# Part One

# Introduction

# 1

# Introduction to Cognitive Communications

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## 1.1 Introduction

Communication devices today are becoming ever more sophisticated and diverse, delivering a plethora of new services and applications. The last hop to the end user, a person or device, is increasingly being delivered wirelessly. This sophistication brings with it complexity, making conventional approaches to organization, implementation and regulation increasingly inadequate.

This is seen especially in the case of usage of the radio spectrum, which has manifested itself as a perceived shortage of spectrum, but this shortage is mainly due to inadequate command and control regulation, and conventional technical understanding – studies have shown up to 90% of the radio spectrum remains idle in any one geographical location.

The rapid improvements in functionality will come to an end if standard approaches to communications delivery are not radically updated. This presents a global challenge that impacts not only on device manufacture, software and firmware, but also on changes to radio regulation, business models and economics. The key to the next revolution in communications delivery is the application of distributed artificial intelligence (i.e. cognition) to the communications devices. This will enable intelligent local decisions to be made on network routing, and spectrum and resource usage, based on interaction with other devices and the local environment. Such decisions can take into account mixed systems and applications, and even devices that break the rules.

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Two fields are already emerging: cognitive radio (CR), which deals with the intelligent assignment and use of the radio spectrum; and cognitive networking, which deals with the intelligent routing of information through a network, taking into account various local constraints. However, this application of distributed artificial intelligence can be extended to other areas in communications that today rely on fixed-rule adaptivity, allowing for the first time, flexible changes to complex varying local circumstances.

Thus the fields of cognitive radio and cognitive networks represent the tip of the iceberg when it comes to how distributed artificial intelligence can be used in communications systems. This is the major reason why we use the more general term *Cognitive Communications* as the main title of this book, so as not to limit ourselves to this somewhat blinkered vision of the application of cognition.

Cognitive Communications brings with it many fundamental challenges, given its breadth and multi-disciplinary nature, taking elements from the main established areas of:

- Wireless communications,
- Distributed artificial intelligence,
- Regulatory policy and economics,
- Implementation.

These areas in themselves derive from the disciplines of electronic engineering, computer science, and economics, creating a complex challenge of how to further this new field. Given the centre of gravity of the research and development today, this has only been partially successful. The vast majority of research is focused on the wireless communications aspects of cognitive radio, including spectrum sensing, dynamic spectrum access, with a tiny minority focused on application of distributed artificial intelligence. Regulatory aspects are largely restricted to application of cognitive radio to the TV White Space (TVWS) bands. The purpose of this book is to try and rebalance and reprioritise this research in the forthcoming chapters, to highlight their contributions to the wider field of Cognitive Communications, and to thereby encourage the existing and future generations of researchers to think further outside of the box; to investigate these new exciting challenges and opportunities that this new way of thinking brings.

In the remaining part of this chapter we delve more deeply into this new way of thinking; we place Cognitive Communications within a wider historical context. We discuss the key components of Cognitive Communications, and finally we provide a short overview of the rest of the book, illustrating how each chapter plays its part in characterizing the different areas of the subject.

## 1.2 A New Way of Thinking

At the core of this new way of thinking is the use of distributed artificial intelligence, where individual agents, but with reference to other agents, make decisions on their next action(s). These local actions replace centralized control or fixed rules, with the aim of better exploiting resources, or controlling behaviour, based on the local environment. What part of communications system or sub-system constitutes an 'agent' is open for definition and study, but in most cases a communication node is considered as a single agent, but there is no reason why an agent cannot be a collection of nodes, or even different parts of a radio system can operate as individual agents, depending on the scale of operation.

Intelligence can be considered as the ability to act appropriately in an uncertain environment, where an appropriate action is one which increases the probability of success, and success is the achievement of behavioural sub-goals that support the system's ultimate goal; that is order is created, rather than anarchy. Intelligence is one of the prerequisites to autonomy. The study of intelligence, learning, and reasoning has been around for a number of years, but it is only now that concepts such as reinforcement-based learning, game theory, evolutionary computation and neural networks are being actively applied to heterogeneous cognitive radio-based systems. With the exception of game theory, historically this work has been focused on centralized homogeneous schemes, which aim to optimize channel usage for a particular configuration [1–3]. Here, in this book we mainly focus on fully distributed techniques. There have been some recent activities using reinforcement based learning [4] and game theoretic approaches [5–8]. However, this has still only been applied to the cognitive radio area of Cognitive Communications.

