Chapter 1
Serving Many Mobile Users in Various Scenarios: Radios to Go Smart(er) and Cognitive

1.1 Towards Cognitive Radio

Anything, anytime, anywhere! The holy grail of wireless communication is coming closer. However, significant hurdles still need to be taken. Indeed, *Anytime* would require the systems to have an infinite amount of energy resources, so as to guarantee an endless operation. Further, *Anything* implicitly means that the Quality of Service (QoS) guarantees are as tough as they are diverse. Finally, *Anywhere* would require the systems to be able to operate effectively in a broad range of heterogeneous environments.

The main difficulty behind the AAA paradigm lies in the scarcity of the used resources. Thus, it is critical to share this resource efficiently and effectively. In this book, we focus on wireless spectrum and energy as scarce resources and which are, hence, becoming expensive. Moreover, the increased flexibility in radio hardware and wireless standards is both opening new opportunities and posing new challenges. As a result, radios need to evolve to smart and cognitive.

In this introductory chapter, we embark by highlighting how HardWare (HW) implementation and policy guidelines are becoming increasingly flexible. We then present the Cognitive Radio (CR) framework that implements the necessary control functionality to harness this flexibility. The need for smart and cognitive radios is explained, and the way forward as proposed in this book is introduced.

1.2 Increasing the Hardware Flexibility

The current and emerging wireless telecommunication landscape is pushing for more hardware flexibility. Software Defined Radios (SDRs) give an answer to this need.

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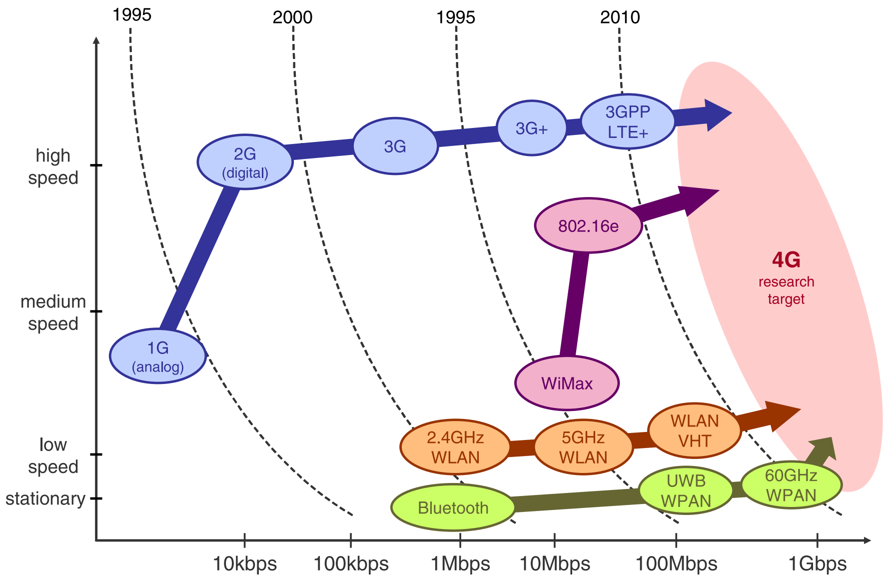


Fig. 1.1 Standards continue to accommodate higher mobility and achieve higher throughput. To accommodate the wishes of the wireless user, a divergence, rather than a convergence, of wireless standards, can be seen today

1.2.1 Wireless Landscape Giving Challenges and Opportunities

Wireless standards continue to diverge, driven by heterogeneous user and application requirements. Increased flexibility in radios may offer the long desired seamless connectivity. This increased flexibility is not only a functional wish, due to the increasing cost of ASIC designs it also becomes an economic necessity [1].

1.2.1.1 Heterogeneity Desires Flexibility

Wireless communications are routinely used today for a large variety of applications, including voice, data transfer, Internet access, audio and video streaming and social networking. For one specific service, several systems have been standardized and some have become the preferred option in several regions of the world.

