Chapter 1
Introduction

1.1 Wireless Growth

Wireless technology has been evolving at a breakneck speed. The total number of cell-phones in use (as of 2011) was over 6 billion for a 7 billion world population [1] constituting 87 % of the world population. Additionally, with user convenience becoming paramount, more and more functions are being implemented wirelessly. For example, the U.S. army utilizes 40 different types of radios for its communications. Moreover, there is a considerable effort toward integrating all this wireless functionality in a single device. Smartphones today use as many as a dozen independent radios inside them.

1.2 Spectral Congestion

Unlike wired communications which use dedicated connections, wireless communications use particular frequencies of electromagnetic waves in space, thus sharing a common connection medium. Consequently, with the growth of wireless technology, spectral congestion has become a substantial concern, and threatens further growth of the technology [2].

However, this spectral congestion is a result of sub-optimal frequency utilization arising from a rigid spectrum licensing process. One example is spectrum licensing by the Federal Communications Commission, USA [3]. Currently, each frequency is strictly allocated for a particular application (for e.g. 850 MHz & 1.9 GHz for cell phones in the USA). When this application experiences excessive usage, the corresponding frequency becomes congested (causing dropped calls and busy lines for cell-phone users for instance). An example of frequency usage snapshot taken at Berkeley, California, USA [4] clearly shows heavy usage and congestion at a few frequencies (e.g. 0 to 1, 1.9, 2.4 GHz) and sparse usage at others (e.g. 0.5 % utilization in the 3–6 GHz band).

This inefficiency in frequency allocation can be resolved by allowing the unlicensed utilization of spectrum. However, this will necessitate new spectrum sharing

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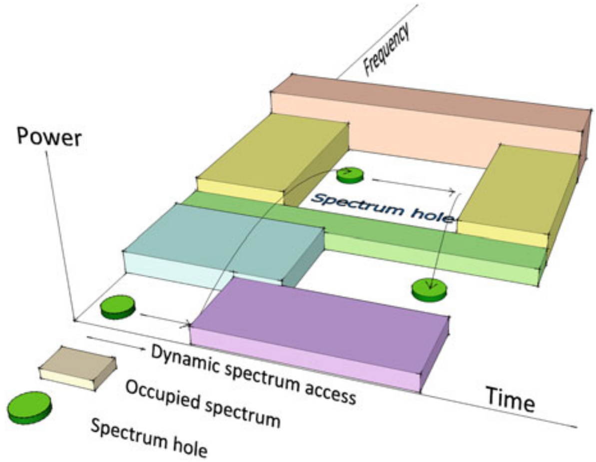
Fig. 1.1 Concept of DSA



protocols to be developed in order to allow multiple users to utilize a single spectrum without causing harmful interference. A couple of approaches to spectrum sharing are being pursued: ultra-wideband (UWB), using a spectral underlay approach, and cognitive radio (CR), using a spectral overlay approach. In the ultra-wideband scenario (IEEE 802.15.3a, IEEE 802.15.4a), a secondary user is allowed to transmit in occupied bands, but with a power spectral density (PSD) so low that it is not deemed as harmful interference. The low PSD is compensated by the usage of a very wide bandwidth ($>$ 500 MHz) to allow a significant transmit rate. In the cognitive radio scenario (IEEE 802.22), dynamic spectrum access (DSA) is utilized for spectrum sharing. This work focuses on the cognitive radio scenario for efficient spectrum utilization.

1.3 Dynamic Spectrum Access

In dynamic spectrum access, a secondary user is allowed to utilize other allocated but temporarily unused frequencies, to solve the problem of spectral congestion. Figure 1.1 shows a diagrammatic representation of the concept. An energy detector detects the power levels at different frequencies on a real-time basis (*spectrum sensing*) and determines spectral occupancy. The different colored cuboids in the figure represent spectral occupancy by different protocols, with different bandwidths, at different power levels, and for varying amounts of time. Frequencies not being used temporarily give rise to spectrum holes as shown using green discs. Dynamic spectrum access strives to seek out these spectral holes, and operate at these unused frequencies. This can greatly improve spectrum usage efficiency, and drastically reduce the problem of spectral congestion. For example, if the users of the 1.88–1.9 GHz frequency (cordless phones) are allowed to use the higher under-utilized frequencies, congestion in these devices could be avoided. In fact, the different spectrum governing bodies around the world are exploring new standards to allow this kind of communication (IEEE 802.22 in the USA).