A significant portion of this book focuses on distributed artificial intelligence strategies using a multi-agent system mapped directly on to the nodes of a heterogeneous wireless system. As we shall see, agents often employ negotiation strategies, such as auctions, to achieve local and global goals. With multi-agent systems the emergent properties of self-organization, robustness, adaptivity and tolerance arise naturally to a wide variety of disturbances (e.g. from interference-, failure-, and change-related issues).

In order for such a distributed set of agents to reach successful decisions they need to interact with each other and the wider environment. Figure 1.1 shows how different agents interact within a cognitive network environment. Two loops are important: the Action and Sensing loop, and the Reasoning and Learning loop. Dealing first with the outer loop, each node observes, or takes in inputs from the environment, for example context of operation, traffic, interference level, primary user operation, which are then processed. Constraints are then applied and this information is then processed by the Reasoning and Learning loop where the information is further processed, taking into account historical context and learned behaviour. A decision is made as to what action to take next, for example a frequency resource to use is selected. The action is then carried out which causes the environment to change. For example a new transmission takes place on a particular frequency band, causing the interference level on the frequency to change. This change in the environment is observed by all the other entities in the system who may in turn choose to react and change their behaviour. This cycle is repeated until there are no further changes to the environment – in practice there is constant change, as it is likely that some outside stimuli, for example node mobility, new message, will cause

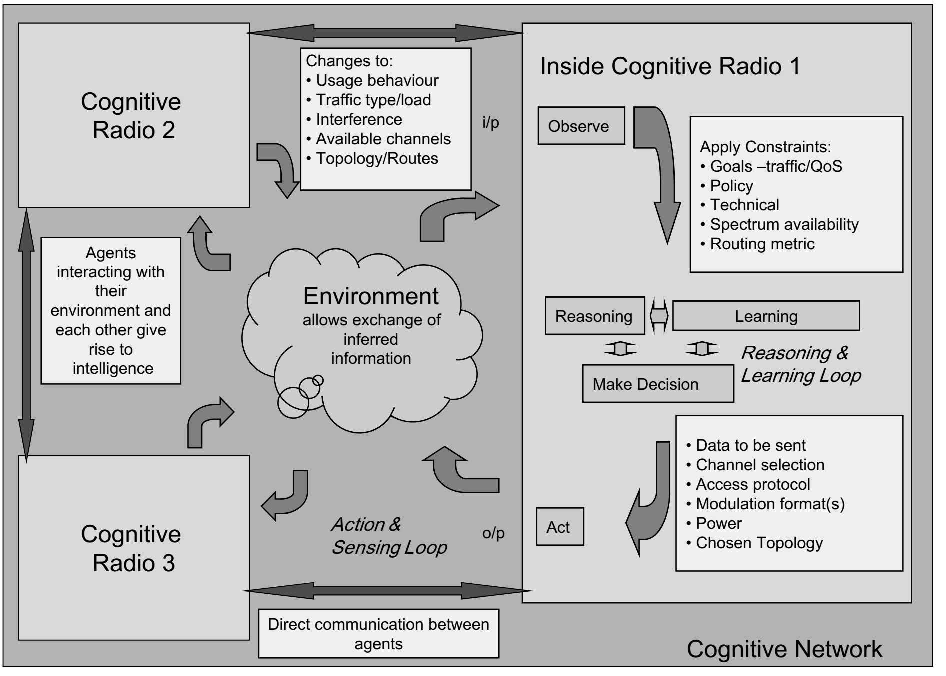


**Figure 1.1** Example of how distributed artificial intelligence is used in a cognitive network.

the environment to change. The inner loop, Reasoning and Learning Loop, is probably the area that requires the most further research and development, and is ultimately responsible for giving the agent (and the loops collectively in each agent, that is the system) its intelligence. This is made up of reasoning and learning. Traditionally dynamic systems and dynamic spectrum assignment make use of reasoning – the application of fixed rules to decide the course of action. An example of this could be 'to pick the best channel'. In Cognitive Communications, such strategies can be influenced by learning (e.g. machine learning), which may be used to take into account historical information, and/or manipulate competing parameter inputs taking into account behaviour of other nodes in the system. This provides a greater degree of flexibility, allowing the behaviour of the agent/node or system to adapt to changes in the system. A good example of this is shown in a later chapter, where users (transmitter and receiver pairs) can learn over time to avoid one another's transmissions.

Significantly, more discussion is given on how different forms of learning can be used in different situations later on in this book.