Pushed by the insatiable demand for bandwidth and pulled by the steady improvement of semiconductor technology, the performance delivered by wireless standards is destined to improve, seemingly without bounds (see Fig. 1.1). To accommodate the diverse wishes of the wireless user, we are witnessing a divergence, rather than convergence, of wireless standards. This is especially true in terms of various modes of use.

From a user perspective, it is, hence, attractive to have a single handheld device that can support a large variety of wireless standards. This ensures interoperability and gives the user access to a wide variety of applications. As a result, mobile handsets have started supporting multiple modes over the past years. Initially, this has been achieved by integrating multiple radios into one handset. However, when the number of radios increases, the cost, size, and weight of the terminal are also affected. Hence, a single radio that comprises all necessary functionality is highly sought-after [1, 2]. Users want to enjoy a multitude of services on one terminal. Predictions claim that handheld devices need to support at least six different radios at the short term. Hence, also from a functionality point of view, flexibility is becoming essential.

1.2.1.2 Enabling Seamless Connectivity

Ubiquitous and seamless connectivity can be achieved in a heterogeneous network environment, under the condition that both terminals and network feature the necessary reconfiguration capabilities to support horizontal (between access points of one technology) and vertical (between access points supporting different technologies) roaming. Recently, the need for such reconfiguration support is receiving attention in specific standardization initiatives (see Chap. 2).

1.2.1.3 Scaling Technology Imposes Reconfigurability

Gordon E. Moore predicted 45 years ago, that the number of transistors on a chip would double about every 2 years. So far, history has proved him correct [3]. Scaling has brought enormous processing capabilities packed on small areas, opening opportunities to implement flexible platforms at low cost and low power.

However, for newer technologies, the Non-Recurring Engineering (NRE) costs related to System-on-Chip (SoC) design are rising exponentially. On top of this, design cost has increased dramatically and is expected to continue to do so. Not only is the design complexity increasing, CMOS scaling has arrived at the point where parasitic problems are becoming dominant. As these effects cannot be resolved at the transistor side, new designs will need to take these problems into account.

The question whether scaling is still viable is sounding louder each day, especially for custom ASIC chips. While higher production volumes can still compensate the NRE costs, cost trade-offs show, already today, an advantage in using reconfigurable radios to single-mode devices for smaller markets. For these instances, the extra area penalty is not significant compared to the cost cutting in NRE.

The extra area penalty can be furthermore easily compensated for multi-mode terminals. In those terminals the possibility exists to reuse silicon and thus significantly reduce overall area, which makes flexible platforms even more attractive. Also other cost factors, like assembly cost, form factor and time-to-market, direct towards chip reuse and, hence, the HW platform paradigm [4, 5].

Table 1.1 SDR Forum's 5-tier concept [7]

Tier	Name
0	Hardware Radio
1	Software Controlled Radio
2	Software Defined Radio
3	Ideal Software Radio
4	Ultimate Software Radio

1.2.2 The Software-Defined Radio Solution

As mentioned above, only flexible radios enable the AAA paradigm, as their flexibility allows them to operate in any environment and under any user request. This observation gave birth to the concept of Software Radio (SR), an extremely flexible radio. Today, the SR-concept is well established, but the ultimate SR (uSR) is still not in reach. According to the SDRForum such an uSR accepts fully programmable traffic and control information, supports operation over a broad range of frequencies and can switch from one air-interface to another in milliseconds [6]. Though the uSR might not yet be in reach, the research community has already made significant advances to increase the hardware flexibility.

In Table 1.1, the initial 5-tier concept of the SDRForum is presented [7]. The early radios were baseline radios with fixed functionality, called Hardware Radios (HRs). Today, it may be argued that virtually all modern wireless communications equipment can be classified as Software Controlled Radios. These radios implement the signal path using application-specific hardware, i.e., the signal path is essentially fixed. A software interface may allow certain parameters to be changed in software. For most applications, the state-of-the-art flexible radios are Software Defined Radios (SDRs) (i.e. Tier 2). These radios allow the signal path to be reconfigured in software without requiring any hardware modifications. As the uSR is considered to be the *blue-sky* vision of SDR, the next target is the ideal Software Radio (iSR). Compared to a standard SDR, an iSR implements much more of the signal path in the digital domain. Ultimately, programmability would extend to the entire system with Analog/Digital Conversion (ADC) taking place at the antenna.