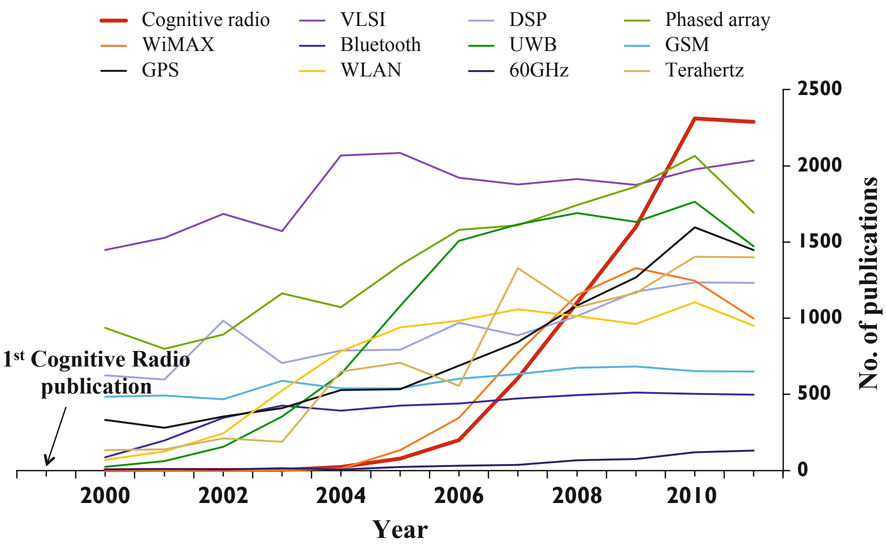


Fig. 1.2 Number of publications on different research areas in the last decade

1.4 Cognitive Radio

The use of dynamic spectrum access to intelligently improve communication efficiency has been the driving force behind the cognitive radio concept. Unfortunately, the definition and scope of what constitutes a cognitive radio has remained unclear to this day (an example definition by the FCC: [5]). In the narrow sense, a cognitive radio is an artificially intelligent device that can dynamically adapt and negotiate wireless frequencies and communication protocols for efficient communications[1]. For this, each participating device will need to be extremely flexible and capable of performing at different frequencies with their different regulations and requirements. Such a radio should have capabilities such as: determination of location, sensing the spectrum used by neighboring devices and analyzing the external spectral environment, to altering frequency and bandwidth, output power level adjustment, and even altering transmission parameters and protocols [6]. Interestingly though, if these devices are capable of such functionality, they would also be able to function as multiple wireless radios and therefore function as an integrated and complete wireless solution. For example, the same wireless radio could work as a cell phone, a GPS receiver, a garage door opener, and even as a remote control for other devices as shown in Fig. 1.3. Note that this is different from multiple different radios *assembled* in a smart-phone.

Figure 1.2 provides an indication of the growth of cognitive radio technology as a research area since its inception. The figure shows the number of publications

[1] It is envisioned, that in the future, the cognitive radio functionality will also include spacio-temporal intelligence, and significant learning capabilities heralding a new era in wireless communications.

Fig. 1.3 Functionality of an envisioned cognitive radio

with different keywords published per year in IEEE publications. Many keywords represent growing research areas in wireless communications, while other popular keywords such as 'VLSI' and 'DSP' have been included for comparison. The first cognitive radio paper was published in 1999; however, research in this area was relatively dormant till 2006. Since then, cognitive radios have seen a tremendous growth in research activity, and is now one of the most researched areas in wireless.

A cognitive radio can be separated into (1) a software defined radio (SDR) unit that forms the hardware of the cognitive radio, and an intelligence unit, that provides the required software based intelligence (cognition) to the radio. In this book, the SDR unit, and more specifically, the receiver front-end of the SDR, will be emphasized.