## 1.3 History of Cognitive Communications

To obtain a complete picture of the history of Cognitive Communications, one has to delve back into the little-known research done on distributed dynamic channel assignment in the early 1990s [9–11]. This dealt with the dynamic assignment of radio resources based on fixed rules, where all nodes operated the same algorithm. The relevant research reached maturity in the late 1990s. Early applications were military-based, and largely for ad hoc networks, and used to ensure the radio spectrum could be (re)assigned to combat enemy threats and jamming [12]. At the end of the 1990s, with the use of the 2.4 GHz unlicensed band, protocols such as IEEE 802.11, and Bluetooth adopted dynamic techniques based on listen before talk strategies, along with DECT at 1.9 GHz, for indoor use.

In 1999 Joseph Mitola III, suggested 'cognitive radio' be developed, where artificial intelligence was used to control radios [13, 14], allowing them to dynamically access the radio spectrum with the appropriate protocol, taking into account context and usage information. Refinements by Simon Haykin [15], suggested new protocols that the techniques could be applied to dynamic spectrum access, now considered as cognitive radio. These two major innovations have now made the research field mainstream over the last five years.

Within two years it is anticipated that cognitive radio will be used in the TV bands by devices that are used to exploit the 'white space' spectrum; a spectrum that is unoccupied in a particular geographical location [16]. To do this, devices need to be aware of their surroundings and who is operating in the spectrum. A mixture of primary user spectrum database and sensing to locate secondary users has been put forward as a solution in both the UK [17] and USA [18].

Mainstream research, as we mentioned earlier, is now focussed on a number of narrow, but relevant, fields within cognitive radio and spectrum sensing [19, 20], both individual and cooperative forms have received much attention recently. Latterly, research into architecture configurations and assignment techniques that can exploit spectrum databases has been put forward. Research is also underway on the spectrum assignment techniques themselves [21, 22] and how cognitive radio can be used to assign the radio spectrum. Work including artificial intelligence is still in its infancy, with early suggestions to use techniques of a centralized nature [23], or in a distributed form for part of the system control [24, 25]. More recently distributed artificial intelligence techniques have been used to help prioritize radio resources (spectrum and other resources) [26–28]. These are largely based on reinforcement learning.

A key focus within cognitive radio has been to replace the conventional command and control approach with something more flexible that improves the utilization of the radio spectrum and efficiency. Focus has been on the development of bandwidth efficient systems, rather than on something that improves the spectrum utilization. This bandwidth efficient design strategy is a result of decades of radio regulatory policy [29], because communication systems were not sufficiently intelligent or adaptive. This has resulted in a perceived spectrum shortage, despite studies that show that up to 90% of the radio spectrum is unoccupied at any one location or time [30]. Today, this is not the case; systems can be made increasingly agile [13, 31], making it now possible to improve the use of the radio spectrum in order to reduce the energy requirement, while also encouraging new applications and users. In principle, users and systems should aim to maximize their use of unoccupied or free spectrum (in order to use more energy efficient, low rate modulation), while also avoiding interference to/from other users. *The key issues are how to intelligently select the free spectrum, and how such intelligent choices of spectrum by one user/system will positively change the behaviour of other like-minded users operating in the same geographical area.*

Significant resources are now being put into the research topic. A well-known early project in the USA dealing with cognitive aspects was the DARPA XG project [21]. There are a number of European Union projects in this general area looking at different cognitive approaches for exploiting the radio spectrum. These include BuNGee [32], COGEU [33], FARAMIR [34], ARAGORN [35], E3 [36], and QOSMOS [37]. Cognitive techniques are also being directly incorporated into LTE-A [38], showing that in general key cognitive aspects are now reaching mainstream applications.

Most recently, using cognitive principles are being considered as way to improve energy efficiency of radio systems, with a number of projects and papers discussing the relevant options. The FP7 project SACRA [39] applied multi-band cognitive radio (CR) technology for energy and spectrum efficiency in a single broadband communication device, rather than the whole system. This kind of research application is very much in its infancy, but given the rise of ‘green issues’ and ‘green radio’, we can expect significant growth in this area over the next four or five years.