1.3 Increasing the Policy Flexibility

Regulatory bodies are being pushed to define spectrum access policies more flexible. The Dynamic Spectrum Access (DSA) concept, the ultimate goal of flexible spectrum access, ideally could realize the optimal usage of the spectrum.

1.3.1 Spectrum: A Scarce Resource

Like water, air or oil, the wireless spectrum is a shared resource. This, however, does not imply that it should be free! Wireless spectrum needs to be shared with many applications, and, hence, it has become expensive. To deliver the required expensive service, regulatory bodies are using a fixed frequency allocation scheme, out of fear of harmful interference, which jeopardizes the quality of the delivered service. They allocate spectrum blocks for multiple years and over large areas. The only exception to this allocation scheme, is the ISM band, where heterogeneous devices can coexist using high-level Listen-Before-Talk (LBT) etiquettes.

Due to this fixed frequency allocation scheme, along with the accelerated deployment of broadband communication systems, spectrum is, hence, becoming a major bottleneck. New applications require more and more spectrum, but no useful spectrum is apparently left to be allocated (see upper part of Fig. 1.2).

However, experiments show that up to 85% of the spectrum remains unused at a given time and location, indicating that a more flexible allocation strategy could solve the spectrum scarcity problem [8]. We have confirmed this through measurements using the IMEC Scaldio [9] (see bottom part of Fig. 1.2).

This inefficient use of spectrum and the success of the ISM bands has coerced regulatory bodies into defining a roadmap towards more local, organic and dynamic spectrum sharing policies [10–12].

1.3.2 The Opportunistic Spectrum Access Solution

As mentioned above, a need for policies to share spectrum dynamically exists. A prime example of such a flexible policy is Opportunistic Spectrum Access (OSA), where users can actively search for unused spectrum in licensed bands and communicate using these *white holes*. OSA is supported by regulatory bodies, such as the Federal Communications Commission (FCC) [10] and the European Commission (EC) [12]. The concept is also often ambiguously referred to as Cognitive Radio (CR). We discuss the ambiguity of this terminology in Sect. 1.4.

The ultimate goal of the roadmap for more local and organic spectrum policies, is called Dynamic Spectrum Access (DSA). In DSA networks licenses and priorities are not fixed at Design Time (DT). DSA networks should allow terminals and technologies to negotiate the use of wireless spectrum locally for a time window of hours, minutes or even seconds. Like the SR, which presents the ultimate flexible radio, DSA is not yet in sight. However, OSA is a first disruptive step towards this ultimate goal.

