, scaling laws of both single-hop and multi-hop cognitive networks have been described. Bounds on the capacity of a cognitive radio channel have been described for two types of interference-mitigating cognitive behavior, namely, opportunistic interference cancellation (or decoding) and asymmetrical cooperation with primary transmitter. The general conclusion is, the higher the level of cognition (i.e., side information) at the cognitive radio nodes, the higher is the maximum achievable rate for the cognitive radio channel. A similar conclusion holds for the cognitive sensing performance - specifically, information about spatial location of the primary and secondary receivers and primary user activity can improve the sensing performance significantly. To limit the impact of interference on primary users, network parameters have to be designed based on interference analysis. Examples of interference analysis have been provided for a beacon-enabled network and a network with primary exclusive regions.

Practical issues and potential approaches in design and engineering of channel access methods in a cognitive radio network have been described. With the interference control approach, a spectrum sharing method has to ensure the rate (or SINR) and fairness constraints for secondary users as well as interference constraints for primary users. With the interference avoidance approach, spectrum sensing has to be performed efficiently so that the utilization of spectrum holes can be maximized and also the QoS requirements for the secondary users are met. Economic aspects of spectrum sharing (e.g., pricing), which have not been addressed in this chapter, will also need to be considered for practical design of cognitive radio systems [50, 51, 86, 99, 108]. Design and engineering of multiuser (single-hop and multihop, single-antenna and multiple-antenna) cognitive radio networks is still in its infancy which deserves more research investigation.

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