## 1.4 Key Components of Cognitive Communications

There are several key components of Cognitive Communications and we will briefly outline them here:

- **Awareness of the environment of operation** – This is fundamental to the awareness of all cognitive systems. Without some form of input stimuli, it would be impractical for devices and systems to make decisions on how to act. Obvious examples of this include spectrum sensing, but also higher level context information may be important, regulatory policy, and even economics. Recently the agenda has shifted to also consider the use of spectrum databases, as a more centralized way of making devices and systems aware of their environment.
- **Wireless architectures** – The architecture of cognitive systems and devices still is not a mature subject area, as we will see in later chapters. There is no common agreement of whether a cognitive communications device in the broadest sense should be based on a software radio or software defined radio, or perhaps something with less sophisticated capabilities. Key aspects of any device will include the ability to reason, maybe to learn, but that can be achieved with very simple processing elements. Complex approaches involving high levels of signal processing, in order to perform spectrum sensing, may not be required. One can even envisage cognition be applied to basic nodes, such as self-powered wireless sensor nodes in order to improve performance.

- **Control information exchange or inference** – This deals with how devices and systems become aware of their environment. Is it through direct information exchange with neighbours or a central entity for instance? Or is it through inference? A good example of inference is spectrum sensing. For spectrum sensing to work we have to have some threshold to judge when a channel is occupied, or other measures of what to expect and compare with such as modulation waveform, or power level, to determine the impact the device will have on others using the same resource. Direct information exchange can be more reliable, but that comes with a signalling overhead, requiring either a common control channel, or an agreed means of communication. Inference, has the potential to be more efficient, but may be more unreliable, especially in noisy environments. In practice it is expected to see a hybrid approach between the two. We will see in later chapters that learning can be used to reduce the reliance on the need for this information.
- **Cognitive engines** – This is the processing entity within a device or system that is responsible for processing the information coming into the device, possibly applying learning, and through a reasoning process deciding on the next action. It can be considered as being made up of a learning engine, knowledge base, and reasoning engine, and is discussed in more detail in later chapters.
- **Resource assignment** – This is at the heart of cognitive communications. In cognitive radio it relates to the temporal occupancy of a portion of the radio spectrum. In the case of cognitive networks it will additionally relate to the number of devices occupying the radio spectrum, and their general spatial behaviour. In the case of cognitive acoustics, as discussed later, it could relate to the occupancy of the acoustic channel.
- **Physical layers** – This is needed in all cognitive communications devices to control the physical medium itself, for example the radio spectrum or acoustic channel. While the learning and reasoning approaches can be made largely independent of the physical layers in each system, systems may behave more accurately if key physical layer parameters are taken into account. Convergence to a local optimum, or optimum solution, may also be faster. It is therefore important that a suitable physical layer model be used when designing these upper layers.

## 1.5 Overview of the Rest of the Book

We have already seen from this brief introduction that Cognitive Communications promises to revolutionize the way wireless communication devices and networks behave through ‘intelligent’ assignment of resources and operation.

Since Cognitive Communications requires a multi-disciplinary approach, this book will be divided into several parts, each dealing with key aspects of this new multi-disciplinary research field:

- Part 2: Wireless communications
- Part 3: Distributed artificial intelligence

- Part 4: Regulatory policy and economics
- Part 5: Implementation

A brief summary is now provided for each part.

### *1.5.1 Part 2: Wireless Communications*

This part deals with aspects relating specifically to wireless communications issues, and is divided into three chapters.

Chapter 2 provides an introduction to cognitive radio and networks when they are used to deliver heterogeneous networking. With current wireless communications systems and networks, people will normally select a wireless network service provider and subscribe to it. This approach has worked well, but in future when pooled radio spectrum is used the actions of one service provider will impact on the others sharing the same spectrum. This independent network design and operation increases inter-cell interference among different networks and may not provide efficient use of the radio resources unless internetworking and cooperation is used. This chapter will examine these issues in the context of upcoming 4G and beyond 4G systems.

Chapter 3 then goes on to address the resource management problem in multi-user multi-carrier (MC) based CR systems. The chapter starts by mentioning the advantages of using MC techniques in a CR environment. Afterwards, the relative work on the resource management problem in OFDM systems is reviewed in both non-cognitive and cognitive environments. An optimal solution to the problem is derived for both downlink and uplink scenarios that ensure that interference to a licensed primary user system can be guaranteed to remain under a pre-specified interference temperature limit. The chapter then discusses the issues of high computational complexity, making it suitable for upper bound comparison only, and instead presents a number of efficient sub-optimal schemes with lower complexity that are more suited to practical implementations. Performance of the schemes is compared.