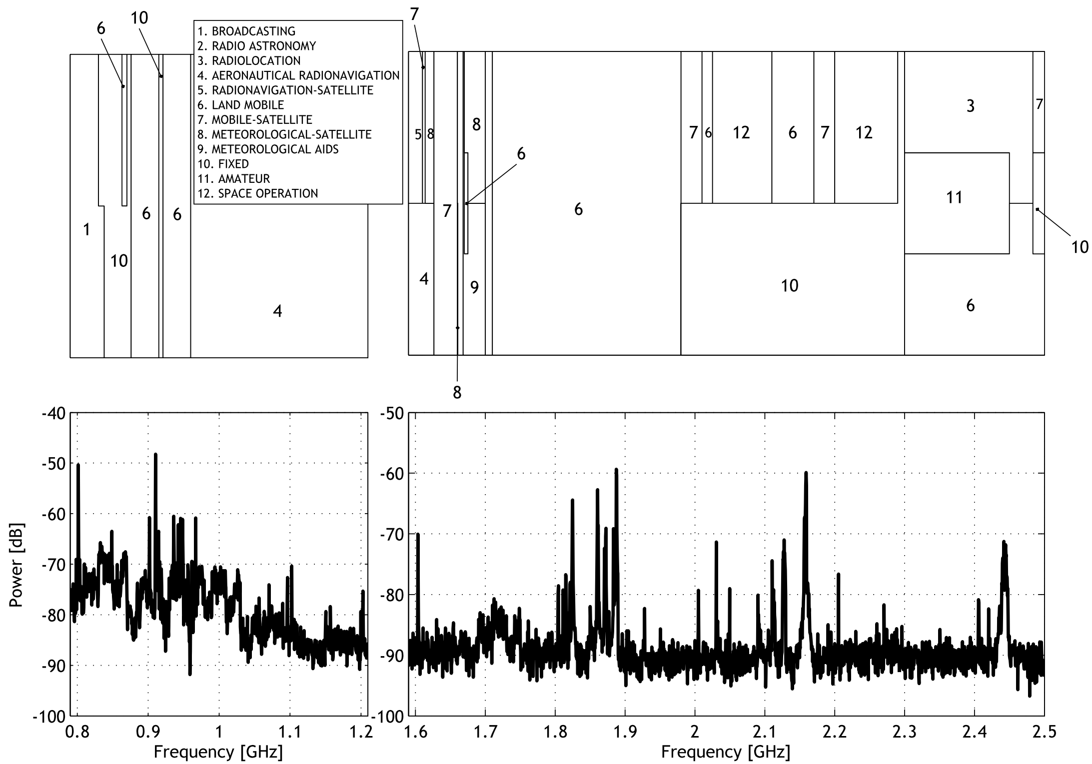
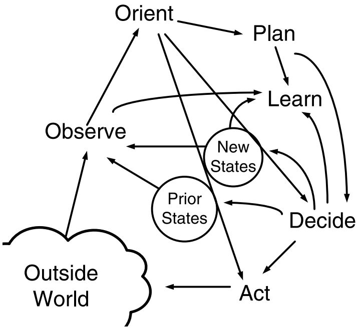
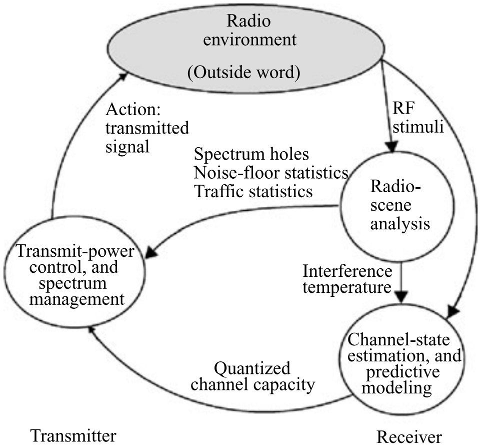


Fig. 1.2 In the *upper part*, the current Belgian spectrum plan is shown [13]. Spectrum appears to be very scarce as no bands are apparently left free to allocate. However, the *lower part* shows measurements of the same frequency range taken by the IMEC Scaldio chip on at 13h15, 6th of July 2009. When we take a snapshot at a certain time and location, a lot of this licensed spectrum is not being used. Indeed, only the popular standards seem to be semi-densely used. However, measurements by TU Berlin have shown that even for the extremely popular GSM standard OSA remains viable [14]



(a) According to Mitola, the CR is a natural extension of the SDR. Centrally, in his cognition cycle is an intelligent control mechanisms, that is able to learn from the environment [15].



(b) Though Haykin largely agreed with Mitola's definition, he instantiated his cognition cycle for OSA. In this cognition cycle only 2 key CR elements remain: environment awareness and adaptivity [17].

Fig. 1.3 A comparison between the cognition cycles of Mitola and Haykin

1.4 Cognitive Radio: Exploiting Flexibility with Intelligent Control

The Cognitive Radio (CR) concept brings an answer to exploit the increased flexibility with smart(er) control solutions.

The CR was first described by Mitola in [15, 16] as a decision making layer in which "*wireless personal digital assistants and the related networks were sufficiently computationally intelligent about radio resources, and related computer-to-computer communications, to detect user needs as a function of use context, and to provide radio resources and wireless services most appropriate to those needs*". Through the eyes of Mitola CR was a natural extension of the SDR. His CR cycle can be seen in Fig. 1.3(a).