Like any communication device, the SDR needs a transmitter and a receiver. However, unlike a traditional wireless tranceiver, a cognitive radio not only needs to perform signal transmission and reception (*signaling*) but also needs to monitor the spectrum in real-time (*spectrum sensing*) in order to execute dynamic spectrum access. Spectrum sensing provides a wideband frequency snapshot helping the cognitive radio identify currently unused (potentially usable) frequencies. The cognitive radio then decides which unused frequency and protocol to use, and starts signaling at that frequency [7] (Fig. 1.3).

1.4.1 Spectrum Sensing

The dynamic spectrum access relies on dynamic spectrum monitoring using a spectrum sensing device. Among other features, this continuous wideband monitoring makes the cognitive radio hardware unique. From the hardware perspective, the spectrum sensor remains extremely challenging. Even for narrowband (small frequency range, < 100 MHz) spectrum sensing, limiting the power consumption is a challenge. On the contrary, the cognitive radio spectrum sensor needs to detect signals at all frequencies of interest instantaneously. Additionally, it needs to detect signals more unfailingly (about two orders of magnitude better sensitivity) than narrowband receivers to overcome the hidden-terminal problem (Fig. 1.4), shadowing, channel fading, multi-path, etc., lest it causes interference to other users due to incorrect sensing [4].

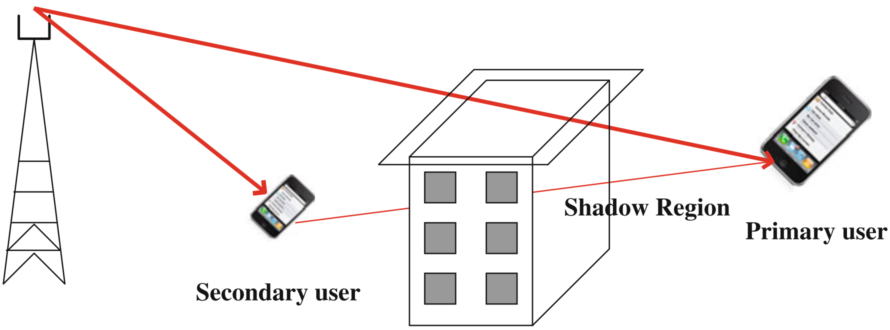


Fig. 1.4 The hidden terminal problem in cognitive radios

1.4.2 Signaling

The signaling in a cognitive radio is somewhat similar to that in traditional radios, in the sense of it being relatively narrowband. However, the cognitive radio signaling transceiver needs to be far more flexible. It should have the capability of operating over a very wide frequency range, changing its bandwidth of operation, altering the transmitted power, as well as using multiple standards for communications.

1.5 Organization

This book focuses on the architecture and circuit design for cognitive radio receiver front-ends.

Chapter 2 explores the different types of architectures for signaling and sensing in software defined radios for cognitive radio applications. A number of competing architectures are reviewed and discussed. Individual blocks and circuit requirements for these architectures are identified, and candidate implementations in literature are described. For spectrum sensing, the need for analog signal processing prior to digitization to lower the total power consumption, is emphasized. Two circuit blocks: the wide-tuning frequency synthesizer for signaling, and the analog signal processor for sensing, are identified as particularly challenging circuit blocks for SDR realization. These circuit blocks are discussed in later sections.

Chapter 3 discusses the design of wide tuning range, low phase noise VCOs for use in SDR signaling applications. The challenges to wide tuning range alongside low phase noise and superior power performance are discussed, followed by an identification of a viable solution using inductor switching. Two prototype designs are discussed that provide excellent power and phase noise performance over a very wide tuning range. Simulation and measurement results of tuning range, power dissipation, and phase noise across the tuning range are presented.

Chapter 4 explores the concept of RF sampling followed by discrete time signal processing prior to digitization for spectrum sensing applications. Specifically, frequency domain discrimination techniques are emphasized to reduce digitizing power. An example architecture is utilized for system level comparison based on analytical power estimates.

Chapter 5 discusses the design of a discrete Fourier transform based RF signal processor prior to digitization. The concept, implementation details, and handling of non-idealities in a Charge Reuse Analog Fourier Transform (CRAFT) engine prototype are described. Measurement results are presented.

Chapter 6 summarizes the book, and draws several conclusions regarding the design of SDR based cognitive radios.

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