Chapter 4 discusses the use of filter bank techniques for multi-carrier cognitive radio systems explaining the similarities and differences with other multi-carrier technologies. Examples of adaptive threshold based filter bank within an IEEE 802.22 WRAN context are investigated. This is followed by discussion of transform decomposition for spectrum interleaving in a multi-carrier cognitive radio systems. A detailed comparative performance evaluation illustrates the main benefits of filter bank techniques.

In the final chapter of Part 2, Chapter 5 then considers how cognitive radios can form infrastructureless wireless networks that adapt to a variety of spectrum allocation and interference conditions by collaboratively selecting appropriate radio and network parameters. The key issue of how to address inter-node coordination in dense network scenarios is discussed, given the significant traffic overhead that coordination traditionally brings. The chapter then reviews techniques that have been designed for ad hoc cluster formation in cognitive radio networks. A distributed approach is then presented which relies on only local network information to form efficient clusters based on the affinity propagation message-passing technique. This approach groups various nodes by measures of similarity, which are selected based on application requirements. Case studies and comparisons to commonly used clustering techniques will be presented to demonstrate the merits and weaknesses of the approach. Future directions are finally presented.

### *1.5.2 Part 3: Application of Distributed Artificial Intelligence*

This part then shows how different forms of distributed artificial intelligence (DAI) can be applied to wireless devices in order to enhance the levels of distributed control of such systems of devices. It is divided into five chapters.

Chapter 6 provides a general overview of various learning techniques and how they can be applied, as well as the ways they have been used in past research for empowering cognitive radios and networks.

Chapter 7 then examines the impact of different forms of reinforcement learning on distributed power control and channel access in cognitive mesh network topologies. Q-learning based intra- and inter-cluster distributed iterative power control is specifically examined. This is followed by conjecture based multi-agent Q-learning techniques applied to both power control and opportunistic channel access, which are later extended to quantify the benefits of cooperation between agents. The chapter concludes with a discussion of future problems and applications.

In Chapter 8 the application of DAI to open spectrum is discussed, which is an increasingly important topic in the area of wireless communications. Open spectrum can be considered as spectrum that is available to many different types of users that obey simple rules, for example coexistence etiquettes, which limit transmit power and transmission duration, often in the absence of a specific primary user. Examples already include the ‘unlicensed’ bands and in the future open spectrum could be extended to lightly licensed frequency bands. This chapter shows how different types of reinforcement learning can be used to enhance the coexistence of different types of users. The fundamentals of applying reinforcement learning to cognitive radio are described, including the techniques developed to tackle the crucial exploration-exploitation trade-off seen in reinforcement learning based cognitive radio approaches. The chapter will also briefly discuss the impact of ‘docition’, weight based information exchanged between cognitive devices, in order to improve the learning rate or adaptability of the system.

Chapter 9 continues the DAI theme further by focusing on the context in which a cognitive device will operate. In most situations knowledge needs to be built from the vast amount of raw data which stems from disparate sources including service, network and user/device domains. This is not trivial, which means that advanced learning techniques are a vital tool for reducing complexity and building truly useful knowledge. The chapter shows how this acquired knowledge can be used to provide intelligent and qualitative decisions on resource usage and configuration by the cognitive elements. For instance, raw data generated by users/devices, services and networks can be combined with learning techniques in order to yield knowledge. These aspects are illustrated through the description of a knowledge-based context diagnosis and prediction scheme and its application to modern, heterogeneous, wireless and cognitive communication environments.

Chapter 10 examines the issue of social behaviour in cognitive radio. It is argued that social behaviour has a wider impact on software defined radio devices, which have many more actions available to them. The chapter initially considers the mechanisms of cooperation and recommendation, and the associated learning techniques. Practical examples, such as cooperative spectrum sensing and collaborative learning are used to illustrate the principles. Comparisons are also drawn between social behaviour in cognitive radio and electronic commerce. Then, social behaviour is analysed using the mathematical techniques of interacting particles and epidemic propagation.

### *1.5.3 Part 4: Regulatory Policy and Economics*

This part deals with the implications of regulatory policy and the economics of adopting a more cognitive approach to radio spectrum usage compared with more conventional approaches. This is dealt with in a single extended chapter.

Chapter 11, looks at the regulatory, policy and economics issues of cognitive communications in the context of secondary spectrum access (SSA), given the high potential value of secondary spectrum access. It is explained that there still is a large degree of uncertainty associated with SSA that will have to be mitigated before successful large scale deployments are developed and the potential economic and social value realized. In order to address these uncertainties, the interdependency between the regulatory environment, the capabilities of the CR technology and the business opportunities have to be considered. The regulatory environment and the technology will facilitate certain business opportunities for secondary spectrum access but at the same time will also put restrictions to these opportunities.