Six years after Mitola's first CR article, Simon Haykin recapitulated the CR idea as an enabler of brain-empowered communication [17]. He identified six key parts of CR: awareness, intelligence, learning, adaptivity, reliability and efficiency. Thus, his definition broadly complies with Mitola's viewpoint. In his seminal paper, Haykin instantiated CR for OSA as can be seen in Fig. 1.3(b). In this simplified cognition cycle only 2 key elements of his CR are instantiated: environment awareness (radio-scene analysis and channel estimation) and adaptivity (transmit power control and dynamic spectrum management).

Together with the initial focus of CR research on enabling environmental awareness through spectrum sensing, this led to people using CR as an equivalent of OR.

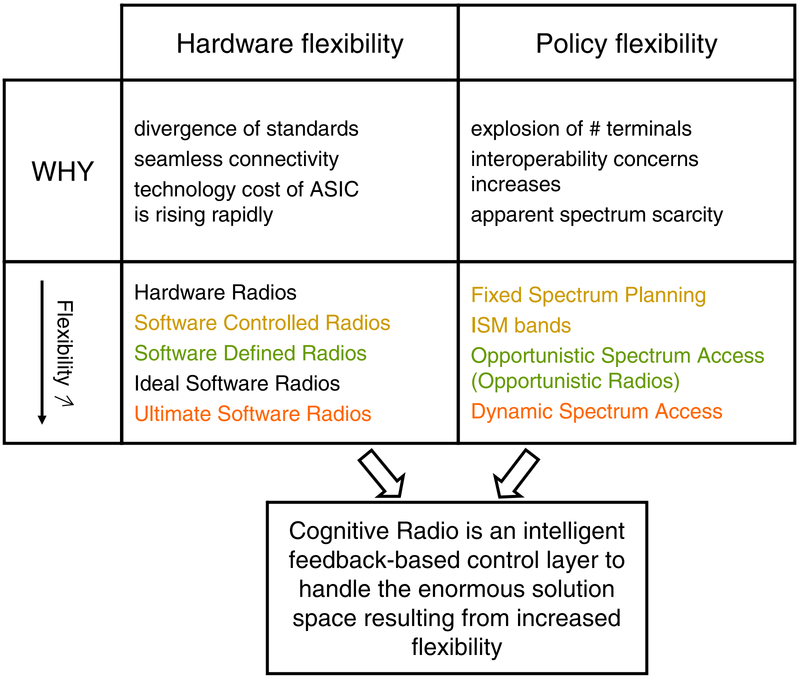


Fig. 1.4 The Cognitive Radio is an adaptive feedback-based layer to control the increasing flexibility, of which prime examples are the SDR (at the hardware side) and OR (at the spectrum side)

For instance, IEEE 802.22 was marketed as the first CR standard, while it actually carries few of the key elements present of the CR as defined by Mitola or Haykin.

Mitola and Haykin actually saw the CR as an answer to the following questions:

- "What can we do with the increasing HW flexibility provided by the SDR?" (Mitola, 1999).
- "What can we do with the increasing policy flexibility provided by regulators?" (Haykin, 2004).

The common denominator of these two visions is to define a CR as an *intelligent control framework to handle the increased flexibility*.

To avoid ambiguity, throughout this book, the spectrum-oriented view on CR (OSA) is denoted as Opportunistic Radio (OR). CR denotes an adaptive feedback-based layer to control the increasing flexibility, of which prime examples are the SDR (at the hardware side) and OR (at the spectrum side). This can be seen in Fig. 1.4. An adaptive radio that exploits flexibility to improve on QoS or energy cost, but does not learn the optimal configuration based on feedback, will be denoted as a smart radio.

