Summary. Cognitive radios have the potential to greatly improve spectral efficiency in wireless networks. In this chapter we explore the fundamental limits of communication in channels employing cognitive radios. We take an information-theoretic approach, making use of information theory’s wide variety of tools and ability to characterize communication limits independent of actual implementations. The chapter first surveys information theoretic results on a simple wireless channel where a primary link and a secondary (or cognitive) link share the same spectrum: the cognitive radio channel. Our survey includes recent capacity and achievable rate region calculations for the case when the channel is known to all transmitters and receivers. We compare the rates achieved through new non-orthogonal schemes where the cognitive and primary user simultaneously use the channel to more traditional spectral gap filling solutions. In the second part of the chapter we outline new results on the limits of cognitive radio channels where the fading coefficients are known to different degrees at the nodes.

17.1 Introduction

The advent of cognitive radios, or software defined radios able to adapt to the sensed environment, along with recent FCC initiatives allowing for secondary spectrum access promise more flexible, and potentially more efficient spectrum access. There are many questions and aspects to be tackled before before cognitive radios can seamlessly and opportunistically employ spectrum licensed to primary user(s). Of both theoretical and practical importance is the question: what are the fundamental limits of communication in the presence of one or more cognitive radios? Information theory provides an ideal framework for analyzing this question. The capacity and rate regions achieved in a network with cognitive radios provide fundamental, unquestionable limits of the possible communication. Such results provide benchmarks for the communication field, where researchers may gauge the efficiency of any practical cognitive radio system. In this chapter, we outline some of the recent theoretical advances pertaining to the limits of cognitive radio systems, first assuming all channel gains are known to all involved nodes, and then extending to the case
when fading coefficients are known to different extents at the involved wireless devices. In both cases we emphasize how the cognitive radios alter classical information theoretic communication scenarios, and what is gained by their introduction.

The FCC’s recent Secondary Markets Initiative (SMI, [17]) was sparked by empirical measurements showing that most of the time certain licensed frequency bands remain unused, and the natural desire to remedy this and increase spectral efficiency. Currently, spectrum is either unlicensed, creating a spectral free-for-all (as, for example in the 2.4 GHz band), or is licensed to certain primary users (such as for example cellular providers). The goal of the SMI is to remove unnecessary regulatory barriers to new secondary market oriented policies. Of the multiple possible types of secondary leasing [16], in this chapter we will focus on dynamic spectrum leasing. There, licensed users (which we will use interchangeably with the term primary users) ultimately hold the right to the spectrum. However, the primary license holder may wish to re-distribute or share his spectrum with other devices not necessarily in his own network. The motivation, and fascinating game theoretical and economic models for doing so is beyond the scope of this chapter, and we refer the interested reader to [22, 39, 42]. In dynamic spectrum leasing, the non-licensed secondary devices would opportunistically (dynamically) employ the spectrum according to the primary licensee’s regulations. Three main types of opportunistic employment of the primary spectrum are possible (although by no means exhaustive).

1. **Interference-controlled:** the primary license holder could stipulate for example maximal permissible secondary user interference levels, in effect guaranteeing the primary users certain transmission rates. This could allow primary and secondary users to transmit in the same bands, that is, in the same time-frequency-space-code blocks. The concept of interference temperature [16] has been introduced with goal of avoiding the compromise of the primary users’ spectrum: secondary devices should control their emissions such that the aggregate interference at the primary users is below a certain level (or interference temperature).

2. **Interference-avoiding:** a subset of the interference-controlled regime is that in which the primary licensee only allows secondary users to use its spectrum on the condition that its user suffer no interference whatsoever. Such systems are much more restrictive than interference controlled systems, but are common in cognitive radio literature [22,25,43,49]. The secondary user could adhere to this strict requirement by filling in spectral holes. That is, a secondary user would transmit only in the absence of primary users.

3. **Interference-free:** when cognitive devices exist in a network but have no information of their own to transmit, they could potentially act as relays, and collaborate with the primary users [38]. Rather than cause interference to the primary link, they boost it. Neglecting any other possibly active cognitive clusters [15], this system is interference-free.

In this work, in order to obtain fundamental limits of communication in the presence of cognitive radios, we turn our attention mostly to the more general interference-controlled model.

For both the interference-controlled as well as the interference-avoiding models, the secondary user must be able to perform some fundamental tasks. Specifically, we require a device which is able to sense the communication opportunities, and then