This chapter starts with a short introduction of the radio regulatory environment, explaining the changes that have to be made to allow secondary spectrum access. This is followed by a summary of the activities that are currently carried out on both an international level and national level to allow secondary access. It is followed by a short description of the various technological solutions to detect and exploit secondary access opportunities. Business opportunities for SSA are then considered, including the technical and regulatory considerations that will put restrictions on the business opportunities of SSA. The section analyses the various criteria that influence the business case for SSA, with examples given of how SSA can be implemented in specific bands. The chapter ends with conclusions and some recommendations on the policy changes and technology advances that are required for successful implementation of SSA.

### 1.5.4 Part 5: Implementation

The remaining part of the book discusses application and implementation of cognitive communications techniques for a variety of different application areas. It is divided into four chapters.

Chapter 12 provides a comprehensive survey of the state-of-the-art in technology (including spectrum databases, sensing and detection, physical layer, coexistence and etiquette protocols) for cognitive access to TV White Spaces (TVWS). It examines the regulation and standardization of cognitive access to TVWS. These are placed in the context of estimates of the spectrum opportunity in the UK, US, Germany, Sweden and elsewhere, along with the commercial use cases associated with this form of secondary spectrum access based on real-life scenarios from wireless industry.

A second application area of cognitive communications, as discussed in Chapter 13, is its application to Cognitive Femtocell Networks (CFN). Femtocell Access Points (FAP) are low-cost, plug-and-play devices which aim to extend radio coverage in indoor environments, in locations where macrocell data services suffer from poor signal strengths. Despite the promise of high data rates for indoor scenarios, FAP pose a number of significant research challenges due to uncoordinated user deployment, which significantly restrict the ability to undertake network planning. This chapter introduces the basic concepts underpinning CFN technology before providing a comprehensive discussion on current challenges and possible solutions relating to CFN and FAP. Key challenges are discussed of managing the different kinds of interference and dynamically allocating resources in the most efficient way.

Chapter 14 discusses the exciting prospect of applying cognitive communications techniques to the emerging field of cognitive acoustics. The chapter first provides an introduction to the concept of cognitive acoustics, as a way of providing those readers with a background in wireless communications with sufficient knowledge to understand the remaining ideas. Techniques applicable to the application area of underwater acoustics are then discussed. The fundamentals of reinforcement learning applied to cognitive acoustics is then explained, and it is shown how such techniques can be used to extend the lifetime of the network. Numerical results and operating examples illustrate the resulting behaviour.

In the final chapter, Chapter 15, the implications of cognitive communications on components and devices are discussed. For example cognitive radios call for specific functionality, like spectrum sensing and agile transmission and reception. It provides system architects an insight into the limitations of practical transceivers. The chapter shows how it is not possible to obtain the functionality by using a digital implementation by directly attaching an Analogue to Digital Converter (ADC) and Digital to Analogue Converter (DAC) to the antenna, but instead requires a transceiver with filtering and frequency conversion. Owing to the potentially significant digital signal processing required to deliver such capabilities, the chapter will show that CMOS based devices are ideal candidates for the analogue hardware, due to their low-cost and their ability to integrate both analogue and digital components on one integrated circuit. The chapter shows, by starting from the dedicated design of traditional CMOS transceivers, that the flexibility required by CR calls for changes in the architecture. Several solutions to improve the design of CR transceivers are discussed.

## 1.6 Summary and Conclusion

This chapter has provided an introduction to the field of Cognitive Communications, a multi-disciplinary field that encompasses the main areas of wireless communications, distributed artificial intelligence, regulatory policy and economics, and implementation. Several key components are critical to Cognitive Communications, including an awareness of the environment, the architecture of the devices, and whether or how control information is exchanged or inferred by the cognitive engine, that is how a system learns and reasons, along with the resource assignment and underlying physical layers. To date most of the research efforts have been spent on the subject of cognitive radio, and the wireless communications aspects, but we emphasize here the other disciplines, particularly how distributed artificial intelligence can be used to allow systems to learn about the environment in which they operate and reduce complexity. Regulatory policy remains a big challenge but as we shall show also presents an opportunity. We have highlighted that various implementations are being developed, particularly for applications in the TV White Space bands, as well as taking advantage of femtocells and exciting opportunities abound in completely new areas such as cognitive acoustics.

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