Introduction

This book presents an inevitable evolution in today's wireless communication world: it concerns "cognitive radio" (CR). This new concept is based on the work of Joseph Mitola published in 1999 and 2000 [MIT 99a, MIT 00a].

From information theory to cognitive radio

In 1948, through a single 55-page publication, Claude Elwood Shannon [SHA 48] radically changed the vision of modern telecommunications by inventing a new theory known as Information Theory. In this publication, Shannon brought, in particular, the response to a fundamental telecommunications problem: how much information can be transferred between two people communicating in a given environment at a particular time, so that everyone understands the respective information without errors? Ever since the formulation of this response by Shannon, we see around us the development of phones, WiFi cards, etc., capable of transmitting more and more data per second. However, we must not delude ourselves, and it is in this that Shannon's work is so fundamental: the rate of information transmitted without error is naturally limited by the communication environment, the frequency band (commonly called bandwidth) used, and the power of transmitted signals. Hence, if any of these three fundamental resources reaches its limit, we cannot transmit information at a higher rate. Ten years ago, Joseph Mitola saw that a revolution in telecommunications was definitely going to take place right away. The principal perception of Mitola is that the rapid and less efficiently controlled use of telecommunication resources (especially bandwidth) had led to an enormous waste of these resources. The simplest of the examples of wastage is the functioning mode of the global system for mobile communication (GSM) standard (also known as 2G): the latter permits eight users of the mobile telephone network to connect simultaneously to a base station of their service provider. When a single user is connected to the base station, this user, however, only uses one-eighth of the total resources available to it. The static nature of the current communication protocols raises the question of how to make the wireless domain more "flexible". From this important comprehension, directly affecting the sustainability of modern telecommunications, the field of CR was thus born, which tends to make communication devices more autonomous, capable of deciding which resources to use and how to use them effectively. For example, if no GSM network coverage is present in the room in a house, then why not take advantage of the WiFi access point. The goal would be that a communication system can make such kinds of decisions autonomously. It is even highly desirable that our telecommunications devices can precisely perform this reasoning in an intelligent manner, reflecting that the human being will do the same when faced with such a situation.

From software radio to cognitive radio

In 1995, Joseph Mitola proposed a new concept entitled "software radio" (SR) [MIT 95]. Ideally, this concept permits equipment to communicate with any radio communications standard, without changing any hardware component and only by modifying the embedded software. This technology, which may appear very simple at first glance, not only introduces many new advantages, but also raises numerous technological challenges. This technology and its related problems are addressed in Part 2 of this book. Mitola realized the need to put intelligence simultaneously into both the network and the equipment to satisfy user needs and resource constraints, ultimately resulting in an increase in spectral efficiency. This is why he proposed the idea of CR [MIT 99a]. This intelligence enables the equipment to choose the best conditions to meet its communication needs. The choice ideally implies a real-time change of transmission parameters, even a change of standard. To do this optimally, Mitola showed that the change in real time should be realized by an SR. He concluded that CR would be more effective if it were supported by SR technology. Our orientation in this book is exactly toward this logic. Part 1 will focus on the CR while Part 2 will discuss the SR as a support technology for the concept of CR.

Book structure

The subject of this book is very broad. We do not claim to examine exhaustively all the aspects associated with it. However, a radio designer or a researcher of the domain will find the necessary information useful to understanding the fundamental concepts and identifying other literature sources that could complete explanations contained in this book.

This book contains two main parts. Part 1, entitled "Cognitive Radio", includes five chapters. It illustrates the expectations and the challenges related to the new concept of CR.

Chapter 1 provides an introduction to CR, starting with the need for optimal spectrum management. Then, a set of definitions is provided. The cognitive cycle based on the work of Mitola is described. The concept of opportunistic radio is presented and various ways of achieving such opportunistic radio are discussed. A more general vision than the classical spectral vision is also proposed, notably due to the notion of "sensorial radio bubble" and a limited "three-layer model" obtained by regrouping the layers of the open system interconnection (OSI) model. Finally, the chapter ends with a state (non-exhaustive) of the current national and international collaborative projects and standardization.

Chapter 2 addresses the question of the intelligence distribution between the network and the terminal equipment. This discussion is far from closed. Clearly, behind this distribution are the industrial and economic interests of different players. Hence, our conclusion is that the intelligence must be in both networks and terminals at the same time.

