# 1

# Introduction



Exciting new feature-rich, interactive, and high bit-rate multimedia services of Third Generation (3G) cellular radio systems have been promised in the past. Benefits for subscribers and increased revenues for service providers and network operators have been expected. However, the wireless research community has perceived the limitations of the existing systems in terms of user throughput and cost of operation. Consequently, research and development efforts have been initiated towards Next Generation (NG) systems that are also referred to as Beyond Third Generation (B3G) or Fourth Generation (4G) radio systems. Such future systems are expected to allow subscribers transparently to access broadband multimedia services via multiple wireless and fixed-line access networks as if they were connected via broadband modems to the Internet.

The increasing demands for wireless communication in consumer electronics applications, and personal high-data-rate networks indicate a promising commercial potential. Throughput, reliability, service quality, and the ever-present availability of wireless services are more and more demanded. The number of devices based on multiple wireless standards and technologies will therefore substantially grow in the future – exciting progress but new problems will be created with these increasingly widespread wireless communications. These problems are the limited availability of radio spectrum and the difficult spectrum coexistence of dissimilar radio systems in a shared spectrum. Until today, such problems could be neglected to a great extent because network operators have usually enjoyed the privilege of exclusive access to their parts of the radio spectrum. We are, however, now at a stage where the identified problems have to be addressed to enable further growth of these promising markets and to found a substantial basis for our future information society.

## 1.1 Access to Radio Spectrum

Today, access to radio spectrum is difficult as it is restricted by a radio regulatory regime that emerged over the last one hundred years. Large parts of the radio spectrum are allocated to licensed radio services in a way that is referred to as command-and-control. Open access to most of the radio spectrum is only permitted with very low transmission powers, in

*Cognitive Radio and Dynamic Spectrum Access* L. Berlemann and S. Mangold

a so-called underlay sharing approach such as that used, for example, used by Ultra Wideband (UWB). The overlay sharing approach, i.e. the free access to an open spectrum, is generally not permitted.

Only some small fractions of the radio spectrum, the unlicensed frequency bands, are more or less openly available. The fraction of a radio spectrum declared as unlicensed is very small, and new unlicensed spectrum will not be available soon, as regulatory changes from licensed to unlicensed spectrum are difficult and take a long time. Changing the status of a licensed radio spectrum can be perilous and painfully slow. It takes a concerted effort between government regulatory agencies, technology developers, and service providers to achieve efficient and timely deployment.

Unlicensed spectrum is a small fraction of the entire radio spectrum. Excitingly, over the past decades, this approach has led, nevertheless, to a wide variety of new wireless standards, technologies, and services, among them the popular IEEE 802.11 Wireless Local Area Networks (WLANs), Wi-Fi, and Bluetooth for IEEE 802.15 Wireless Personal Area Networks (WPANs). The demonstrated commercial success of wireless applications operating in unlicensed spectrum, and the many radio systems utilizing this fraction of the radio spectrum, indicate that it may be helpful to change the existing radio regulatory regime towards a more flexible, open spectrum access.

The limitation and delays in spectrum access form the restricting bottleneck that slows down the development of new radio services. These radio services can substantially improve health, safety, work environment, education of people, and quality of leisure time. The expected growth of the number of radio devices based on multiple wireless standards and technologies may be delayed with the existing limitations.

## 1.2 Artificial Spectrum Scarcity from Unexploited Frequencies

The radio spectrum is a finite resource. With the term 'radio spectrum', electromagnetic frequencies between 3 kHz and 300 GHz are referred to. Figure 1.1 illustrates the range of frequencies that are commonly regarded as radio spectrum. Most of today's radio communications systems require rigorous protection against interference from other radio systems. Nowadays, such protection from interference is guaranteed in licensing radio spectrum for exclusive usage. Most of the radio spectrum is therefore licensed to traditional communications systems and services as indicated in Figure 1.2. However, with such an approach, spectrum resources are sometimes wasted for various reasons.

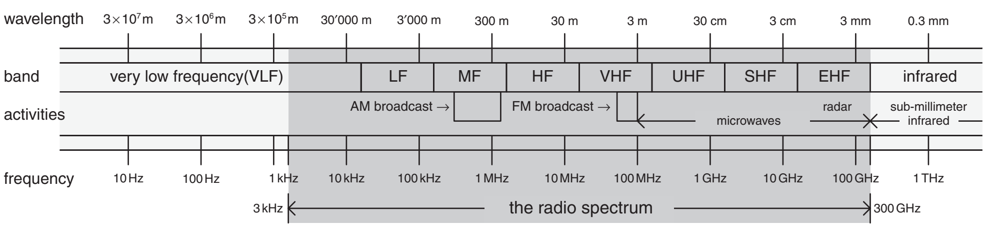


**Figure 1.1** The radio spectrum refers to frequency between 3 kHz and 300 GHz

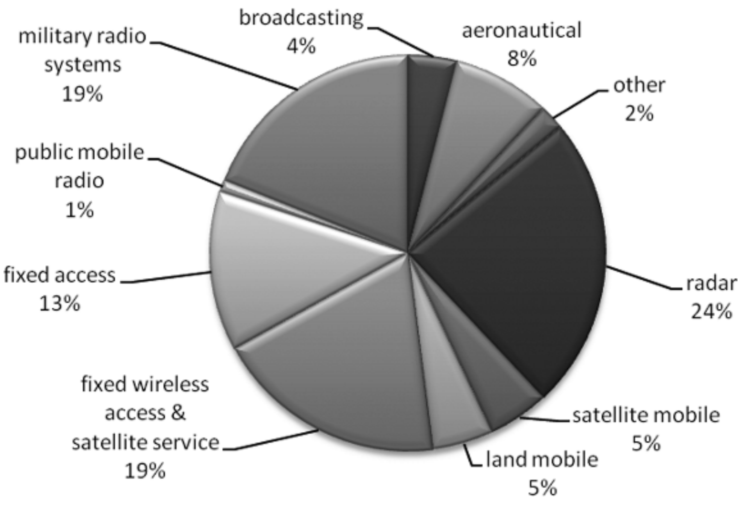


**Figure 1.2** Radio spectrum is licensed to traditional communication systems

Firstly, any economic failure of licensed radio services and systems may lead to unused spectrum. For example, at the time of writing, WiMAX appears to be commercially unsuccessful. WiMAX spectrum has been allocated and licensed in many countries, but appears not to be utilized at all by nationwide network operators. WiMAX spectrum is hence considered wasted for the time being.