1.5 The Need for a New Approach

This book proposes a framework that is able to exploit the flexibility offered by the disruptive radio hardware and spectrum access paradigms. The main problem considered is the sharing of wireless spectrum. To intelligently share this spectrum, terminals need to interact with their actual environment to learn its behavior and adapt accordingly. As mentioned in Sect. 1.4, a CR system heavily relies on the existence of a feedback channel from the environment. Hence, the proposed framework is fully compatible with the CR paradigm. In the Mitola vision it is theoretically proposed to learn everything in real time. For practical applications, we introduce a framework that is able to extract useful information upfront, when designing the system. Consequently, the performance in operation can be improved greatly. In [18, 19] it is demonstrated that a hybrid Design Time (DT)–Run Time (RT) framework allows for very efficient operations. In such DT-RT framework, procedures are developed at DT. At RT, these procedures can be efficiently executed by monitoring the environment and selecting the appropriate procedure. However, due to the increasing flexibility of wireless terminals, it is becoming harder to predict all possible situations. Furthermore, due to the increasing environment dynamics, it is also becoming harder to model these situations. Our framework should hence be flexible enough to allow calibration and learning.

We propose an extended DT-RT framework and maintain its efficient operation. In line with the CR paradigm, the framework is made flexible enough so the terminal can change its behavior based on interaction with the environment. Feedback-based learning is enabled in the framework, fully in line with the CR definitions introduced earlier.

1.6 Radios to Go Smarter and Cognitive

In this book, we aim to introduce how Software Defined Radios can be conceived to become smart(er) and cognitive. Indeed the opportunities brought about by the improved flexibility and degrees of freedom, bring along an increased control complexity. Exploiting this complexity is a challenge, which holds the opportunity to use scarce resources spectrum and energy in an optimal way. The optimization itself should work in practical cases and come at minimal overhead.We thereto sketch the standardization scene, introduce methodological concepts, and discuss the application to relevant case studies:

- **Chapter 2** discusses some of the major wireless standards to illustrate how increased flexibility and control is becoming abundant, even within a single wireless technology. Next to flexibility within standards, focus is on coexistence between standards and finally cooperation across standards. The latter often requires a flexibility across standards and increased intelligence. This drives the need for SDR and finally CR.

- **Chapter 3** introduces a general control strategy that is able to adapt flexibly to the environment without heavily impacting the run-time complexity. The method proposed consists of a preparation ('design time') and an operation phase ('run time process'). The degree of intelligence and adaptation enabled in the run time process typically determines how *smart* the radio is. It will be shown that the run time involves four main tasks: monitoring or observing, determining the current scenario, acting on the scenario following a procedure and finally learning or calibrating the procedure. In the subsequent chapters, case studies will be presented that involve each of the four tasks, but however, emphasis will be on one of the tasks.
- **Chapter 4** discusses a scenario where licensed users share their resources with opportunistic radios. In this case, the OR needs to sufficiently monitor the actual situation to avoid interference to the licensed technology. In Chap. 4 the flow will hence be applied to a OR scenario with special focus on the monitoring.
- **Chapter 5** discusses a coexistence situation. Specifically, it considers the scenario where an IEEE 802.15.4 networks coexists with an IEEE 802.11 network in the ISM band by adapting its channel. In this case, monitoring is shown not to be sufficient and determining the actual situation is based on both monitoring and learning based on feedback from the environment. It is shown how nevertheless, is possible to instantiate the flow to design a radio that is capable to adapt based on an identification of the actual scenario.
- **Chapter 6** gives an example of how the flow can be instantiated on a well-defined procedure that does not necessary involve a CR or OR. The context will be an IEEE 802.11 network in which multiple users coexist and have to share the medium, while meeting performance constraints and minimizing energy cost. Even for such an IEEE 802.11 network, a flexible radio within a network of flexible radios can be managed smartly to improve the overall QoS or energy efficiency of the network.
- **Chapter 7** then gives an example of the most important task of a cognitive radio: learning and calibrating how it behaves in the environment. How to achieve this efficiently is illustrated in the context of IEEE 802.11 networks that aim at minimizing the co-channel interference in a distributed way by adapting the output power, sensing threshold and transmission parameters.
- **Chapter 8** finally closes the book with major conclusions and a glance at the future.