Chapter 3 focuses on the "sensing" function of the cognitive cycle. The sensors of the three layers of the model are presented and some are described in detail. Particularly, the role of "hole detection sensor" in the spectrum, a sensor considered in the literature as the main CR sensor, is explained. This chapter thus broadens the classical understanding of the sensors in CR, which typically consists of the physical layer sensors.

Chapter 4 points out that with all the available information provided by the sensors of any kind, as explained in Chapter 3, and due to the known behavior rules or the learned rules from past experience, the equipment, in accordance with the cognitive cycle, must make decisions. This aspect of CR is discussed extensively in the literature. It results in a large number of potential solutions, with their advantages and disadvantages. These are described in this chapter. The necessity of learning is emphasized and methods taking into account that learning are presented.

Chapter 5 presents the need to manage the intelligent cycle. This management is crucial for proper functioning of the equipment, both at the design level of this equipment and its functioning in real time. After explaining the need to manage the cycle, we present a solution known as hierarchical and distributed cognitive radio architecture management (HDCRAM) in detail.

Part 2, entitled "Software Radio as Support Technology", includes six chapters. Although the concept of SR dates back to 1995, and despite the rapid technological advances in past 20 years, there remain a large number of difficulties to be overcome before realizing an SR that conforms to the original concept. This part illustrates all these difficulties.

Chapter 6 describes the SR in its historical and economic contexts. It presents the ideal concept and the resulting architecture. After emphasizing the difficulties of implementing such an architecture, the concept of "software-defined radio"

(SDR) is proposed, with different possible architectures. Despite reduced difficulties encountered in this SDR architecture, there remain numerous problems to be solved. These are the subject of the subsequent chapters.

Chapter 7, starting from the SDR architecture, in which an analog part is retained, deals with the "transmitter/receiver analog front end" (AFE). In this chapter, three problems, which follow the sequential order of signal processing, are reviewed:

– the first concerns the antennas that must be wideband or multiband and/or highly directive depending on the application context;

– the second deals with the amplification stages. This difficulty is often neglected in the literature, but from our point of view it is fundamental. Indeed, the signals processed by the amplifiers will be the sum of a large number of modulated carriers and therefore present a large variation in power;

– the third concerns the problems of analog-to-digital and digital-to-analog conversion. This was the first identified problem in the beginning of the work on the SR. Indeed, the levels to be sampled are such that no circuit can perform this conversion on a very wideband of several GHz for example. This problem has generated much research activity both in terms of signal processing and electronics. An update on this activity and the most promising solutions is presented in this chapter.

Chapter 8 deals with the second part of the SDR architecture. It follows the analog-to-digital conversion stage and precedes the digital-to-analog conversion stage, in which a number of functions previously processed in analog are processed digitally in the SR context. This part is called "transmitter/receiver digital front end" (DFE). In this chapter, functions such as (de)-modulation, filtering of desired channels, and clock synchronization with the sampling clock are described. A particular point is made on the synchronization function, which in a CR/SR context has new constraints, more difficult than conventional digital reception.

Chapter 9, based on the nonlinear amplification problem described in Chapter 7, proposes a theoretical analysis of the signals involved, and identifies a set of methods to reduce the significant power variation of the signals to be amplified. In the context of dynamic spectrum access, the methods of adding signal over reserved carriers are preferred and detailed.

Chapter 10 explains the need to take into account the real-time (re-)configuration constraints imposed by the SR and by the design phase of the equipment. The advantage of reducing the computational complexity of processing by factorization techniques is emphasized. The technique of parameterization using common operators is also presented in this chapter. To provide a high-level design environment, which is as general as possible, the model-driven architecture (MDA) approach is presented as a pertinent solution. In this framework, several design flow solutions are described.

Chapter 11, the last chapter of this book, describes the objective reality of the SR existence. There is a need to process the data at different frequencies and the nature of this processing involves the use of heterogeneous platforms. Like the management of the intelligent cycle described in Chapter 5, the need for (re-)configuration management is highlighted and the solutions of configuration management are presented. The need for the real-time (re-)configuration and the generated constraints affects the solutions on different platforms. The solution of partial (re-)configuration of field-programmable gate array (FPGA) to this constraint is also described. Finally, some existing platforms with SR capabilities are presented.

We conclude this book by presenting an application, the *green cognitive radio*, which aims at reducing energy consumption and electromagnetic pollution, and the possible evolutions such as collective intelligence, spontaneous communication, and a radio with aptitudes approaching the cognitive aptitudes of the CR.