Secondly, public safety and military radio systems require spectrum for occasional operation, which leads to an additional amount of often unused spectrum.

Thirdly, technological progress in communications results in the improvement of the spectrum1 efficiency of existing licensed communications systems like, for example, the digitalization of television (TV) broadcasting, so that less spectrum is required to provide the same service.

As a result of all these observable trends, large parts of the spectrum are currently used inefficiently. Consequently, the traditional regulation of spectrum requires a fundamental rethinking in order to avoid waste of spectrum and, hopefully, to increase public welfare. The existing radio regulatory regime is, however, too complex to handle the increasingly dynamic nature of emerging wireless applications. This is one of the reasons why, paradoxically, 90 . . . 95 % of the licensed radio spectrum is not in use at any location at any given time. As a result, we waste precious spectrum. What is often called ‘spectrum scarcity’ and ‘limited radio resources’ is really an artificial result of the way spectrum is regulated.

Even more problematic, the demand for additional spectrum is growing faster than the technology is able to increase spectrum efficiency, although latest research illustrated tremendous success in increasing spectrum efficiency and capacity in radio communications. As consequence, costs increase due to higher complexity for squeezing maximum data rates out of few spectrum. Multiple Input Multiple Output (MIMO) and Space Division Multiple Access (SDMA) are just two examples of the recent advances in communication technology.

## 1.3 Cognitive Radio and Dynamic Spectrum Access as Solution

Dynamic spectrum access refers to the time-varying, flexible usage of parts of the radio spectrum under consideration of regulatory and technical restrictions.

Cognitive radios together with dynamic spectrum access attempt to overcome the described problems. Cognitive radio is not only a new radio technology, it also includes a revolutionary change in how the radio spectrum is regulated. New radios designed for efficiently using shared spectrum and not causing at the same time significant harmful interference to incumbent (primary, license holding) radio systems are referred to as 'cognitive radios' (Mitola, 1995, 2000).

Cognitive radios are radio systems that autonomously coordinate the usage of spectrum. They identify radio spectrum when it is unused by the incumbent radio system and use this spectrum in an intelligent way based on spectrum observation. Such unused radio spectrum is called 'spectrum opportunity,' also referred to as 'white space.'

Current existing radio systems are not fully designed for mutual coordination and information exchange. New radio systems need intelligent capabilities to support Quality-of-Service (QoS) when sharing spectrum with dissimilar radio systems and in the presence of systems which have no coexistence capabilities. It is natural to foresee an evolutionary step from existing standards towards extended standards comprising the cognitive radio features. Future cognitive radio systems and networks will then autonomously coordinate themselves to support QoS in scenarios where spectrum is shared, i.e. in the presence of other, possibly competing, radio systems.

The cognitive radio technology, and the ideas discussed here, are inspired by the Defense Advanced Research Projects Agency (DARPA) Next Generation Communication (XG) program. Many other trends in research and industry are emerging. For example, a new standard IEEE 802.22 is currently being defined. This standard is a modification of IEEE 802.16 and will enable what is referred to as Wireless Regional Area Networks (WRANs). Such networks operate in rural regions in the unused VHF/UHF bands, and include mechanisms to protect incumbent radio systems (such as terrestrial TV broadcasting) from harmful interference.

## 1.4 This Book

Within this book, we summarize and discuss the main concepts behind radio regulation, dynamic spectrum access, and cognitive radio. In the next chapter, the way radio spectrum is handled today is discussed. We also introduce spectrum measurements that were taken by our team to illustrate the inefficiencies in today's spectrum usage. In Chapter 3, already known and in part already used approaches to improve the spectrum utilization are summarized. The following chapter, Chapter 4, lists institutions and standardization approaches in academic research and industry, all of which will lead to commercial exploitation of dynamic spectrum access and cognitive radio. This list includes a thorough discussion of IEEE 802.11n for MIMO and IEEE 802.11s for mesh networks, because both standards enable greater flexibility and spectrum efficiency in WLANs, which is important for cognitive radio solutions. We propose a number of enablers for horizontal spectrum sharing in Chapter 5 and for vertical spectrum sharing in Chapter 6 that may help to establish the concepts of dynamic spectrum access and cognitive radio. Among others, we discuss in Chapter 5 unlicensed WiMAX and coexistence with Wi-Fi, spectrum policies, and solution concepts for coexistence approaches derived from game theory. In Chapter 6 a new concept for Wi-Fi operation in the Frequency Division Duplex (FDD) spectrum allocated for WiMAX or UMTS, a dual beaconing concept for operator-assisted cognitive radio and finally our concept of spectrum load smoothing derived from 'waterfilling' are discussed. In Chapter 7, we provide an outlook on our vision about what we believe a true cognitive radio will be composed of and its potential impact on the telecommunications business. The book ends with concluding remarks in the final chapter, Chapter 8, with some additional information on our tools in the Appendix.